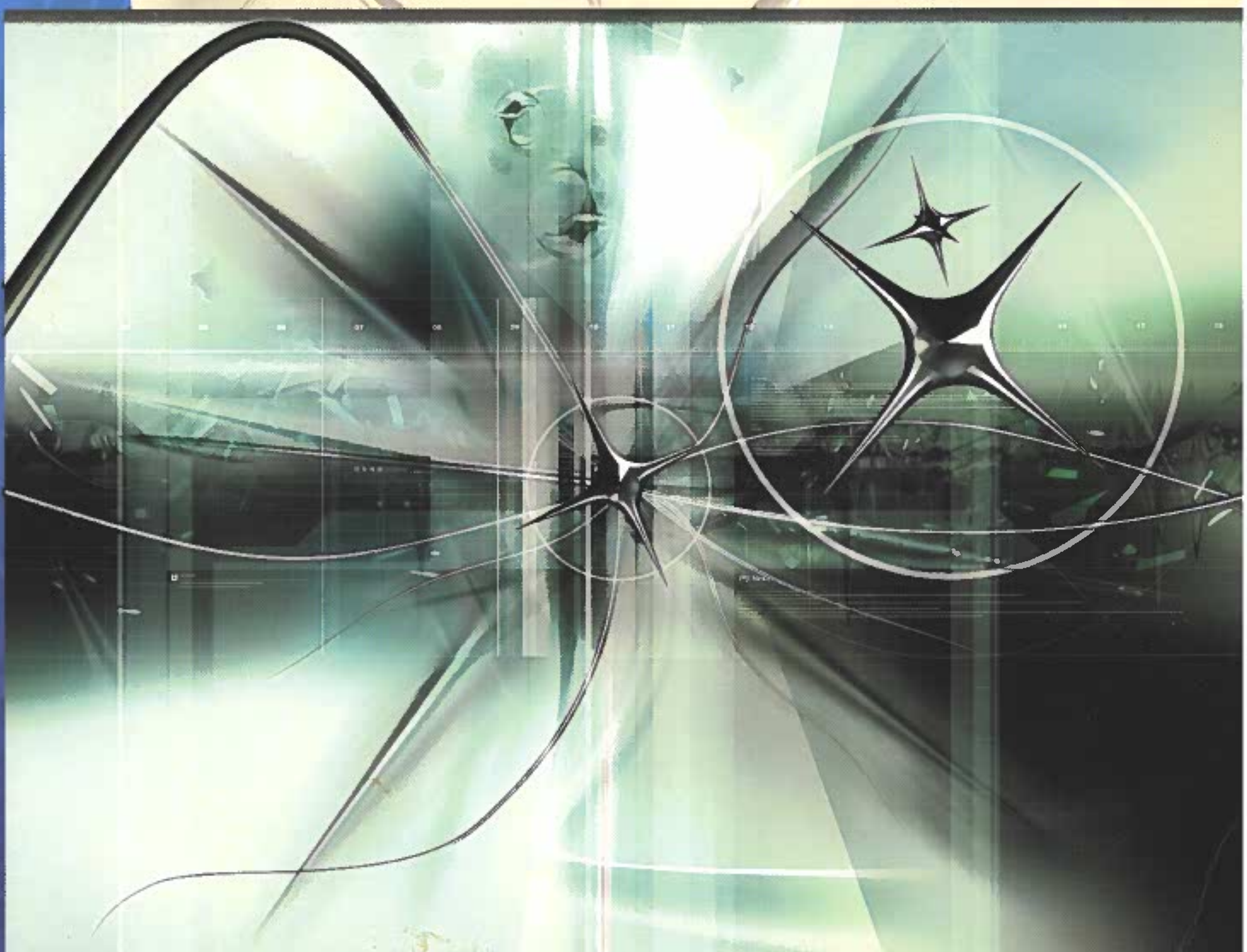
Instrumentation and Process Control



Terry Bartelt

INSTRUMENTATION AND PROCESS CONTROL

Contents

Preface xi

Section 1 Industrial Control Overview

Chapter 1 Introduction to Industrial Control Systems 3

Introduction 3
1-1 Industrial Control Classifications 4
Motion and Process Controls 4
Open- and Closed-Loop Systems 5
1-2 Elements of Open- and Closed-Loop Systems 8
1-3 Feedback Control 10
1-4 Practical Feedback Application 12
1-5 Dynamic Response of a Closed-Loop System 13
1-6 Feed-Forward Control 13
Problems 15

Chapter 2 Interfacing Devices 17

Introduction 17
2-1 Fundamental Operational Amplifiers 17
Operational Amplifier Comparator 18
Inverting Op Amp 19
Summing Amplifier 20
Noninverting Amplifier 21
Difference Operational Amplifier 21
2-2 Signal Processors 22
Integrator Operational Amplifier 22
Differentiator Operational Amplifier 23
Wave-Shaping Schmitt Trigger 24
2-3 Comparator Devices 26
Digital Magnitude Comparator 26
2-4 Optoelectronic Interface Devices 27
Photodiodes 29
Phototransistors 29
Photo SCR 29
Photo Triac 30
Optoelectronic Packaging 30
2-5 Digital-to-Analog Converters 31
Integrated-Circuit Digital-to-Analog Converter 34
2-6 Analog-to-Digital Converters 34
Integrated-Circuit Analog-to-Digital Converter 36
2-7 Timing Devices 38
555 Astable Multivibrator 40
555 Monostable Multivibrator 42
Problems 44

Section 2 The Controller

Chapter 3 The Controller Operation 49

Introduction 49
3-1 Control Modes 50
3-2 On-Off Control 50
3-3 Proportional Control 53
Controller Amplification 55
Steady-State Error 56
3-4 Proportional-Integral Control 59
3-5 Proportional-Integral-Derivative Control 61
3-6 Time-Proportioning Control 65
3-7 Time-Proportioning Circuit 66
Problems 68

Section 3 Process Control and Instrumentation

Chapter 4 Pressure Systems 73

Introduction 73
4-1 Pressure Laws 74
4-2 Properties of a Liquid 74
Height 74
Weight 75
Temperature 75
Atmospheric Pressure 75
Mechanical Machines 76
4-3 Properties of a Gas 76
Temperature of the Gas 76
Volume of the Gas Container 76
Gas Removal from a Container 77
4-4 Pressure Measurement Scales 77
Gauge Pressure Scale 77
Absolute Pressure Scale 78
Differential Pressure Scale 79
Vacuum Pressure Scale 80
4-5 Pressure Measurement Instruments 80
4-6 Nonelectrical Pressure Sensors 80
Liquid Column Gauges 80
Mechanical Gauges 83
4-7 Electronic Pressure Sensors 85
Semiconductor Strain Gauges 85
Transverse Voltage Strain Gauge 85
Variable Capacitor Pressure Detector 87
4-8 Pressure Control Systems 87
Hydraulic Systems 87
Pneumatic Systems 89
Vacuum Systems 89

Static Pressure Systems 90
Steam Pressure Systems 91
Problems 92

Chapter 5 **Temperature Control** **93**

Introduction 93
5-1 Fundamentals of Temperature 94
5-2 Thermal Control Systems 94
5-3 Thermodynamic Transfer 94
5-4 Thermal Energy Source 95
Industrial Furnaces 95
Cooling Systems 96
5-5 Temperature Measurements 97
Temperature Scales 98
Differential Temperature 99
5-6 Temperature Indicating Devices 100
Crayons 101
Paints 101
Pellets 101
Labels 101
Liquid Crystal Indicator 101
Liquid Filled Thermometers 102
5-7 Electronic Sensors 103
Thermistor 103
Resistance Temperature Detectors 105
Thermocouple 106
Probe Assemblies 111
Radiation Thermometry 112
Problems 115

Chapter 6 **Flow Control** **117**

Introduction 117
6-1 Systems Concepts 118
Reasons for Control 119
6-2 Flow Units of Measurement 119
Volumetric Flow Rate 119
Flow Velocity 120
Mass Flow Rate 120
6-3 Solid Flow Measurement 120
6-4 Fluid Flow Measurement 121
Pipe Flow Principles 122
Fluid Flowmeter Classification 123
6-5 Electronic Sensors 129
Coriolis Meters 129
Rotor Flow Detectors 129
Electromagnetic Flow Detectors 129
Thermal Flowmeters 130

Vortex Flowmeters . . . 130
Ultrasonic Flowmeters . . . 131
Time-of-Flight Flowmeter . . . 132
6-6 Flowmeter Placement . . . 133
6-7 Selecting a Flowmeter . . . 133
Problems . . . 134

Chapter 7 **Level Control Systems** . . . **135**

Introduction . . . 135
7-1 A Level Control System . . . 136
Power Sources . . . 137
Transfer Systems . . . 137
7-2 Methods of Measurement . . . 137
Point Level Measurements . . . 138
Continuous Level Measurements . . . 138
7-3 Level Measurement Methods . . . 138
Float and Displacement Methods . . . 139
7-4 Electronic Sensors . . . 144
Conductive Probes . . . 144
Capacitive Probes . . . 144
Ultrasonic Sensors . . . 145
7-5 Selecting a Level Sensor . . . 147
Problems . . . 148

Chapter 8 **Analytical Instrumentation** . . . **149**

Introduction . . . 149
8-1 pH Measurement and Control . . . 150
pH Measurements . . . 152
Controlling pH . . . 154
8-2 Conductivity . . . 156
Conductivity Electrode Probe . . . 157
Conductivity Inductive Probe . . . 158
Conductivity Applications and Control . . . 158
8-3 Combustion Analyzers and Control . . . 160
Combustible Gases . . . 160
Hydrocarbon Gases . . . 161
Controlling Combustion . . . 162
8-4 Humidity . . . 163
Quantitative Measures of Humidity . . . 163
Absolute Humidity Sensor . . . 164
Relative Humidity Detectors . . . 165
Dew Point Measurements . . . 167
Controlling Humidity . . . 168
8-5 Sampling Measurement System . . . 169
Problems . . . 169

Chapter 9 **Industrial Process Techniques and Instrumentation** . . . **171**

Introduction . . . 172
9-1 Batch Processes . . . 172
Control Requirements . . . 173

Types of Batch Processes 174
Chemical Reaction 174
9-2 Continuous Processes 175
Control Requirements 175
9-3 Instrumentation 178
9-4 Measurement Devices (Sensors) 179
Dynamic 179
Static 179
9-5 Feedback Loop Interface Instruments 182
Transmitters 182
Transducers 183
9-6 Controllers 186
Pneumatic Controllers 186
Panel-Mounted Controllers 187
Personal Computers 187
Programmable Logic Controllers 188
Distributed Control Systems (DCS) 188
9-7 Monitoring Instruments 189
Indicators 189
Alarms 190
Recorders 190
9-8 Manipulation Devices (The Final Control Element) 191
The Control Valve 191
DC and AC Motors 199
Problems 199

Chapter 10 **Instrumentation Symbology** **201**

Introduction 201
10-1 General Instrument Symbols 201
Individual Instruments 201
10-2 Tag Numbers 202
10-3 Line Symbols 205
10-4 Valve and Actuator Symbols 206
Control Valves 206
Actuators 207
10-5 Reading a Single Loop 207
10-6 Information Block 208
Problems 210

Chapter 11 **Process Control Methods** **213**

Introduction 214
11-1 Open-Loop Control 214
11-2 Closed-Loop Control 214
Process Behavior 215
11-3 Single-Variable Control Loop 216
Response Time of the Instruments 216
Pure Lag of the Controlled Variable 217
Dead Time 218
11-4 Selecting a Controller 219

11-5 On-Off Control 219
Case Studies—Using Different Control Modes 221
11-6 Continuous Control 223
Proportional Mode 223
Integral Mode 229
Derivative Mode 231
11-7 Advanced Control Techniques 234
Cascade Control 235
Feed-Forward Control 237
Ratio Control 238
Adaptive Control 239
Problems 241

Chapter 12 **Instrument Calibration and Controller Tuning 245**

Introduction 245
12-1 Instrument Calibration 246
12-2 Reasons for Performing Calibrations 246
12-3 Calibration Preparation 247
12-4 Standard Calibration Procedure 248
12-5 Five-Point Calibration Procedure 249
Calibration Check 250
Calculating the Input Values 250
Calculating the Output Values 250
Analysis of Calibration Data 250
Transmitter Zero and Span Adjustments 250
Verification of Adjustments 251
12-6 Tuning the Controller 252
Trial-and-Error Tuning Method 253
Ziegler-Nichols Tuning Methods 254
Ziegler-Nichols Continuous Cycling Method 254
Ziegler-Nichols Reaction Curve Tuning Method 260
Controller Autotuning 265
Problems 265

Answers to Odd-Numbered Problems 267

Glossary 271

Index 277

Intended Audience

This book is intended for use in electronics-based industrial courses. It is designed for either two- or four-year technology programs, such as Electronics Technology, Instrumentation Technology, Industrial Maintenance, Electromechanical Technology, and Automated Manufacturing Systems.

The book provides comprehensive coverage of components, circuits, instruments, and control techniques used in industrial process control systems. The focus is on operation, rather than mathematical design concepts. To understand the material, recommended prerequisites include DC/AC fundamentals, solid state devices, and digital electronics.

Textbook Organization

The book is organized in a logical sequence that first examines a block diagram of an industrial control system and then expands on the function of measurement devices, instruments, and control techniques.

SECTION 1: Industrial Control Overview

Chapter 1, *Introduction to Industrial Control Systems,* introduces the basic concepts of open- and closed-loop systems common to motion and process control.
Chapter 2, *Interfacing Devices,* describes the operation of various IC devices such as operational amplifiers, D/A and A/D converters, 555 timers, and optocouplers used in circuits throughout the text.

SECTION 2: The Controller

Chapter 3, *The Controller Operation,* describes On-Off, proportional, integral, derivative (PID), and time proportioning operations performed by the control block of a closed-loop system.

SECTION 3: Process Control and Instrumentation

Chapter 4, *Pressure Systems,* describes the scientific fundamentals of pressure and the operation of instruments used to make measurements.
Chapter 5, *Temperature Control,* describes the scientific principles of temperature and the operation of instruments used to make measurements.
Chapter 6, *Flow Control,* describes the scientific fundamentals of flow and the operation of instruments used to make measurements.
Chapter 7, *Level Control Systems,* describes the scientific principles of level and the operation of instruments used to make measurements.
Chapter 8, *Analytical Instrumentation,* describes the chemical properties of solutions, such as pH, conductivity, combustion, humidity, and instruments used to make measurements.
Chapter 9, *Industrial Process Techniques and Instrumentation,* provides information on production processes and the instruments used to monitor, control, and manipulate process variables, such as pressure, temperature, level, and flow.
Chapter 10, *Instrumentation Symbology,* provides information about drawings used in process control called P&IDs (Piping and Instrumentation Diagrams), such as symbols, Tag Numbers, Functional Identifiers, Line Symbols, and Title Blocks.
Chapter 11, *Process Control Methods,* describes various control techniques, such as On-Off, PID, feed-forward, ratio, cascade, and adaptive.
Chapter 12, *Instrument Calibration and Controller Tuning,* describes how to perform calibration procedures on instruments, and how to properly tune controllers using the Ziegler-Nichols method.

Features

- Systems approach to understanding industrial process control systems. Organization begins with a block diagram of an industrial control system and then expands on the function of measurement devices, instruments, and control techniques.
- Broad and comprehensive coverage of instrumentation and process control.
- Follows a non-mathematical approach to industrial control techniques, such as On-Off, PID, ratio, cascade, feed-forward, adaptive, and time proportioning.

Supplements

Lab Manual

Contains 26 class-tested experiments written by the author. All answers to the Lab Manual are provided for instructors. (ISBN: 1-4180-6339-8)

e.resource™

This electronic Instructor's Management System is an educational resource that creates a truly electronic classroom. The CD contains tools and instructional resources that will enrich your classroom and make your preparation time shorter. The elements of *e.resource* link directly to the text and tie together to provide a unified instructional system. (ISBN: 1-4180-4172-6)

Features contained in *e.resource* include:

- **Instructor's Guide:** This comprehensive instructor's guide contains solutions to all end-of-chapter problems. It also includes a list of vendors who sell training equipment to perform laboratory experiments.
- **Lab Manual Solutions:** Solutions to the Lab Manual's Procedure and Experiment Questions are provided.
- **PowerPoint Presentation:** These slides provide the basis for a lecture outline that helps you to present concepts and material. Key points and concepts can be graphically highlighted for student retention.
- **Computerized Testbank:** This computerized testbank includes over 600 questions such as true/false, multiple choice, completion, and short answer, provided in multiple formats to assess student comprehension.
- **Image Library:** Images from the textbook allow you to customize PowerPoint presentations, or to use them as transparency masters. Image Library enables the user to browse and search images by using key words. This is a quick and easy tool for enhancing teaching and research projects.
- **Electronics Technology Web site:** Additional online resources are available at ***www.electronictech.com.***

Additional Resources

During the past three years, the author has participated in a National Science Foundation (NSF) project to create lessons on a computer called learning objects. Learning objects are brief lessons that utilize Flash software to provide animation to describe a concept. In 2005, Terry Bartelt was awarded an NSF grant to continue the project for three more years to create more learning objects, many of which will cover concepts in this textbook. These learning objects are accessible at the following Web site address: ***http://its.fvtc.edu/bartelt***

Acknowledgments

The author and Thomson Delmar Learning gratefully acknowledge the contributions of the following reviewers:

Chenggang Mei
Southeast Missouri State University
Cape Girardeau, MO

George Washburn
West Kentucky Community
and Technical College
Paducah, KY

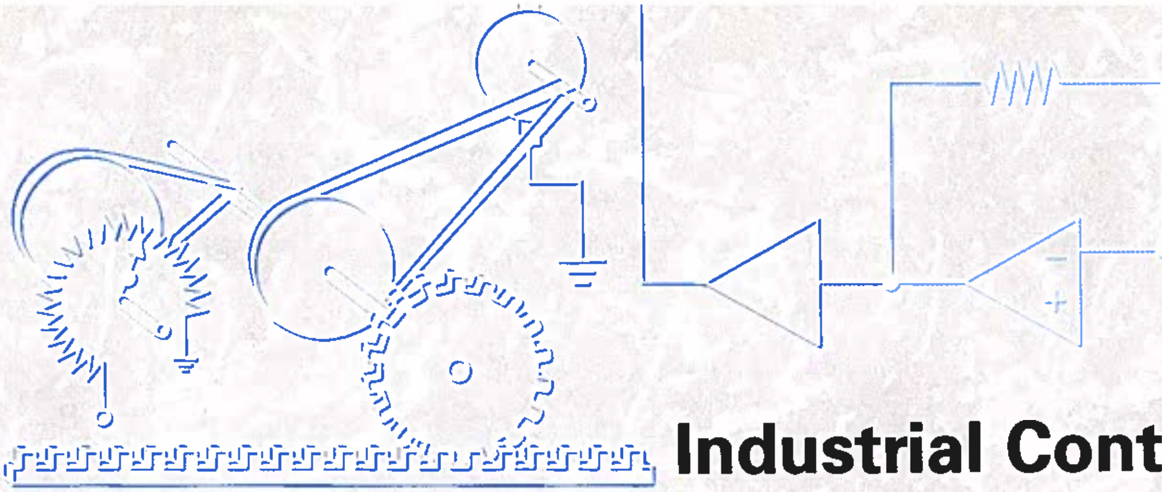
Biswajit Ray
Bloomsburg University
Bloomsburg, PA

Randall Moser
Pennsylvania College of Technology
Williamsport, PA

Ken Warfield
Shawnee State University
Portsmouth, OH

David Luneau
University of Arkansas
Little Rock, AR

I would like to express my appreciation to Craig Hemken, John Casey, students, and reviewers who provided many valuable suggestions for the manuscript. I also thank Michelle Ruelos Cannistraci of Thomson Delmar Learning for her efforts during the developmental stages of the book.



SECTION

1

Industrial Control Overview

OUTLINE

Chapter 1 Introduction to Industrial Control Systems

Chapter 2 Interfacing Devices

Section one introduces key concepts in industrial control. The first chapter introduces the student to the ways in which industrial control systems are classified. It then provides an introductory overview of the elements that make up an industrial control loop.

Chapter 2 describes the operation of discrete components and integrated circuits that are used throughout the book.

The remaining sections describe each element of a control loop in detail so that the entire spectrum of industrial control is addressed.

CHAPTER 1

Introduction to Industrial Control Systems

OBJECTIVES

At the conclusion of this chapter, you should be able to:

- List the classifications of industrial control systems.
- Describe the differences among the different industrial control systems and provide examples of each type.
- Define the following terms associated with industrial control systems:

Servos	Batch	Instrumentation
Servomechanisms	Continuous	

- Describe the differences between open-loop and closed-loop systems.
- Define the following terms associated with open- and closed-loop systems:

Negative Feedback	Error Detector	Disturbance
Controlled Variable	Error Signal	Measured Variable
Measurement Device	Controller	Manipulated Variable
Feedback Signal	Actuator	Controller Output Signal
Setpoint	Manufacturing Process	

- List the factors that affect the dynamic response of a closed-loop system.
- Describe the operation of feed-forward control.
- List three factors that cause the controlled variable to differ from the setpoint.

INTRODUCTION

The industrial revolution began in England during the mid-1700s when it was discovered that productivity of spinning wheels and weaving machines could be dramatically increased by fitting them with steam-powered engines. Further inventions and new ideas in plant layouts during the 1850s enabled the United States to surpass England as the manufacturing leader of the world. Around the turn of the twentieth century, the electric motor replaced steam and water wheels as a power source. Factories became larger, machines were improved to allow closer tolerances, and the assembly line method of mass production was created.

Between World Wars I and II, the feedback control system was developed, enabling manually-operated machines to be replaced by automated equipment. The feedback control system is a key element in today's manufacturing operations. The term **industrial controls** is used to define this type of system, which automatically monitors manufacturing processes being executed and takes appropriate corrective action if the operation is not performing properly.

During World War II, significant advances in feedback technology occurred due to the sophisticated control systems required by military weapons. After the war, the techniques used in military equipment were applied to industrial controls to further improve the quality of products and to increase productivity.

Because many modern factory machines are automated, the technicians who install, troubleshoot, and repair them need to be highly trained. To perform effectively, these individuals must understand the elements, operational theory, and terminology associated with industrial control systems.

Industrial control theory encompasses many fields, but uses the same basic principles whether controlling the position of an object, the speed of a motor, or the temperature and pressure of a manufacturing process.

In this chapter, the various types of industrial control systems, their characteristics, and important terminology will be studied.

1-1 Industrial Control Classifications

Motion and Process Controls

Industrial control systems are often classified by *what* they control: either motion or process.

Motion Control

A **motion control** system is an automatic control system that controls the physical motion or position of an object. One example is the industrial robot arm that performs welding operations and assembly procedures.

There are three characteristics that are common to all motion control systems. First, motion control devices control the position, speed, acceleration, or deceleration of a mechanical object. Second, the motion or position of the object being controlled is measured. Third, motion devices typically respond to input commands within fractions of a second, rather than seconds or minutes, as in process control. Hence, motion control systems are faster than process control systems.

Motion control systems are also referred to as *servos*, or *servomechanisms*. Other examples of motion control applications are computer numeric controlled (CNC) machine tool equipment, printing presses, office copiers, packaging equipment, and electronics parts insertion machines that place components onto a printed circuit board.

Process Control

The other type of industrial control system is **process control**. In process control, one or more variables are regulated during the manufacturing of a product. These variables may include temperature, pressure, flow rate, liquid and solid level, pH, or humidity. This regulated process must compensate for any outside disturbance that changes the variable. The response time of a process control system is typically slow, and can vary from a few seconds to several minutes. Process control is the type of industrial control system most often used in manufacturing. Process control systems are divided into two categories, *batch* and *continuous*.

Batch Process **Batch processing** is a sequence of timed operations executed on the product being manufactured. An example is an industrial machine that produces various types of cookies, as shown in Figure 1-1. Suppose that chocolate-chip cookies are made in the first production run. First, the oven is turned on to the desired temperature. Next, the required ingredients in proper quantities are dispensed into the sealed mixing chamber. A large blender then begins to mix the contents.

After a few minutes, vanilla is added, and the mixing process continues. After a prescribed period of time, the batter is the proper consistency, the blender stops turning, and the compressor turns on to force air into the mixing chamber. When the air pressure reaches a

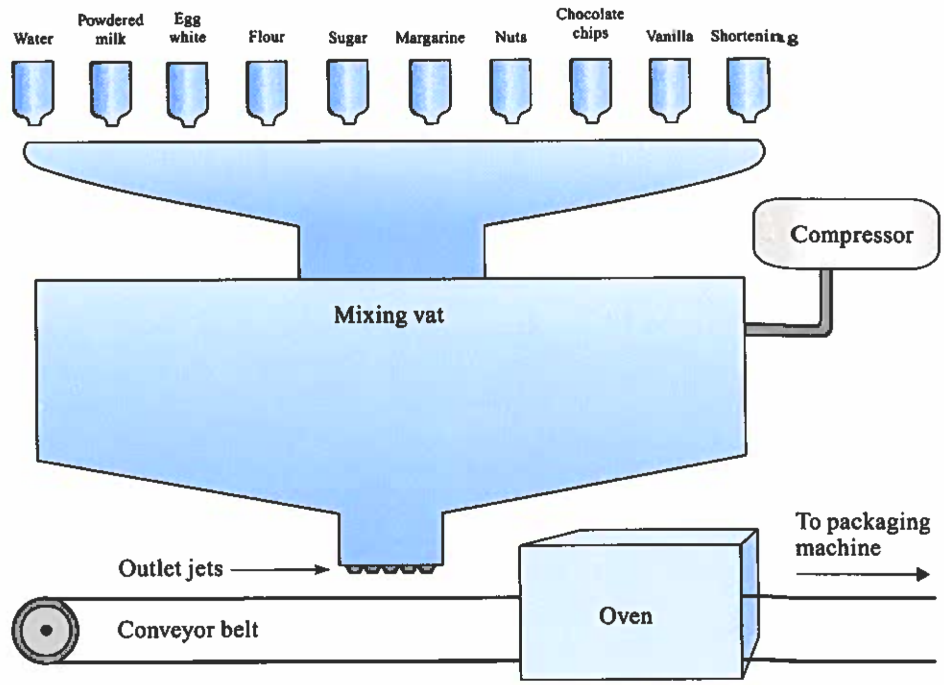


FIGURE 1-1 Batch processing cookie machine

certain point, the conveyor belt turns on. The pressurized air forces the dough through outlet jets onto the belt. The dough balls become fully baked as they pass through the oven. The cookies cool as the belt carries them to the packaging machine.

After the packaging step is completed, the mixing vat, blender, and conveyor belt are washed before a batch of raisin-oatmeal cookies is made. Products from foods to petroleum to soap to medicines are made from a mixture of ingredients that undergo a similar batch process operation.

Batch process is also known as *sequence* (or *sequential*) *process.*

Continuous Process In the **continuous process** category, one or more operations are being performed as the product is being passed through a process. Raw materials are continuously entering and leaving each process step. Producing paper, as shown in Figure 1-2, is an example of continuous process. Water, temperature, and speed are constantly monitored and regulated as the pulp is placed on screens, fed through rollers, and gradually transformed into a finished paper product. The continuous process can last for hours, days, or even weeks without interruption. Everything from wire to textiles to plastic bags is manufactured by using a continuous manufacturing process similar to the paper machine.

Other examples of continuous process control applications are wastewater treatment, nuclear power production, oil refining, and natural gas distribution through pipe lines.

Another term commonly used instead of process control is *instrumentation.*

The primary difference between process and motion control is the control method that is required. In process control, the emphasis is placed on sustaining a constant condition of a parameter, such as level, pressure, or flow rate of a liquid. In motion control, the input command is constantly changing. The emphasis of the system is to follow the changes in the desired input signal as closely as possible. Variations of the input signal are typically very rapid.

Open- and Closed-Loop Systems

The purpose of any industrial system is to maintain one or more variables in a production process at a desired value. These variables include pressures, temperatures, fluid levels, flow rates, composition of materials, motor speeds, and positions of a robotic arm.

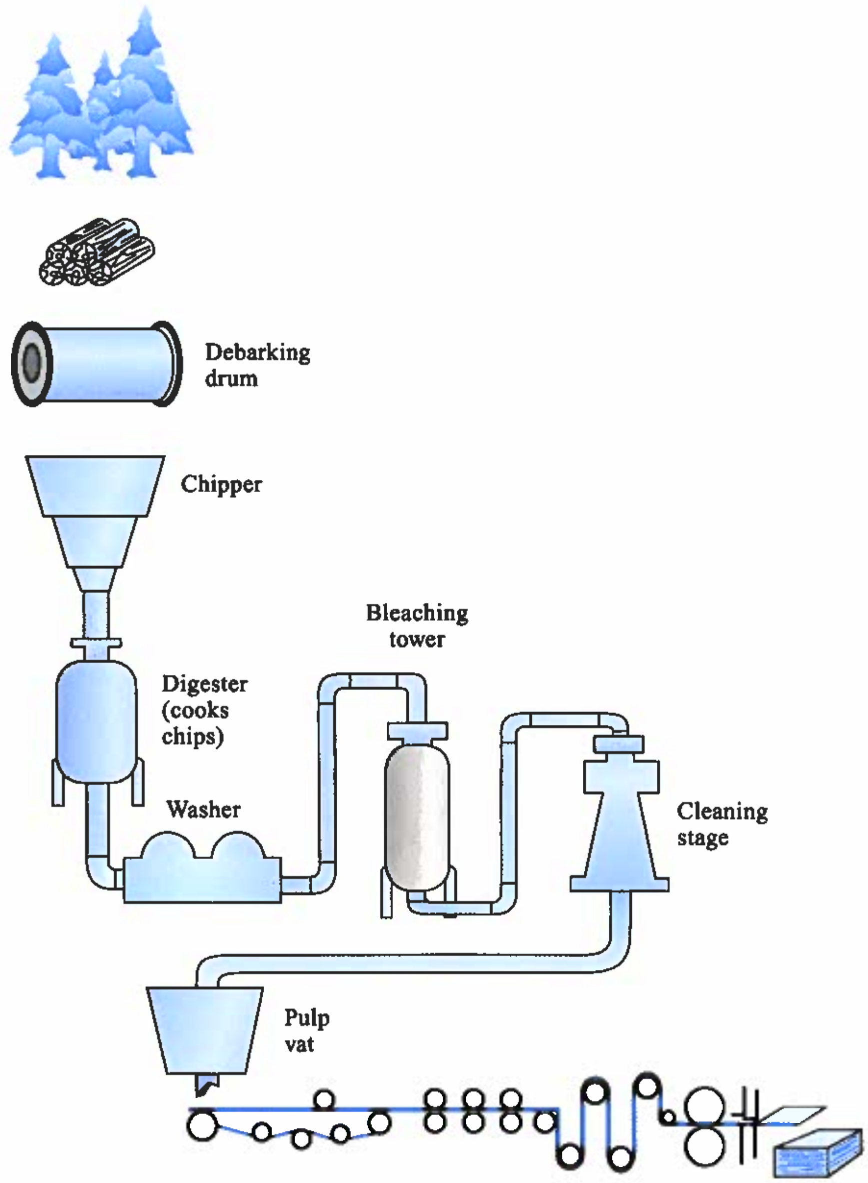


FIGURE 1-2 A pulp and paper operation is a process control application

Industrial control systems are also classified by how they control variables, either manually in an **open-loop** system or automatically in a **closed-loop** system.

Open-Loop Systems

An open-loop system is the simplest way to control a system. A tank that supplies water for an irrigation system can be used to illustrate an open-loop (or manual control) system. The diagram in Figure 1-3 shows a system composed of a storage tank, an inlet pipe with a manual control valve, and an outlet pipe. A continuous flow of water from a natural spring enters the tank at the inlet, and water flows from the outlet pipe to the irrigation system. The process variable that is maintained in the tank is the water level. Ideally, the manual flow control valve setting and the size of the outlet pipe are exactly the same. When this occurs, the water level in the tank remains the same. Therefore the process reaches a steady-state condition, or is said to be *balanced.* The problem with this design is that any change or disturbance will upset the balance. For example, a substantial rainfall may occur, causing additional water to enter the storage tank from the top. Since there is more water entering the tank than exiting, the level will rise. If this situation is not corrected, the tank will eventually

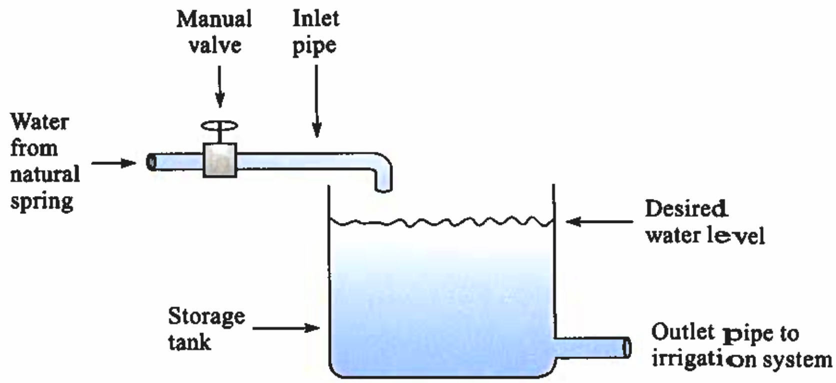


FIGURE 1-3 An open-loop reservoir system that stores water for an irrigation system

overflow. Excessive evaporation will also upset the balance. If it occurs over a prolonged period of time, the water level in the tank may become unacceptably low.

A human operator who periodically inspects the tank can change the control valve setting to compensate for these disturbances.

An example of a manually operated open-loop system is the speed of a car being controlled by the driver. The driver adjusts the throttle to maintain a highway speed when going uphill, downhill, or on level terrain.

Closed-Loop Systems

There are many situations in industry where the open-loop system is adequate. However, some manufacturing applications require continuous monitoring and self-correcting action of the operation for long periods of time without interruption. The automatic closed-loop configuration performs the self-correcting function. This automatic system employs a feedback loop to keep track of how closely the system is doing the job it was commanded to do.

The reservoir system can also be used to illustrate a closed-loop operation. To perform automatic control, the system is modified by replacing the manually controlled valve with an adjustable valve connected to a float, as shown in Figure 1-4. The valve, the float, and the linkage mechanism provide the feedback loop.

If the level of the water in the tank goes up, the float is pushed upward; if the level goes down, the float moves downward. The float is connected to the inlet valve by a mechanical linkage. As the water level rises, the float moves upward, pushing on the lever and closing the valve, thus reducing the water flow into the tank. If the water level lowers, the float moves

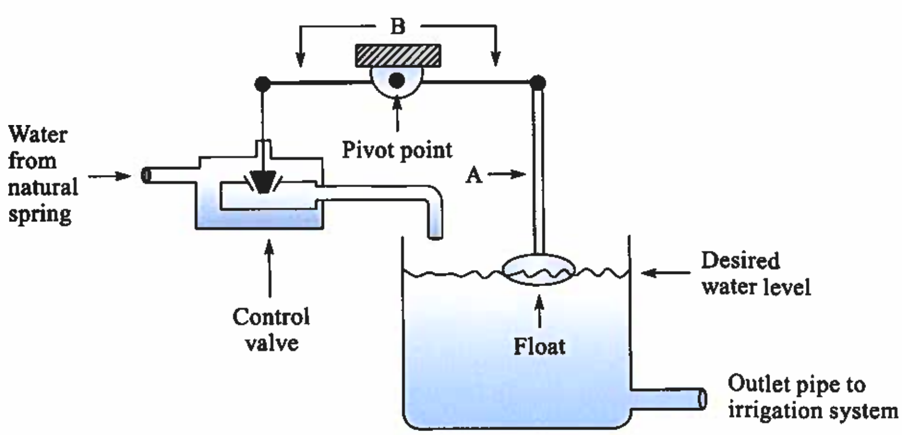


FIGURE 1-4 A closed-loop system that uses a linkage mechanism as a feedback device to provide self-correcting capabilities

downward, pulling on the lever and opening the valve, thus allowing more water into the tank. To adjust for a desired level of water in the tank, the float is moved up or down on the float rod A.

Most automated manufacturing processes use closed-loop control. These systems that have a self-regulation capability are designed to produce continuous balance.

1-2 Elements of Open- and Closed-Loop Systems

A block diagram of a closed-loop control system is shown in Figure 1-5. Each block shows an element of the system that performs a significant function in the operation. The lines between the blocks show the input and output signals of each element, and the arrowheads indicate the direction in which they flow.

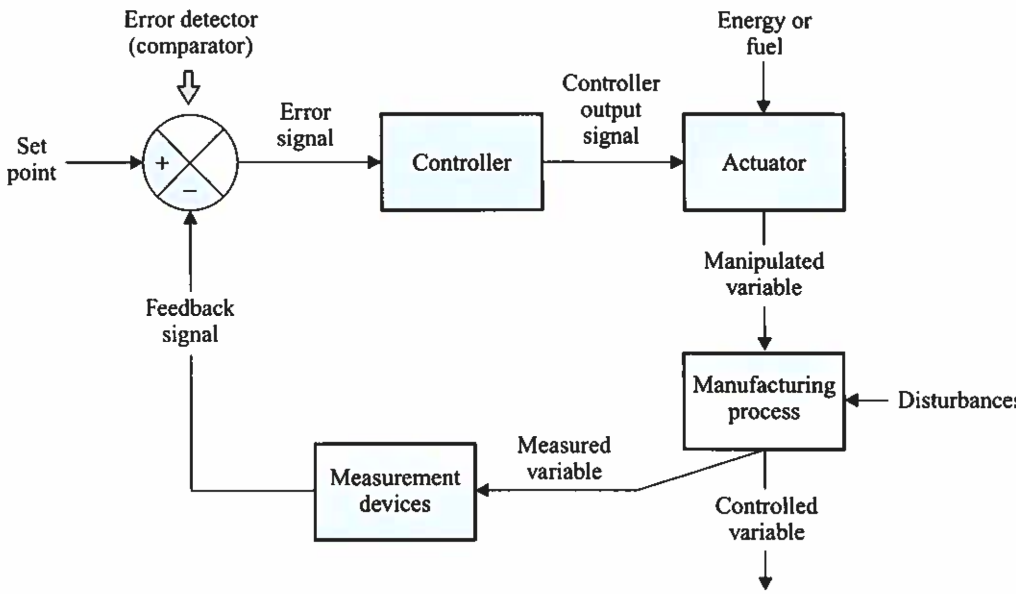


FIGURE 1-5 Closed-loop block diagram that shows elements, input/output signals, and signal direction

This section describes the functions of the blocks, their signals, and common terminology used in a typical closed-loop network:

Controlled Variable. The **controlled variable** is the actual variable being monitored and maintained at a desired value in the manufacturing process. Examples in a process control system may include temperature, pressure, and flow rate. Examples in a motion control system may be position or velocity. In the water reservoir system (Figure 1-4), the water level is the controlled variable. Another term used is *process variable.*

Measured Variable. To monitor the status of the controlled variable, it must be measured. Therefore, the condition of the controlled variable at a specific point in time is referred to as the **measured variable.** Various methods are used to make measurements. One method of determining a controlled variable such as the level of water, for example, is to measure the pressure at the bottom of a tank. The pressure that represents the controlled variable is taken at the instant of measurement.

Measurement Device. The **measurement device** is the "eye" of the system. It senses the measured variable and produces an output signal that represents the status of the controlled variable. Examples in a process control system may include a thermocouple to measure temperature or a humidity detector to measure moisture. Examples in a motion control system may be an optical device to measure position or a tachometer to measure rotational speed. In the water reservoir system, the float is the measurement device. Other terms used are *detector, transducer,* and *sensor.*

Feedback Signal. The **feedback signal** is the output of the measurement device. In the water reservoir system, the feedback signal is the vertical position of member A in the linkage mechanism (see Figure 1-4). Other terms used are *measured value, measurement signal,* or *position feedback* if in a position loop, or *velocity feedback* if in a velocity loop.

Setpoint. The **setpoint** is the prescribed input value applied to the loop that indicates the desired condition of the controlled variable. The setpoint may be manually set by a human operator, automatically set by an electronic device, or programmed into a computer. In the water reservoir system, the setpoint is determined by the position at which the float is placed along rod A. Other terms used are *command,* and *reference.*

Error Detector. The **error detector** compares the setpoint to the feedback signal. It then produces an output signal that is proportional to the difference between them. In the water reservoir system, the error detector is the entire linkage mechanism. Other terms used are *comparator* or *comparer* and *summing junction.*

Error Signal. The **error signal** is the output of the error detector. If the setpoint and the feedback signal are not equal, an error signal proportional to their difference develops. When the feedback and setpoint signals are equal, the error signal goes to zero. In the reservoir system (Figure 1-4), the error signal is the angular position of member B of the linkage mechanism. Other terms used are *difference signal* and *deviation.*

Controller. The **controller** is the "brain" of the system. It receives the error signal (for closed-loop control) as its input, and develops an output signal that causes the controlled variable to become the value specified by the setpoint. Most controllers are operated electronically, although some of the older process control systems use air pressure in pneumatic devices. The operation of an electronic controller is performed by hardwired circuitry or computer software. The controller produces a small electrical signal that usually needs to be conditioned or modified before it is sent to the next element. For example, it must be amplified if it is applied to an electrical motor, or connected to a proportional air pressure if it is applied to a pneumatic positioner or a control valve. The control function is also performed by programmable logic controllers (PLCs) and panel-mounted microprocessor controllers.

Actuator. The **actuator** is the "muscle" of the system. It is a device that alters some type of energy or fuel supply, causing the controlled variable to match the desired setpoint. Examples of energy or fuel are the flow of steam, water, air, gas, or electrical current. A practical application is a commercial bakery where the objective is to keep the temperature in an oven at 375 degrees. The temperature is the controlled variable. The temperature is determined by how much gas is fed to the oven burner. A valve in the gas line controls the flow by the amount it opens or closes. The valve is the actuator in the system. In the reservoir system, the actuator is the flow control valve, connected to the inlet pipe. Other terms used are the *final control element,* and *final correcting device.* Common types of actuators are louvers, hydraulic cylinders, pumps, and motors.

Manipulated Variable. The amount of fuel or energy that is altered by the actuator is referred to as the **manipulated variable.** The amount at which the manipulated variable is changed by the actuator affects the condition of the controlled variable. In the commercial oven example, the gas flow rate is the manipulated variable, and the temperature is the controlled variable. In the reservoir system, the flow is the manipulated variable. The flow rate is altered by the control valve (actuator), which affects the condition of the controlled variable (level).

Manufacturing Process. The **manufacturing process** is the operation performed by the actuator to control a physical variable, such as the motion of a machine or the processing of a liquid.

Disturbance. A **disturbance** is a factor that upsets the manufacturing process being performed, causing a change in the controlled variable. In the reservoir system, the disturbances are the rainfall and evaporation that alter the water level.

A block diagram of an open-loop system is shown in Figure 1-6. The Controller, Actuator, and Manufacturing process blocks perform the same operations as the closed-loop system shown in Figure 1-5. However, instead of the error signal being applied to the controller, the setpoint provides its input. Also, there is no feedback loop, and a comparator is not used by the open-loop system.

It is possible for open-loop system to perform automated operations. For example, the washing machine that launders clothes in your home uses a timer to control the wash cycles. An industrial laundry machine also uses timing devices to perform the same functions but on a larger scale. However, there is no feedback loop that monitors and takes corrective action if the timer becomes inaccurate, the temperature of the water changes, or a major problem arises that requires the machine to shut down.

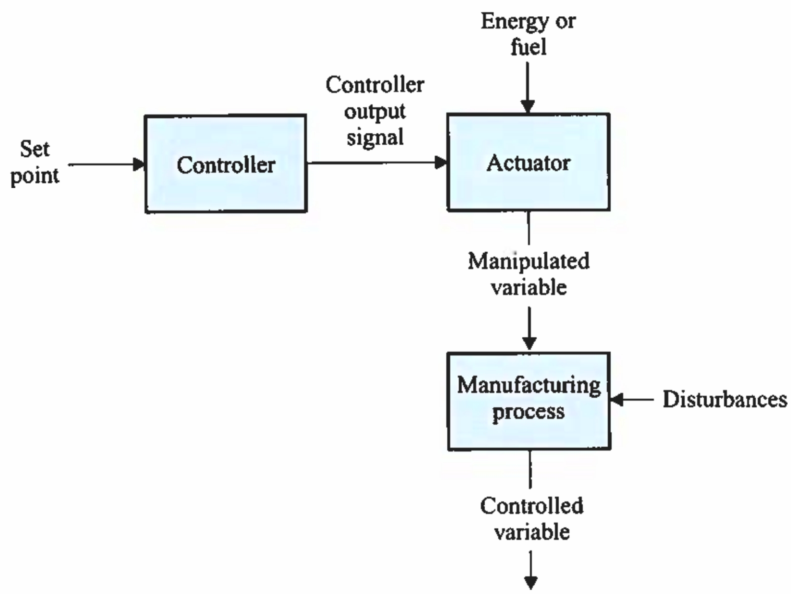


FIGURE 1-6 Open-loop block diagram that shows elements, input/output signals, and signal direction

1-3 Feedback Control

Industrial automated control is performed using closed-loop systems. The term *loop* is derived from the fact that, once the command signal is entered, it travels around the loop until equilibrium is restored.

To summarize the operation of a closed-loop system, the objective is to keep the controlled variable equal to the desired setpoint. A measurement device monitors the controlled variable and sends a measurement signal to the error detector that represents its condition along the feedback loop. An error detector compares the feedback signal to the setpoint and produces an error signal that is proportional to the difference between them. The error signal is fed to a controller, which determines which kind of action should occur to make the controlled variable equal to the setpoint. The output of the controller causes the actuator to adjust the manipulated variable. Altering the manipulated variable causes the condition of the controlled variable to change to the desired value.

The basic concept of feedback control is that an error must exist before some corrective action can be made. An error can develop in one of three ways:

1. The setpoint is changed.
2. A disturbance appears.
3. The load demand varies.

In the reservoir system of Figure 1-4 the setpoint is changed by adjusting the position of the float along linkage A. A disturbance is caused when rain supplies additional water to the tank, or evaporation lowers the level. The water flowing out of the tank to the irrigation system is referred to as the load. If the level of the water in the irrigation system suddenly lowers, the back pressure on the outlet pipe will decrease and cause the fluid to drain faster. This downstream condition is referred to as a load change. The setpoint and load demand are changes that normally occur in a system. The disturbance is an unwanted condition.

Feedback signals may be either positive or negative. If the feedback signal's polarity aids a command input signal, it is said to be positive or regenerative feedback. Positive feedback is used in radios. If the radio signal is weak, an Automatic Gain Control (AGC) circuit is activated. Its output is a feedback signal that boosts the radio signal's overall strength.

However, when positive feedback is used in industrial closed-loop systems, the input usually loses control over the output. If the feedback signal opposes the input signal, the system is said to use negative or degenerative feedback. By combining negative feedback values from the command signal, a closed-loop system works properly.

An example of closed-loop control that uses negative feedback is the central heating system in a house. The thermostat in Figure 1-7 monitors the temperature in the house and compares it to the desired reference setting. Suppose the room temperature drops to 66 degrees from the reference setting of 72 degrees. The measured feedback value is subtracted from the setpoint command and causes a six-degree discrepancy. The thermostat contacts will close and cause the furnace to turn on. The furnace supplies heat until the temperature is back to the reference setting. When the negative feedback is sufficient to cancel the command, the error no longer exists. The thermostat then opens and switches the furnace off until the house cools down below the reference. As this cycle repeats, the temperature in the house is automatically maintained without human intervention.

The speed of an automobile can also be controlled automatically by a closed-loop system called a cruise control. The desired speed is set by an electronic mechanism usually

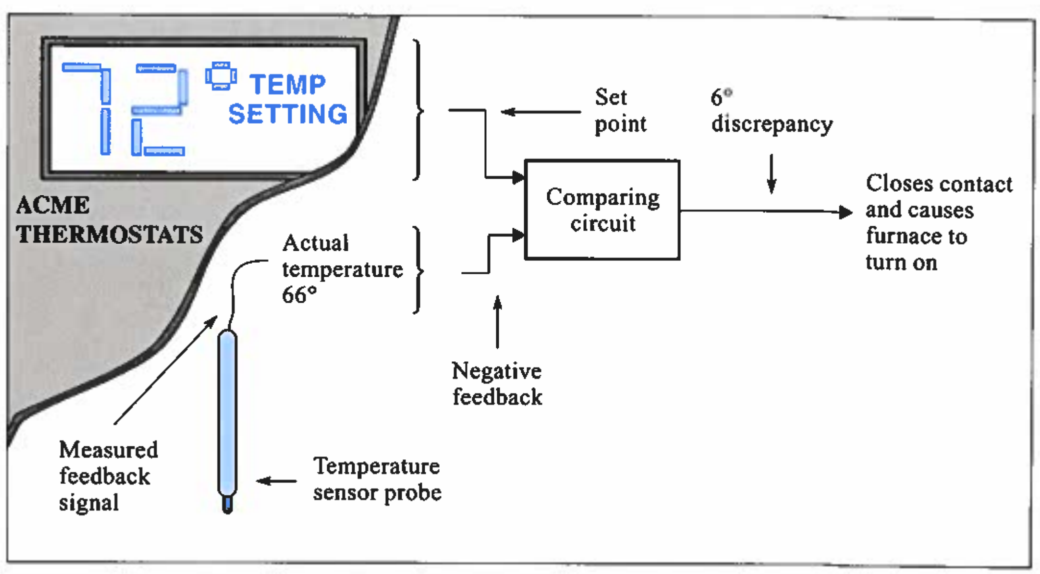


FIGURE 1-7 A thermostat uses a negative feedback signal to control the temperature of a house

placed on the steering wheel assembly. A Hall-effect speed sensor connected to the front axle generates a signal proportional to actual speed. An electronic error detector compares the actual speed to the desired speed, and then sends a signal representing the difference between them to a controller. The controller sends a demand signal to a electromechanical device called an actuator. A part of the electromechanical device is a rod connected to the throttle, which varies the fuel flow to the engine. If a car that is traveling on a level road suddenly encounters an uphill grade, it begins to slow down. Because the actual speed is lower than the desired speed, the error detector sends a signal to the actuator. The electromechanical device causes the rod to move the throttle so that more fuel flows to the engine. The additional fuel causes the car to accelerate until it reaches the desired speed.

1-4 Practical Feedback Application

An actual practical application of a feedback system used in a manufacturing process is shown in Figure 1-8. The diagram shows a heat exchanger. Its function is to supply water at a precise elevated temperature to a mixing vat that produces a chemical reaction. Cold water enters the bottom of the tank. The water is heated as it passes through steam-filled coils and leaves the tank through a port located at the top.

This example illustrates how the elements of a closed-loop feedback system provide automatic control. The elements consist of a thermal sensor, controller, and actuator. Together, they keep the temperature of the water that leaves the tank as close as possible to the setpoint when process conditions change.

There are three factors that can cause the condition of the controlled variable to become different from the setpoint. Two of the three factors are intentional. One intentional factor is changing the setpoint to a new desired temperature level. Another intentional factor is a *load change.* An example of a load change in the heat exchanger is an increase in the pump's flow rate so that the water leaves the top port of the tank much faster than usual. This condition would cause the water to flow through the tank more quickly. As a result, the water will not be heated as much as it flows through the coils causing the outgoing temperature to be lower. An unintentional factor is a *disturbance.* One example of a disturbance in the heat exchanger is a decrease in the temperature of the water entering the tank. When this condition exists,

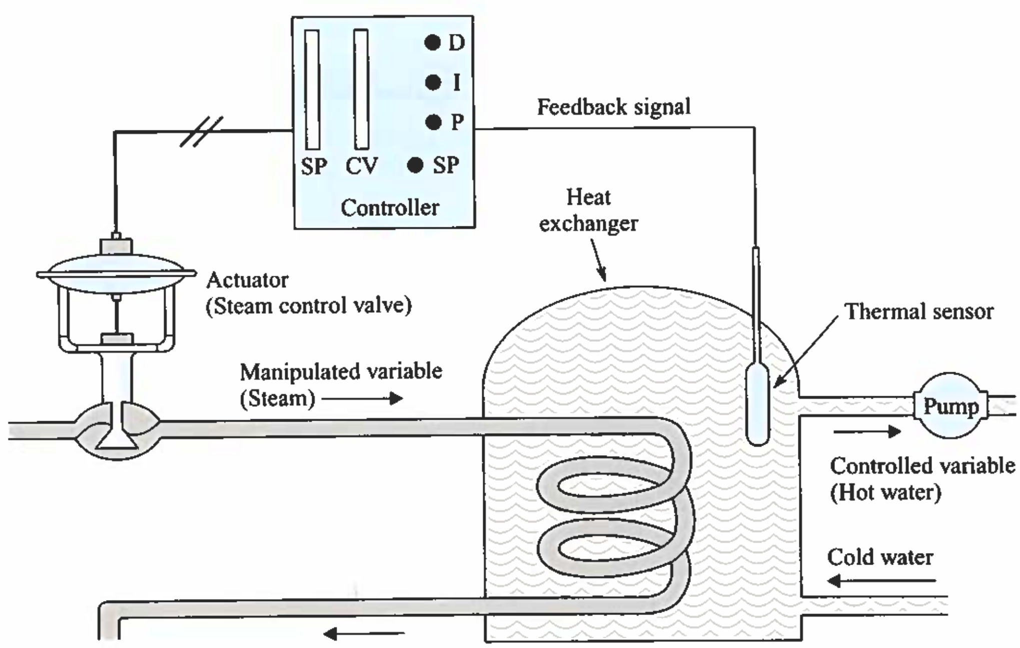


FIGURE 1-8 Closed-loop temperature control system

the temperature of the water in the tank will drop below setpoint. This situation occurs because the water entering the tank is colder. Since the temperature of the heating (steam) coils remains unchanged, the temperature of the water leaving the tank will be lower.

Whenever there is a difference between the setpoint and the condition of the controlled variable, the control system with feedback compensates for any error. For example, suppose that the temperature of the water leaving the heat exchanger falls below the setpoint. Thermal energy, which is the measured variable, is detected by the sensor. The sensor produces an electrical signal, which is the feedback signal to the controller. The controller compares the measured value to the setpoint. The size of the deviation determines the value of the controller output signal. This output signal goes to the final control element, which is a steam control valve. To return the water temperature back to the setpoint, the valve is opened farther by the actuator, allowing more steam, which is the manipulated variable, to enter the coils. As the coils become hotter, the temperature of the water, which passes through them, also rises.

As the water temperature returns to the setpoint, the deviation becomes smaller. The controller responds by changing its output signal to the valve. The new output signal causes the valve to reduce the flow of steam through the coils and causes the water to be heated at the proper rate.

1-5 Dynamic Response of a Closed-Loop System

The objective of a closed-loop system is to return the controlled variable back to the condition specified by the command signal when a setpoint change, a disturbance, or a load change occurs. However, there is not an immediate response. Instead, it takes a certain amount of time delay for the system to correct itself and re-establish a balanced condition. A measure of the loop's corrective action, as a function of time, is referred to as its **dynamic response.** There are several factors that contribute to the response delay:

- The **response time** of the instruments in the control loop. The instruments include the sensor, controller, and final control element. All instruments have a *time lag.* This is the time beginning when a change is received at its input ending at the time it produces an output.
- The **time duration** as a signal passes from one instrument in the loop to the next.
- The **static inertia** of the controlled variable. When energy is applied, the variable opposes being changed and creates a delay. Eventually the energy overcomes the resistance and causes the variable to reach its desired state. This delayed action is referred to as **pure lag.** The amount of lag is determined by the capacity (physical size) of the material; the lag is proportional to the amount of its mass. The type of material a controlled variable consists of also affects the lag. For example, the temperature of a gas will change more quickly than that of a liquid when exposed to thermal energy. The chemical properties of the controlled variable can also affect the amount of delay.
- The elapsed time between the instant a deviation of the controlled variable occurs and the corrective action begins. This factor is referred to as **dead time.** A pipeline that passes fluid can be used to illustrate an example of dead time. The control function of the closed-loop system is to regulate the temperature of the fluid flowing through the pipe. If the temperature of the fluid entering the pipe suddenly drops, there is a brief time period that passes before the fluid reaches a sensor downstream. The time from when the fluid enters the pipe until the sensor begins to initiate the closed-loop response is the dead time.

1-6 Feed-Forward Control

Two conditions can minimize the effectiveness of feedback control. The first is the occurrence of large magnitude disturbances. The second is long delays in the dynamic response of the control loop. To compensate for these limitations of feedback control, **feed-forward** control can be used.

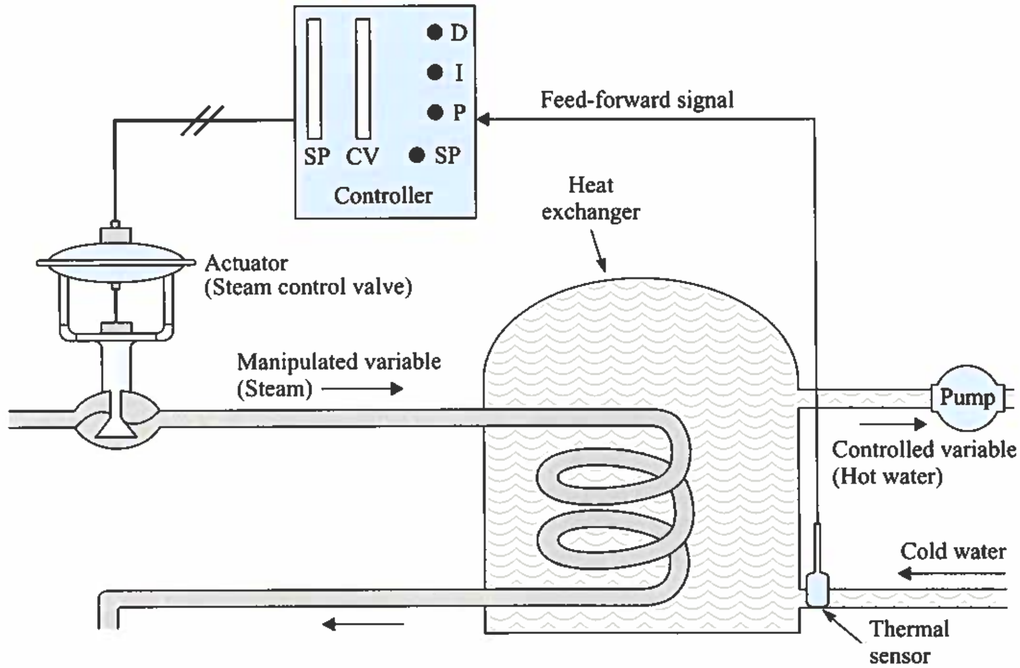


FIGURE 1-9 Feed-forward control of a temperature control system

The operation of feed-forward control is very different from feedback control. Feedback control takes corrective action after an error develops. The objective of feed-forward control is to prevent errors from occurring. Typically, feed-forward cannot prevent errors. Instead, it minimizes them.

The heat exchanger system described in Section 1-4 can be modified for feed-forward control, as shown in Figure 1-9. Instead of placing the thermal sensor inside the tank to detect a temperature deviation of the heated water, a thermal sensor is placed in the inlet pipe. As soon as there is a change in the temperature of the incoming cold water, it is detected before entering the tank. The controller responds by adjusting the position of the steam valve. By varying the steam through the coil at this time, corrective action occurs before the controlled variable leaving the outlet pipe can deviate from the setpoint temperature.

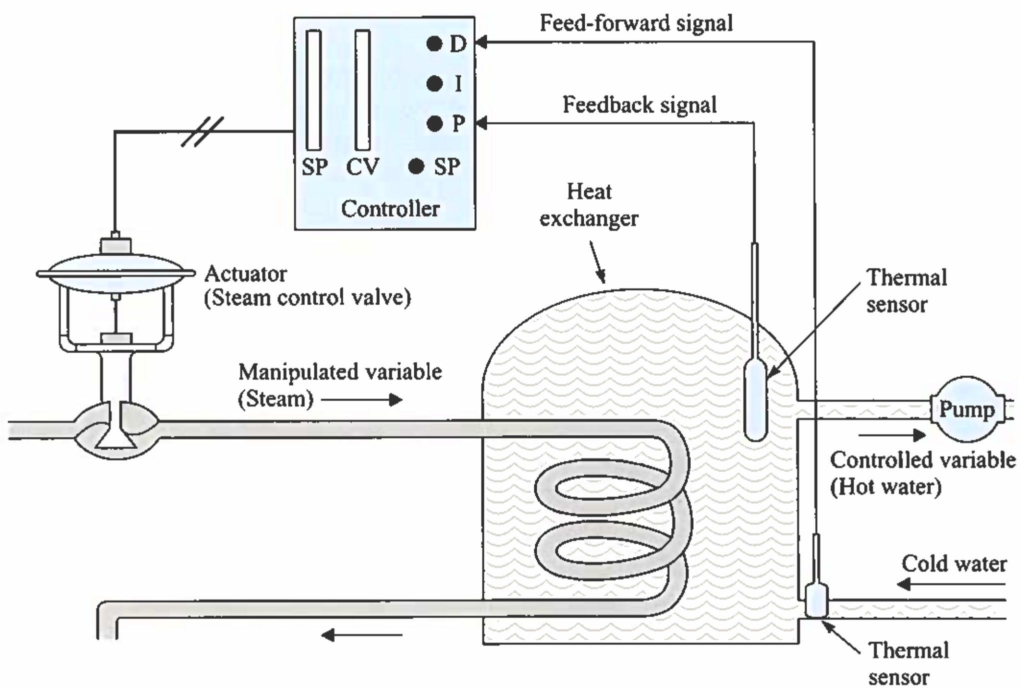


FIGURE 1-10 Feed-forward control loop with a feedback control loop

The feed-forward control system does not operate perfectly. There are always unmeasurable disturbances that cannot be detected, such as a worn flow valve, a sensor out of tolerance, or inexact mathematical calculations processed by the controller. Over a period of time, these unmeasurable disturbances affect the operation and eventually the water temperature in the tank, finally causing the water to reach an unacceptable temperature level. Due to the inaccuracy of feed-forward control, it is seldom used by itself. By adding feedback control to the system, corrections by the controller can be made if the controlled variable deviates from the setpoint due to unmeasurable disturbances.

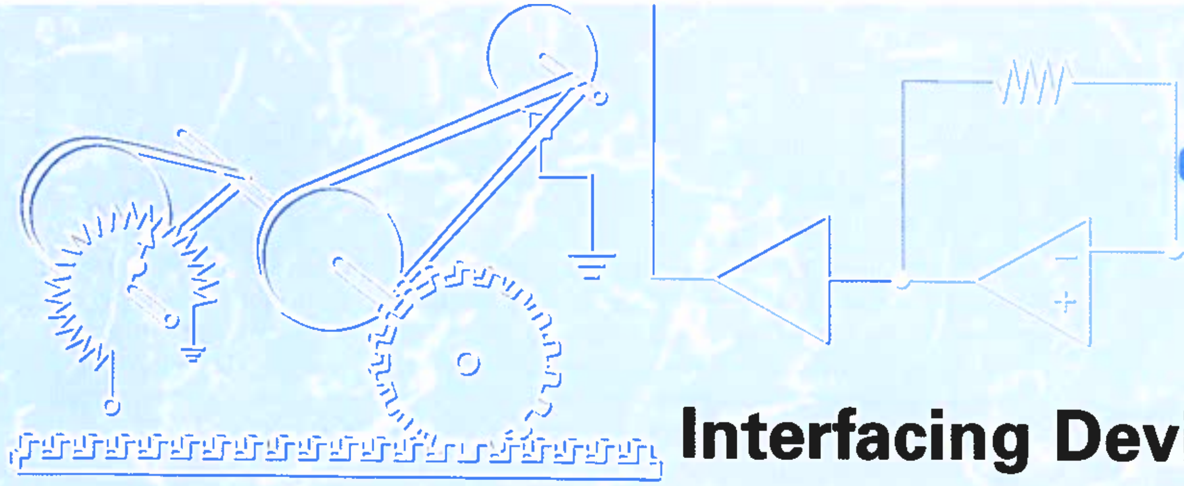
Figure 1-10 shows a heat exchanger system that uses both feed-forward and feedback control. The controller receives input signals from two sensors. The sensor in the inlet line provides the feed-forward signal, and the sensor near the outlet provides the feedback signal.

In summary, feed-forward control adjusts the operation of the actuator to prevent changes in the controlled variable. Feed-forward controllers must make very sophisticated calculations to compute the changes of the actuator needed to compensate for variations in disturbances. Since they require highly skilled engineers, they typically are used only in critical applications within the plant.

Problems

1. The two classifications of industrial control systems are __________ control and __________ control.
2. List another name for each of the following terms.
   Motion Control
   Process Control
   Batch Process
3. A closed-loop industrial system typically uses __________ (negative, positive) feedback.
4. List two examples of controlled variables for motion control applications and two examples for process control applications.
   Motion Control
   Process Control
5. List one example of a measurement device for a motion control application and one example for a process control application.
   Motion Control
   Process Control
6. The control method used in ____ control applications is to sustain a constant condition of the controlled variable.
   a. servo b. process
7. An open-loop system does not have a ____.
   a. controller c. feedback loop
   b. final control element d. none of the above
8. T/F The measured variable represents the condition of the controlled variable.
9. The output of the measurement device is called the __________ __________.
10. Define setpoint.
11. The difference between the setpoint and feedback signal is referred to as the __________ signal, and is produced by the __________ detector.
12. T/F The controller can be considered the brain of a closed-loop system.
13. Altering the __________ variable causes the condition of the __________ variable to change.
   a. controlled b. manipulated
14. The device that provides the muscle to perform work in the closed-loop system is referred to as the __________.
15. The ____ is sent to the final control element.
   a. measured variable c. error signal
   b. feedback signal d. control signal
16. Which of the following influences cause a controlled variable to change? ____
   a. A disturbance occurs. c. The setpoint is adjusted.
   b. A load demand varies. d. All of the above.
17. Which of the following factors contribute to the dynamic response of a single control loop? ____
   a. The instrument in a control loop
   b. The inertia of the controlled variable
   c. Dead time
   d. All of the above
18. T/F The manipulated variable and controlled variable are synonymous terms in a closed-loop system.
19. T/F The basic concept of feedback control is that an error must exist before some corrective action can be made.
20. A pressurized tank must maintain a gas at 325 psi. A pressure sensor is used to measure the condition of the controlled variable. As the gas cools, the pressure in the tank decreases. When it drops to 300 psi, a valve is opened, which allows steam to flow to a heat exchanger inside the tank. The additional steam heats the gas and causes pressure to rise.
   ____ What is the controlled variable in this process?
   ____ What is the manipulated variable in this process?
   ____ What is the setpoint?
   ____ What is the measured variable?
   a. gas pressure d. 300 psi
   b. steam flow e. pressure
   c. 325 psi f. heat
21. T/F Feed-forward control is seldom used except in combination with feedback control.

22. Which of the following conditions are compensated for by using feed-forward control? ____
    a. Excessive lag time
    b. Large disturbances
    c. An error signal
    d. Feedback signal
23. The objective of ____ control is to prevent the controlled variable from deviating from the setpoint.
    a. feedback
    b. feed-forward
24. When feedback and feed-forward control are performed together, the primary function of feed-forward is to make corrections for ____ disturbances, and feedback control to make corrections for ____ disturbances.
    a. measurable
    b. unmeasurable



CHAPTER 2

Interfacing Devices

OBJECTIVES

At the conclusion of this chapter, you should be able to:

- Identify the schematic diagrams, describe the operations, and calculate the outputs of the comparator, inverting, summing, noninverting, and difference operational amplifiers (op amps).
- Identify the schematic diagrams of the integrator and differentiator op amps and draw the output waveforms they produce when various input signals are applied.
- Given applied input signals, indicate the resulting output of the digital comparator device.
- Describe the wave-shaping capability and operating characteristics of a Schmitt trigger.
- Determine how optoelectronic devices are switched and explain the isolation function they perform.
- Explain the operation of analog-to-digital and digital-to-analog converters, determine their resolution, and make the proper wiring connections to their integrated circuit packages.
- Assemble monostable and astable multivibrators using a 555 monolithic integrated circuit and use calculations to determine their output.

INTRODUCTION

In Chapter 1, a block diagram was used to describe the operation of the elements of a closed-loop system. Each element plays a significant role in the operation of the system. One of the requirements of any system is the successful interfacing or connecting together of the various blocks. In a block diagram, an interface is represented by the lines between two blocks, indicating that some type of signal passes from one to another.

There are many components and circuits that perform the functions of each element. Sometimes the signals processed in one element are incompatible with those that can be used in the next element. To make the elements compatible, various types of conversion components are used to interface them together.

To help the reader understand the material covered in later chapters, this chapter describes the basic operation of discrete components and integrated circuits that are used within and between the elements. The components covered here have been selected based on many of the circuits covered in the remainder of the book.

2-1 Fundamental Operational Amplifiers

A very versatile amplifier device is the **operational amplifier** (op amp). One of the most popular op amp is the uA741, which is fabricated inside an 8-pin integrated circuit package. There are three important characteristics of op amps that make them ideal amplifiers:

1. High input impedance
2. High voltage gain
3. Low output impedance

Figure 2-1 shows the standard schematic symbol of the uA741 op amp. Represented by a triangle, the op amp has two input terminals located at the base on the left and a single output located at the apex of the triangle. There are also two separate power-supply lines. The one located at the top base is connected to a positive potential, and the other located at the bottom base is connected to a negative potential. These two power supplies allow the output voltage to swing to either a positive or negative voltage with respect to ground.

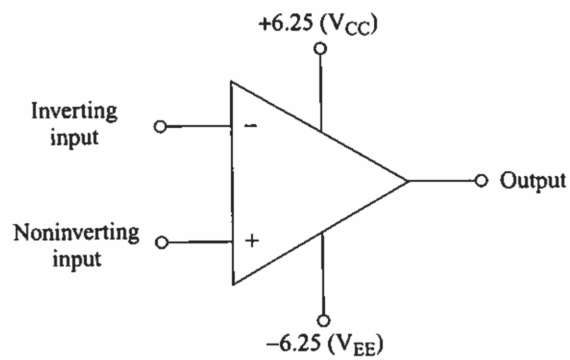


FIGURE 2-1 Standard symbol of an operational amplifier

One of the inputs has a minus sign. This is called the inverting input, because any DC or AC signal applied to its input produces an output voltage of the opposite polarity. The other input has a plus sign and is called the noninverting input. Any DC or AC signal applied at this input produces an output of the same polarity.

When external components are connected to the input and output leads, the op amp is capable of performing several functions. How the components are connected determines which function the op amp performs.

Operational Amplifier Comparator

Figure 2-2 shows an op amp configuration that operates as a voltage comparator. This device compares the voltage applied to one input to the voltage applied at the other input. Any difference between the voltages drives the op amp output into either a positive- or a negative-volt saturation condition. Saturation is about 80 percent of the supply voltage. Therefore, 5 volts is produced if the power supply is 6.25 volts. The polarity of the output is determined by the polarity of the voltages applied at the inputs. When the voltage applied to the inverting

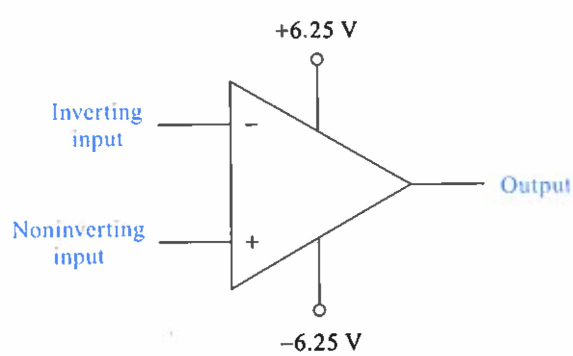


FIGURE 2-2 Op amp comparator

input is more positive than the voltage at the noninverting terminals, the output swings to a −5-volt saturation potential. Likewise, when the voltage applied to the inverting input is more negative than the voltage at the noninverting input, the output swings to the +5-volt saturation potential. However, when the input voltages are the same amplitude, the output is zero. The following equations provide a summary of the operation for the voltage comparator:

Inverting input voltage < noninverting input voltage = positive output voltage
Inverting input voltage > noninverting input voltage = negative output voltage
Inverting input voltage = noninverting input voltage = zero output voltage

Table 2-1 provides examples of how the op amp, operating as a comparator, responds to several input voltages.

TABLE 2-1 Operation of an Op Amp Comperator

Inverting Input Terminal (Volts)	*Noninverting Input Terminal (Volts)*	*Output Saturation Voltage (Volts)*
+1	−1	−5
+1	+2	+5
+2	+1	−5
0	0	0
−1	+1	+5
0	−1	−5
0	+1	+5
+3	+3	0

Inverting Op Amp

A typical op amp can have a voltage gain of approximately 200,000. However, the output voltage level cannot exceed approximately 80 percent of the supply voltage. For example, the maximum output voltages of the op amp in Figure 2-1 are +5 volts and −5 volts because the power-supply potentials are +6.25 volts and −6.25 volts. Therefore, it only takes a 25-uV input to result in a positive or negative 5-volt output voltage, depending on the input-signal polarity and the terminal to which it is applied.

However, the op amp is used for many applications that require a voltage gain less than 200,000. A technique called *feedback* is used to control the gain of this device, and it is accomplished by connecting a resistor from the output terminal to an input lead. A negative-feedback circuit is shown in Figure 2-3. Its operation is as follows:

- Both input terminals have high impedances; therefore, they do not allow current to flow into or out of them.
- The potential at the inverting input lead is called 0-volt virtual ground (that is, it acts like a 0-volt ground). The positive input lead is connected to an actual 0-volt ground potential.

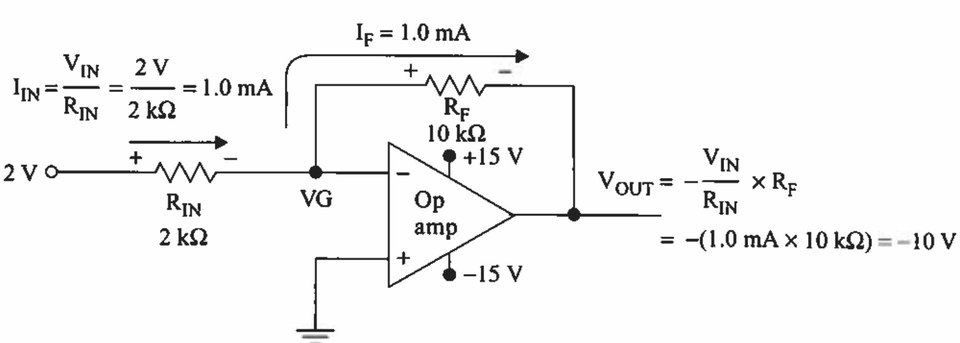


FIGURE 2-3 Inverting op amp

- Because point VG is 0 volts, there is a voltage drop of 2 volts across the 2-kilohm resistor, R_{IN}. 1 mA flows through it.
- The 1 mA cannot flow into the op amp. Therefore, it flows up through the 10-kilohm feedback resistor R_F, developing a 10-volt drop across it.
- Because V_{OUT} is measured with respect to the virtual ground, its voltage is −10 volts.

The voltage *gain* of the op amp is determined by:

$$V_{GAIN} = \frac{V_{OUT}}{V_{IN}}$$

The gain of the inverting op amp in Figure 2-3 is 5 because a 2-volt signal is applied to the input and an inverted −10-volt signal is at the output. A negative input voltage applied to this amplifier produces a positive output. The gain is influenced by the resistance ratio of R_F compared to R_{IN}. The larger R_F becomes compared to R_{IN}, the larger the gain.

The output voltage can also be determined by:

$$V_{OUT} = -\frac{R_F}{R_{IN}} \times V_{IN}$$

Figure 2-4 provides examples of how the inverting amplifier with a gain of 10 responds to several input voltages.

FIGURE 2-4 Input and output voltages of an inverting op amp with a gain of 10

V_{IN}	V_{OUT} (Volts)
+0.2	−2
−0.4	+4
0	0
+0.32	−3.2

Summing Amplifier

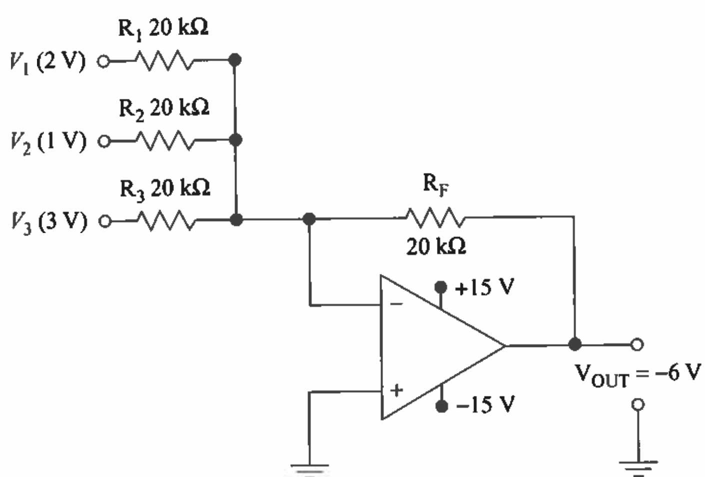
When two or more inputs are tied together and then applied to an input lead of an op amp, a summing amplifier is developed. This type of amplifier is capable of adding the algebraic sum of DC or AC signals. The circuit in Figure 2-5 is that of an inverting summing amplifier. It consists of a 20-kilohm feedback resistor R_F, three parallel 20-kilohm summing resistors tied together and connected to the inverting input lead, and +2-volt, +1-volt, and +3-volt signals applied to the inputs. The calculations to the right of the diagram show how to determine the voltage at the output terminal.

The current of each input is calculated and then summed to obtain the resulting current flow through R_F. Next the output voltage is determined by multiplying I_{RF} times R_F.

Table 2-2 provides examples of how the summing amplifier in Figure 2-5 responds to several input voltages.

TABLE 2-2 Operation of an Inverting Summing Amplifier

Input Voltages V_1	V_2	V_3	Algebraic Sum of Output Voltages
+1	+1	+1	−3
+1	−1	−1	+1
+2	−1	−1	0
−3	−1	+3	+1
+1	+2	−1	−2



$$I_{R1} = \frac{V_{R1}}{R_1} = \frac{2\text{ V}}{20\text{ k}\Omega} = 0.1\text{ mA}$$

$$I_{R2} = \frac{V_{R2}}{R_2} = \frac{1\text{ V}}{20\text{ k}\Omega} = 0.05\text{ mA}$$

$$I_{R3} = \frac{V_{R3}}{R_3} = \frac{3\text{ V}}{20\text{ k}\Omega} = 0.15\text{ mA}$$

$$I_{R_F} = 0.1\text{ mA} + 0.05\text{ mA} + 0.15\text{ mA} = 0.3\text{ mA} \quad \text{or} \quad -0.3\text{ mA (inverted)}$$

$$V_{OUT} = I_{RF} \times R_F = -0.3\text{ mA} \times 20\text{ k}\Omega = -6\text{ V}$$

FIGURE 2-5 Inverting summing amplifier

Noninverting Amplifier

Some applications require that an amplified output signal be in phase with the input. Using an operational amplifier, this is accomplished by applying the input signal to the noninverting input, while the feedback to control gain is still provided by connecting the output terminal to the inverting input through a resistor (R_F). One lead of resistor R_{IN} is also connected to the inverting input. The other lead of R_{IN} is connected to a 0-volt ground potential.

Figure 2-6 shows the schematic diagram of a noninverting amplifier. The gain of the circuit is influenced by resistors R_{IN} and R_F. The equation used to determine the gain of the noninverting amplifier is derived by adding 1 to the resistance ratio of R_F and R_{IN}. Thus:

$$\text{Gain} = 1 + \frac{R_F}{R_{IN}}$$

The output voltage is determined by:

$$V_{OUT} = \left[1 + \frac{R_F}{R_{IN}}\right](V_{IN})$$

The gain will always be greater than 1.

Table 2-3 provides examples of how the noninverting amplifier shown in Figure 2-6 responds to several input voltages.

TABLE 2-3 Operation of a Noninverting Op Amp

V_{IN}	V_{OUT}
+0.3	+3.3
-1.0	-11
+.75	+8.25
-.52	-5.72

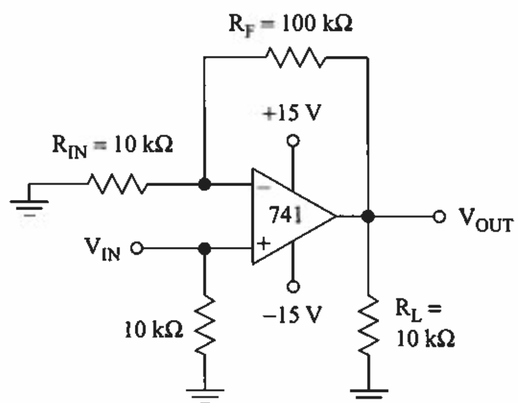


FIGURE 2-6 Noninverting operational amplifier

Difference Operational Amplifier

The **difference operational amplifier** (shown in Figure 2-7) finds the algebraic difference between two input voltages. Neither the inverting input nor the noninverting input is grounded. Instead, signals are applied to both inputs at the same time, and the difference between them is amplified. If the signals are the same, the output voltage is zero.

Note that the circuit utilizes the closed-loop feedback configuration, which results in a controlled amplified output voltage. If all the external resistors are equal, no amplification takes place. Instead, the voltage difference op amp performs the arithmetic operation of subtraction. For example, suppose that 3 volts are applied to the inverting input V_1, and 6 volts to the noninverting input V_2. The voltage difference between these inputs is 3 volts, which is developed at the op amp output.

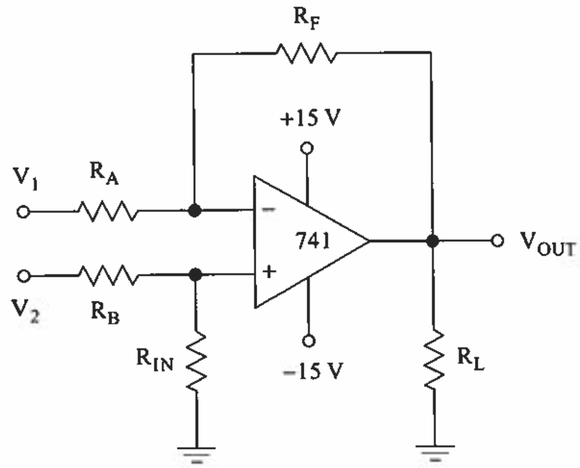
The non-amplified output can be calculated using the following formula:

$$\begin{aligned} V_{OUT} &= V_2 - V_1 \\ &= 6V - 3V \\ &= +3V \end{aligned}$$

If the voltage at the inverting input (V_1) is more negative than the voltage at the noninverting input V_2, the polarity of the output will be positive, and vice versa. Table 2-4 provides

TABLE 2-4 Operation of a Difference Operational Amplifier

Input Voltage V_1	*Input Voltage* V_2	*Output Voltage Algebraic Difference (Inverted)*
+2	+4	+2
+4	+2	−2
+4	−2	−6
−2	+4	+6
−4	−2	+2
−2	−4	−2



All resistors are 10 kΩ.

FIGURE 2-7 Difference op amp

examples of various input conditions and the resulting output voltages for the circuit in Figure 2-7.

If the ratios of the resistor values in the circuit are changed, the difference op amp provides amplification. The output voltages can be determined by using a different formula than the one above.

2-2 Signal Processors

Signal processors are special devices that change or modify signals applied to their inputs. The output signals of these devices can then be used to perform specific functions. Three signal processor devices will be described: the *integrator*, the *differentiator*, and the *Schmitt trigger*.

Integrator Operational Amplifier

An **integrator** is an amplifier circuit that continuously increases its gain over a period of time. The magnitude of the output is proportional to the period of time that a DC input signal is present. Figure 2-8(a) shows the schematic diagram of the op amp integrator. The circuit resembles that of an inverting op amp. The difference is that a capacitor replaces the resistor as the feedback element. The waveform diagrams in Figure 2-8(b) illustrate the operation of the circuit when different DC voltages are applied to the input.

When the input voltage changes from zero to +5 volts, at T_1 of the waveform, the capacitor initially has a low impedance because it is discharged. The gain of the op amp is zero because the ratio of the feedback resistance to the input resistance is zero. This action is expressed by the formula for the inverting op amp: $V_{OUT} = R_{FB}/R_{IN}$.

As the capacitor begins to charge, the impedance path to current flow increases. Because the feedback resistance rises, the R_{CFB} ratio increases. The result is that the output of the op amp increases in a linear fashion. Since the inverting input is used, the output will be a negative-going waveform. Eventually the waveform levels off because the op amp reaches saturation, as shown at T_2 of the diagram.

At T_3, the input voltage changes from +5 volts to zero volts. The capacitor discharges and causes the output to return to zero volts. If a negative voltage is applied to the input, a positive-going signal develops at the output. If a square wave is applied to the input, a sawtooth waveform will develop at the output, as shown in Figure 2-8(c). The rate at which the output changes is determined by the capacitor and resistor values.

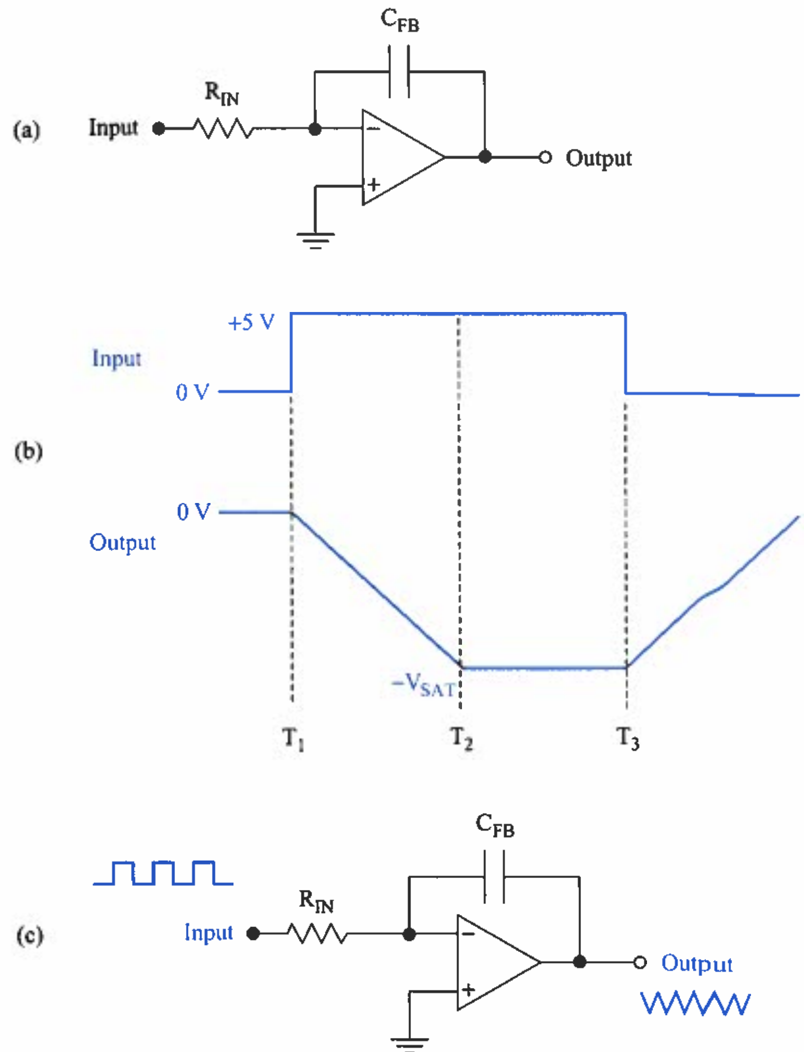


FIGURE 2-8 Integrator operational amplifier

Differentiator Operational Amplifier

A **differentiator** is an amplifier circuit that produces an output proportional to the rate of change of the input signal. Figure 2-9(a) shows the schematic diagram of the op amp differentiator. Its configuration is opposite to that of the integrator because the capacitor replaces the input resistor instead of the feedback resistor. The waveform diagrams in Figure 2-9(b) illustrate how the differentiator responds to different input signals. Since the inverting lead is used, the output signal that develops will be in the opposite direction as the rate of change of the signal applied to the input.

When the input voltage is DC and remains constant, as shown from T_1 to T_2 on the waveform, the output of the differentiator is 0 volts. If the voltage changes at a slow, steady rate, the output will be a small constant DC voltage, as shown from T_2 to T_3. If the voltage changes at a fast, steady rate, as shown from T_3 to T_4, the output will be a high constant DC voltage. When a sawtooth is applied to the input, a square-wave signal is produced, as shown in Figure 2-9(c). As the sawtooth goes in the positive direction, the square-wave alternation is negative. A negative-going sawtooth produces a positive alternation of the square wave. Figure 2-9(d) shows that when a square wave is applied to the input, a series of spikes is produced at the output. The polarity of each spike is determined by the positive- or negative-going transition of the square wave.

Integrators and differentiators are used to control output actuators in closed-loop automated systems.

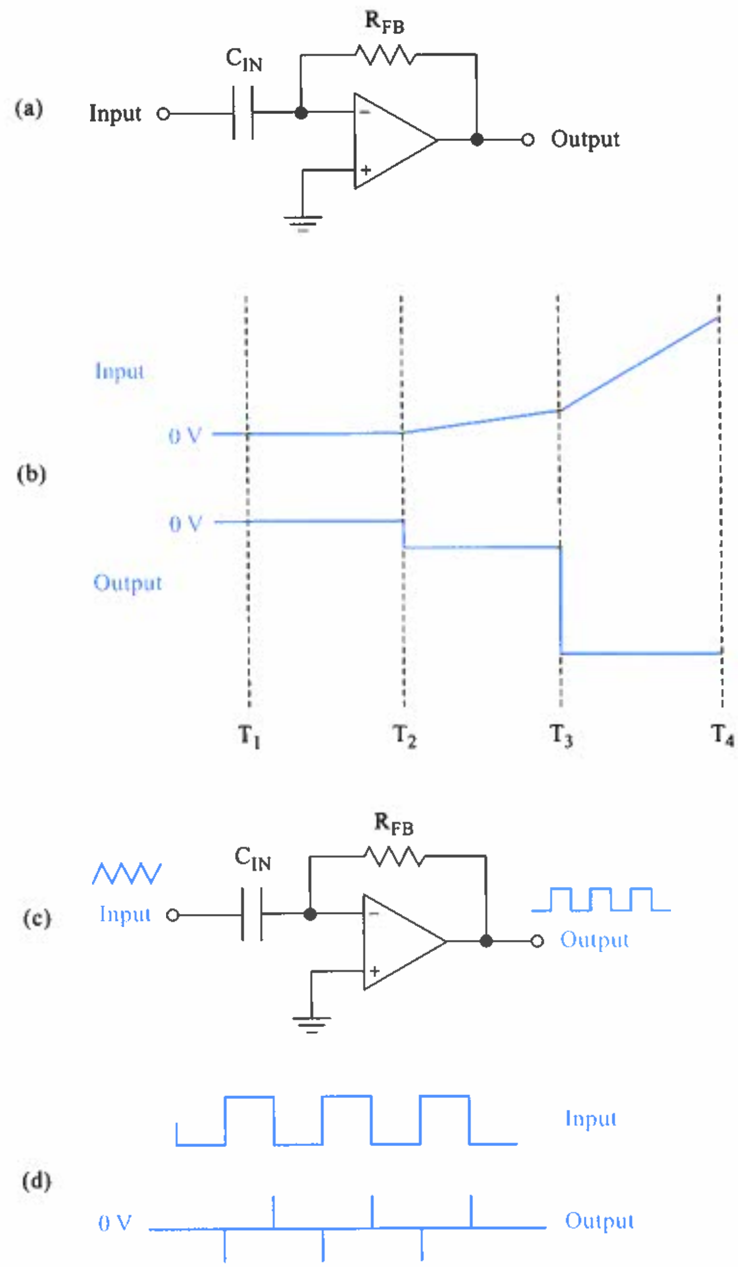


FIGURE 2-9 Differentiator operational amplifier

Wave-Shaping Schmitt Trigger

The **Schmitt trigger** is a device that produces rectangular wave signals. It is often used to convert sine waves or arbitrary waveforms into crisp square-shaped signals. It is also used to restore square waves, which sometimes become distorted due to electromagnetic interference (called *noise*) during transmission, back to their required square-shaped waveforms. The Schmitt trigger uses positive feedback internally to speed up level transitions. It also utilizes an effect called *hysteresis,* which means that the switching threshold on a positive-going input signal is at a higher voltage level than the switching threshold on a negative-going signal. Schmitt triggers can also be used to transform the following waveforms into rectangular-shaped signals:

- A low-voltage AC wave
- Signals with slow rise times, such as those produced from charging and discharging capacitors, and temperature-sensing transducers

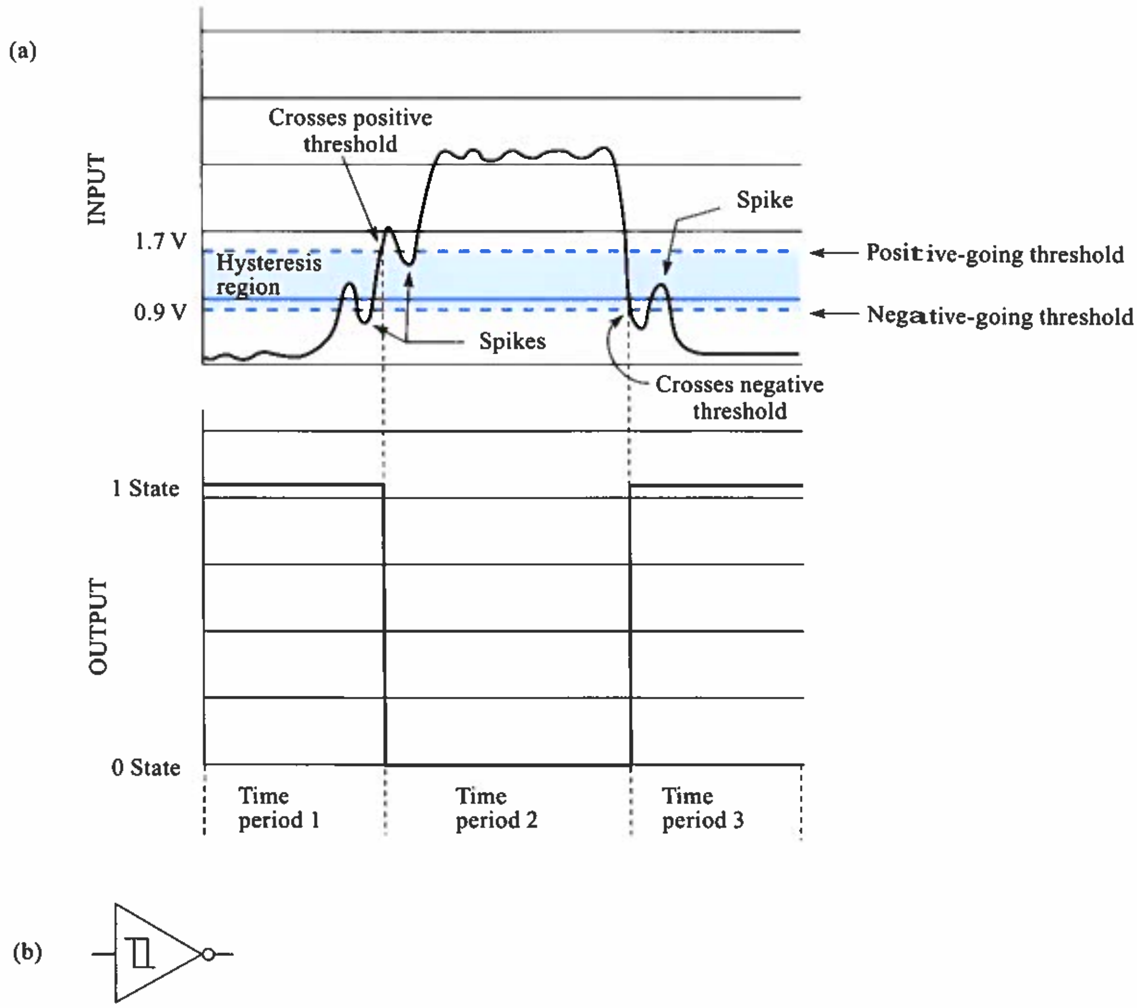


FIGURE 2-10 Schmitt trigger

Figure 2-10(a) illustrates the switching action of a Schmitt trigger inverter and also shows how the hysteresis characteristics reconstruct a distorted square wave.

Operation

Time Period 1. A logic 0 is recognized at the input, and a 1 state is generated at the inverting output.

Time Period 2. A logic 1 at the input is recognized if the input voltage exceeds the 1.7-volt positive-going threshold level that causes the output to snap to a logic 0 value. Note that the ragged spike on the input signal caused from noise drops below 1.7 volts into the hysteresis region during period 2. The output does not change unless the input drops below the 0.9-volt negative-going threshold level.

Time Period 3. A logic 0 at the input is recognized if the voltage drops below the 0.9-volt negative-going threshold level, which causes the output to snap to a logic-1 value. Note that a spike on the input rises above 0.9 volts into the hysteresis region during time period 3. The output does not change unless the input reaches the 1.7-volt positive-going threshold level.

The logic symbol for a Schmitt trigger inverter is shown in Figure 2-10(b). It includes a miniature hysteresis waveform inside the symbol to indicate that it is a Schmitt trigger instead of a regular inverter.

2-3 Comparator Devices

The comparator element of a closed-loop system shown in Figure 1-5 has two inputs and one output. The command signal is applied to one input lead and the feedback signal is applied to the other input lead. The function of the **comparator,** is to produce an output error signal that is determined by the difference between the two inputs. The input and output signals can be either analog or digital. The op amp comparator and the op amp difference amplifier are capable of comparing analog signals, and the magnitude comparator compares digital signals.

Digital Magnitude Comparator

The **magnitude comparator** is capable of comparing two binary numbers and indicating whether one number is greater than, less than, or equal to the other. Figure 2-11 shows the block diagram of a 4-bit magnitude comparator. It has four lines for input A, four lines for input B, and three logic state output lines. The A > B output will go high if input A is larger than B; the A < B output will go high if input B is larger than A; and the A = B output will go high if A is equal to B.

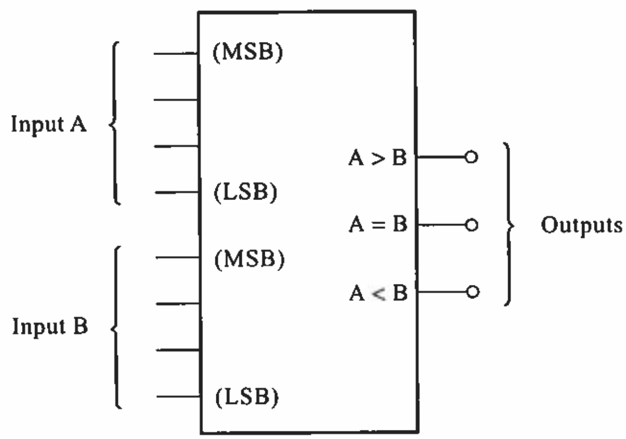
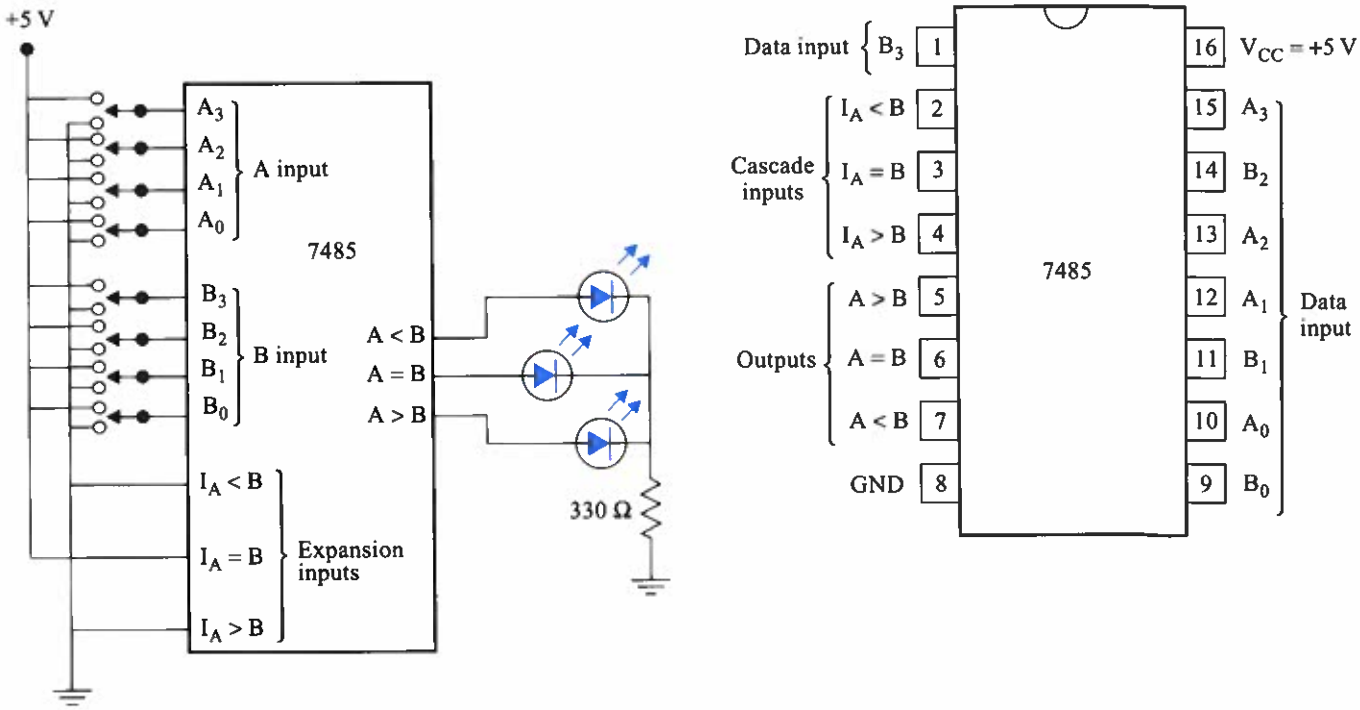


FIGURE 2-11 Block diagram of a magnitude comparator

A TTL 7485 magnitude comparator integrated circuit (IC) is shown in Figure 2-12(a). Its operation is identical to the block diagram circuit in Figure 2-11. It also has three inputs called the expansion (also cascade) input lines, labeled $I_A < B$, $I_A = B$, and $I_A > B$. If only 4-bit words are being compared, the $I_A = B$ input should be wired to a high and the $I_A < B$ and $I_A > B$ inputs should be wired to a low. Figures 2-12(b) and 2-12(c) show the pin diagram and the truth table of the 7485 IC.

Several 7485 ICs can be connected together to compare binary numbers larger than 4 bits. The block diagram of Figure 2-13 on page 28 shows how two 7485 ICs are cascaded to make an 8-bit comparator. The four least significant bits of each 8-bit word are connected to inputs A_0–A_3 and B_0–B_3 of the comparator on the left. The four most significant bits of each 8-bit word are connected to inputs A_0–A_3 and B_0–B_3 of the comparator on the right. The A > B, A = B, and A < B outputs of the least significant comparator are connected to the expansion inputs of the most significant comparator. The expansion lines of the least significant comparator should be wired as if it were comparing only two 4-bit words. The comparison results of the two 8-bit words are generated at the three output lines of the most significant comparator.

The cascaded inputs resulting from the comparison of the low-order numbers are always overridden by the high-order numbers. The only time the cascaded input affects the output is when the two high-order numbers are equal.



(a) (b)

FUNCTION TABLE (X = Don't care)

Comparing Inputs				*Cascading Inputs*			*Outputs*		
A3, B3	**A2, B2**	**A1, B1**	**A0, B0**	**I_A > B**	**I_A < B**	**I_A = B**	**A > B**	**A < B**	**A = B**
A3 > B3	X	X	X	X	X	X	H	L	L
A3 < B3	X	X	X	X	X	X	L	H	L
A3 = B3	A2 > B2	X	X	X	X	X	H	L	L
A3 = B3	A2 < B2	X	X	X	X	X	L	H	L
A3 = B3	A2 = B2	A1 > B1	X	X	X	X	H	L	L
A3 = B3	A2 = B2	A1 < B1	X	X	X	X	L	H	L
A3 = B3	A2 = B2	A1 = B1	A0 > B0	X	X	X	H	L	L
A3 = B3	A2 = B2	A1 = B1	A0 < B0	X	X	X	L	H	L
A3 = B3	A2 = B2	A1 = B1	A0 = B0	H	L	L	H	L	L
A3 = B3	A2 = B2	A1 = B1	A0 = B0	L	H	L	L	H	L
A3 = B3	A2 = B2	A1 = B1	A0 = B0	X	X	H	L	L	H
A3 = B3	A2 = B2	A1 = B1	A0 = B0	H	H	L	L	L	L
A3 = B3	A2 = B2	A1 = B1	A0 = B0	L	L	L	H	H	L

X = Does not apply

(c)

FIGURE 2-12 The 7485 magnitude comparator IC

2-4 Optoelectronic Interface Devices

The voltage used by one element of a closed-loop system is not always equal to the voltage used by another element. Therefore they cannot be directly connected to one another. Optoelectronic devices are used to make the output of one section compatible with the input of another section. Optoelectronic devices pass electrical signals from one element to another by means of light energy and semiconductors. An optoelectronic device consists of a light source and a photo detector, as shown in Figure 2-14(a). The light source converts electrical energy to light. The detector converts light energy to electrical energy.

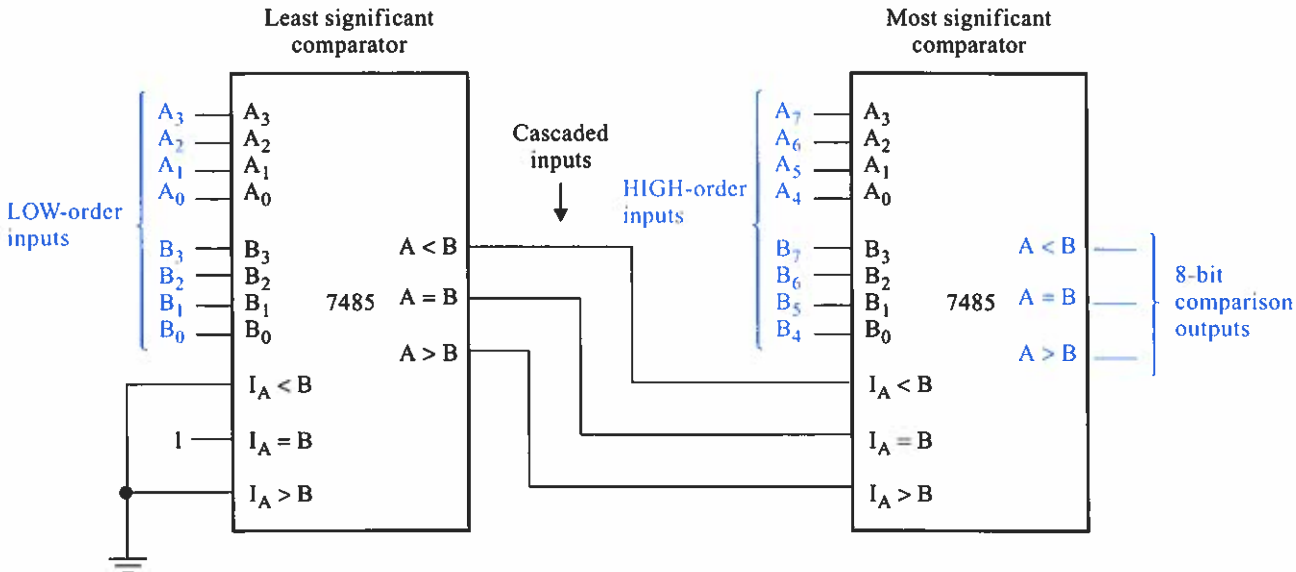


FIGURE 2-13 Magnitude comparison of two 8-bit strings (or binary words)

The light source is usually a semiconductor light emitting diode (LED). In the forward-biased state, light emission occurs when electrons combine with holes around the PN junction, as shown in Figure 2-14(b). During this process the electrons fall to a lower energy level and energy in the form of photons is released. Photons are light particles that travel in a waveform pattern.

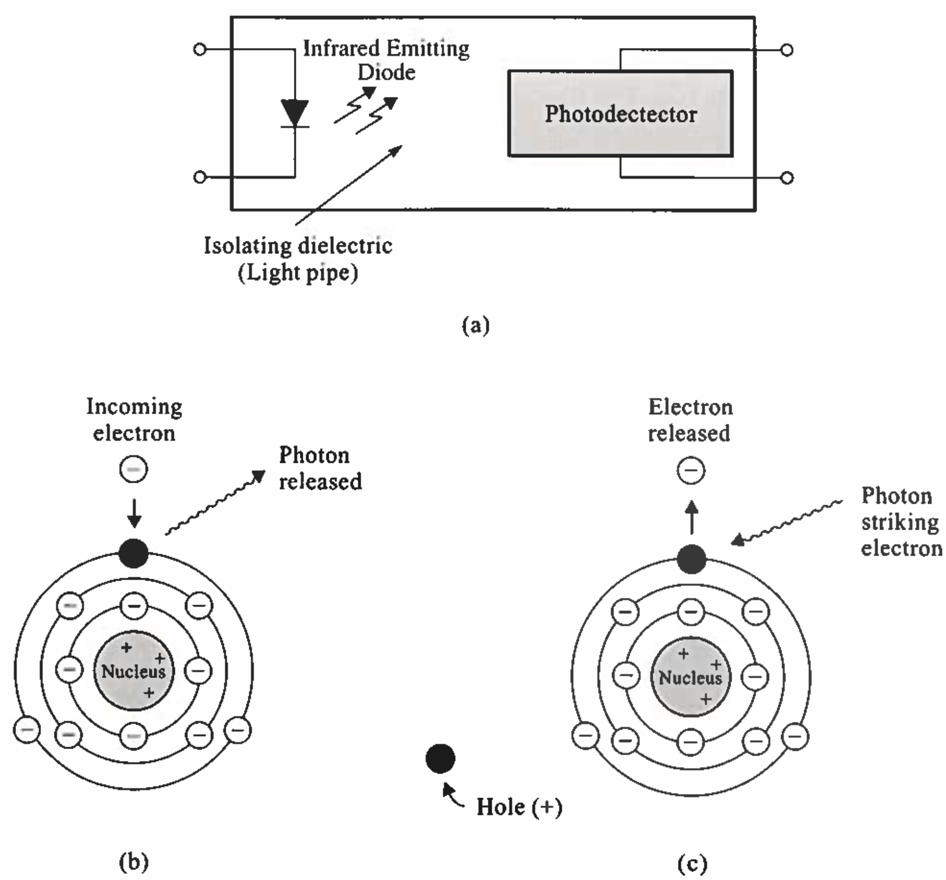


FIGURE 2-14 (a) Block diagram of an optoisolator; (b and c) atomic structure of photoelectronic devices

Light detection of photons is accomplished by semiconductor devices. As the photons strike the semiconductor material at the PN junction, valance electrons are released, as shown in Figure 2-14(c). The valance electrons available in the semiconductor then enable current to pass through the PN junction.

The detection of light and conversion into current is performed by light-activated devices such as photodiodes, phototransistors, photo SCRs (silicon-controlled rectifiers), and phototriacs.

Photodiodes

The **photodiode,** shown in Figure 2-15, is a PN junction device that operates in the reverse-bias mode. When a PN junction is reverse biased, heat causes the freeing of minority carriers in the depletion layer, which contributes to a small leakage current. High-energy photons strike the PN junction of the diode when it is exposed to light from the LED. The impact of photons causes electrons to be dislodged from their orbit and leave holes behind. This action of electron-hole pairs due to light exposure causes minority carriers to increase. The resulting current flow through the diode increases proportionately with light intensity. Photodiodes are used in applications that require quick response time for fast switching detection. Their primary limitation is that they allow current only in the microamp range between 50 uA and 500 uA to flow.

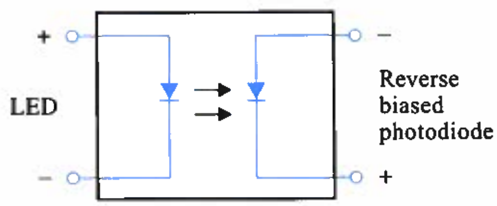


FIGURE 2-15 Photodiode in optocoupler

Phototransistors

The **phototransistor** depends on a light source for its operation. Typically, the phototransistor has no external base lead, as shown in Figure 2-16. Therefore, there is no bias source for external control. Instead, a light source operates the transistor in the same manner as a bias source. When photons from the LED strike the transistor's collector-base junction, the flow of minority carriers increases. This action causes the emitter-collector current to rise. If light intensity increases, more emitter-to-collector current will flow. Because the transistor amplifies, the amount of the output current it produces is much higher than the photodiode under the same illuminating conditions. However, its response time is slower than that of the photodiode.

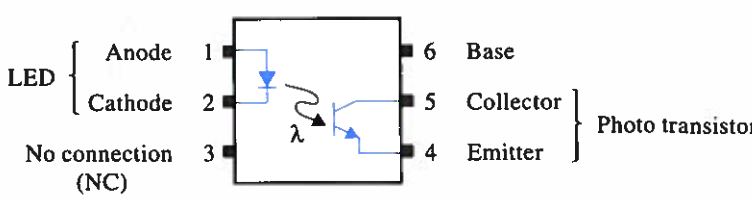


FIGURE 2-16 Phototransistor in optocoupler

Photo SCR

The **photo SCR** is also referred to as a light-activated SCR, or LASCR. The operation of the LASCR is similar to the conventional SCR except that it is usually activated by light instead of by a gate voltage that draws gate current. The LASCR symbol is shown in Figure 2-17.

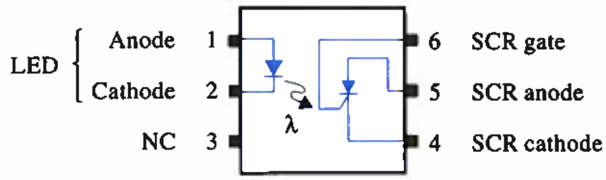


FIGURE 2-17 Photo SCR (LASCR) in optocoupler

The SCR is normally in the off condition. Its three leads enable the SCR to be triggered in one of three ways:

1. By light shining on the PN junction;
2. By a positive voltage drawing gate current applied to the gate; and
3. By a combination of the gate voltage and light intensity.

The output power an SCR controls is much higher than the amount required to trigger it. The level of light intensity used to turn on the LASCR can be controlled by adjusting the gate-cathode bias resistance. For example, a larger value resistance prevents the LASCR from turning on until a large amount of light intensity is reached. The LASCR remains on even after the light or the gate voltage is removed. When the current flowing through it is reduced below its holding current value, the SCR turns off and effectively blocks any current.

Because its power handling capacity is far beyond that of other optoelectronic devices, the LASCR is a superior high-power switch. Photo SCRs are capable of switching current of 2 amperes and withstanding voltages as high as 200 volts.

Photo Triac

The **photo triac** is a bidirectional device designed to switch AC signals and pass current in both directions. Its symbol is shown in Figure 2-18. The photo triac is normally off if its PN junction is not exposed to light radiation of a certain density. During each alternation, it turns on when triggered by a specified light intensity, and turns off when the conducting current falls below a certain level. The current capacity of the photo triac is not as high as the LASCR.

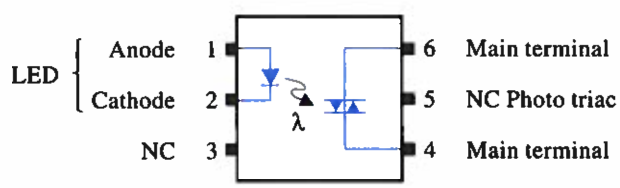


FIGURE 2-18 Photo triac in optocoupler

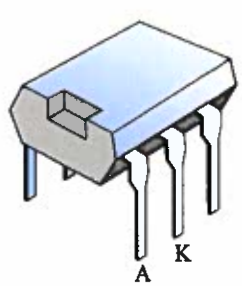


FIGURE 2-19 Photoelectronic (optoisolator) package

Optoelectronic Packaging

Optoelectronic devices are often constructed so that the light emitter and detector are sealed inside ambient-protected 6-pin packages, similar to the one in Figure 2-19 used for ICs. This package, often referred to as an optocoupler, does not allow any external light to enter. The input, usually a +5 voltage, is applied to two pins of the IC package. These two pins are connected to the terminals of the internal light emitting diode. A different voltage source, for example, +12 volts, +100 volts, or 120 VAC, is connected to two detector output leads of the IC. If the LED is turned on, its light illuminates the photodetector, which initiates an output current. The insulation resistance between the emitter and the detector is great enough to withstand an output voltage 5000 times greater than the input voltage.

Some devices are capable of operating as high as 100 kHz. Since there is no electrical connection between the emitter and detector, the package is often called an *optoisolator.* IC packages are often used as an interface between a low-voltage microprocessor and a high-voltage AC motor that the microprocessor controls. They also protect against unwanted signals being induced into control circuitry due to power line noise that can improperly turn on a machine.

2-5 Digital-to-Analog Converters

Digital-to-analog converters (**DACs** or D/A converters) are used to convert digital signals representing binary numbers into proportional analog voltages. Although these devices are now available in IC packages, they are analyzed here in a discrete form to better describe how they function.

A 4-bit input DAC is shown in Figure 2-20. It consists of a summing amplifier with its feedback resistor (R_F), four summing resistors, and four switches that are used to provide a 4-bit binary input. A switch in the open position represents the 0 state. In the closed position, it represents the 1 state. The placement of each switch corresponds to the same 8-4-2-1 weighted values of a 4-bit binary number. Resistors R_1 through R_4 are also selected with a weight proportional to the next. The 12.5-kilohm resistor R_4 is connected at the MSB (Most Significant Bit) input line. The values of the remaining resistors are selected by making each progressive resistor twice the size of the preceding one. The analog voltage is always at the op-amp output. The circuit is designed to operate so that a 4-bit binary number represented by the four switches is converted into voltages. Because 16 different combinations of switch positions are possible, (0–15), 16 different analog voltage levels proportional to the digital number applied are produced. The circuit in Figure 2-20 is designed so that it develops an analog output voltage equivalent to the binary number applied. For example, when all switches are in the open position to represent a binary input of 0000, the output is 0 volts. If SW1 is moved to the closed position, (binary 0001), the op-amp output will be –1 volts. If SW1 and SW3 are in the closed position, (binary 0101), the op-amp output will be –5 volts. If all four switches are in the closed position (binary 1111), the analog output voltage will be –15 volts. The analog output voltage for each combination of switch setting can be determined by the same formula used for the summing operational amplifier.

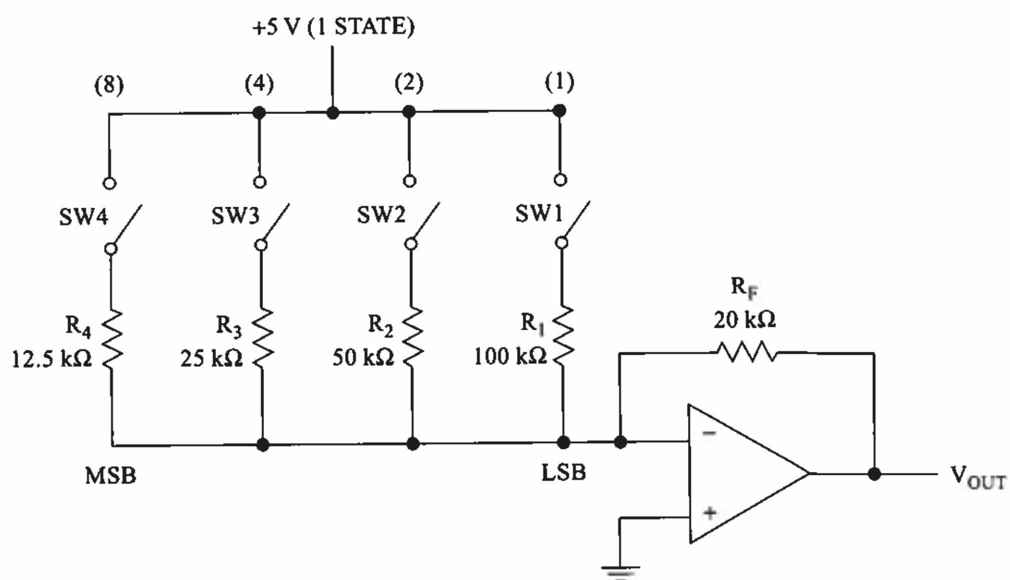


FIGURE 2-20 Binary-weighted D/A converter

EXAMPLE 2-1

What is the analog output voltage of the DAC in Figure 2-19 when a binary 1001 is applied?

Solution

$$I_{R_1} = \frac{V_{R_1}}{R_1} = \frac{5\text{ V}}{100\text{ kohms}} = .05\text{ mA}$$

$$I_{R_4} = \frac{V_{R_4}}{R_4} = \frac{5\text{ V}}{12.5\text{ kohms}} = .4\text{ mA}$$

$$I_{R_F} = .05\text{ mA} + .4\text{ mA} = .45\text{ mA}$$

$$V_{OUT} = I_{R_F} \times R_F$$

$$= .45\text{ mA} \times 20\text{ kohms} = 9\text{ V}$$

The table in Figure 2-21(a) provides all possible digital inputs and the corresponding output voltages for the circuit in Figure 2-20. Figure 2-21(b) provides the same information in a graphic format. The 4-bit DAC divides the reference analog output into fifteen equal divisions.

DACs in IC form are available with 8, 12, and 16 binary inputs. As the number of inputs increases, the reference analog voltage is divided into smaller divisions. For example, 8-bit DACs divide the analog output voltage into 255 equal parts, 12-bit converters into 4095 equal parts, and 16-bit converters into 65,535 equal divisions.

The number of equal divisions into which a DAC divides the reference voltage is called the *resolution*. The resolution of a DAC can be determined by the following formula:

$$\frac{V_{REF}}{2^n - 1}$$

- The 2 in the formula represents the binary number system.
- The n is the exponent that specifies to what power 2 is raised. It is determined by the number of binary inputs used at the input of the DAC. By taking 2 to the nth power, the maximum binary (equivalent decimal) number is determined.
- A 1 is subtracted from the maximum binary number to determine the number of equal steps (resolution) between the maximum binary number and minimum binary number.

EXAMPLE 2-2

Find the resolution of a DAC with a reference voltage of 30 volts and 4 inputs.

Solution

- Determine that the reference voltage is 30 volts.
- Because there are four digital inputs, n = 4.
- Raise $2^4 = 16$.
- Subtract 1 from 16 = 15.
- Divide 30 volts/15 = 2-volt resolution.

If the reference voltage is not provided, it is still possible to determine the resolution if the analog output voltage and the decimal input values are both provided.

(a)

SW4 8	SW3 4	SW2 2	SW1 1	V_{OUT} (−V)
0	0	0	0	0
0	0	0	1	1
0	0	1	0	2
0	0	1	1	3
0	1	0	0	4
0	1	0	1	5
0	1	1	0	6
0	1	1	1	7
1	0	0	0	8
1	0	0	1	9
1	0	1	0	10
1	0	1	1	11
1	1	0	0	12
1	1	0	1	13
1	1	1	0	14
1	1	1	1	15

(b)

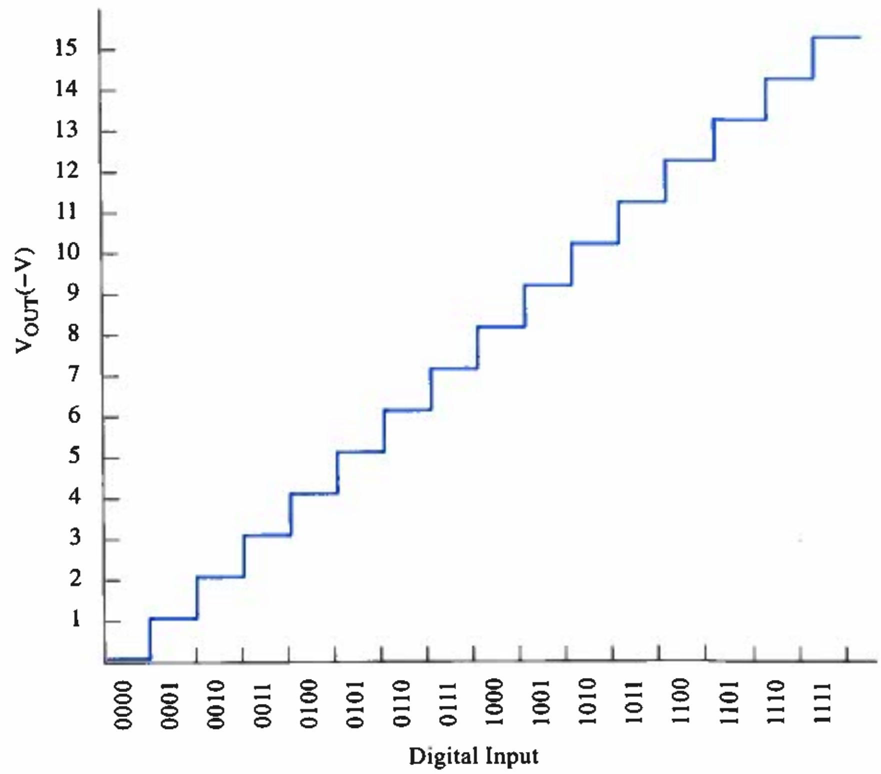


FIGURE 2-21 Analog output vs. digital input for the circuit shown in Figure 2-20

EXAMPLE 2-3

A 6-bit DAC produces an output voltage of 2.1 volts when the binary number applied to its input is 101010_2. What is the output voltage if the binary number changes to 111000_2?

Solution

Step 1: Convert the original binary number to the equivalent decimal value.

$$101010 = 42_{10}$$

Step 2: Determine the resolution by dividing the original analog output voltage by 42.

$$2.1/42 = .05 \text{ V (resolution)}$$

Step 3: Convert the new binary input number to its equivalent decimal value.

$$111000_2 = 56$$

Step 4: Multiply the resolution times 56.

$$.05 \times 56 = 2.8 \text{ V}$$

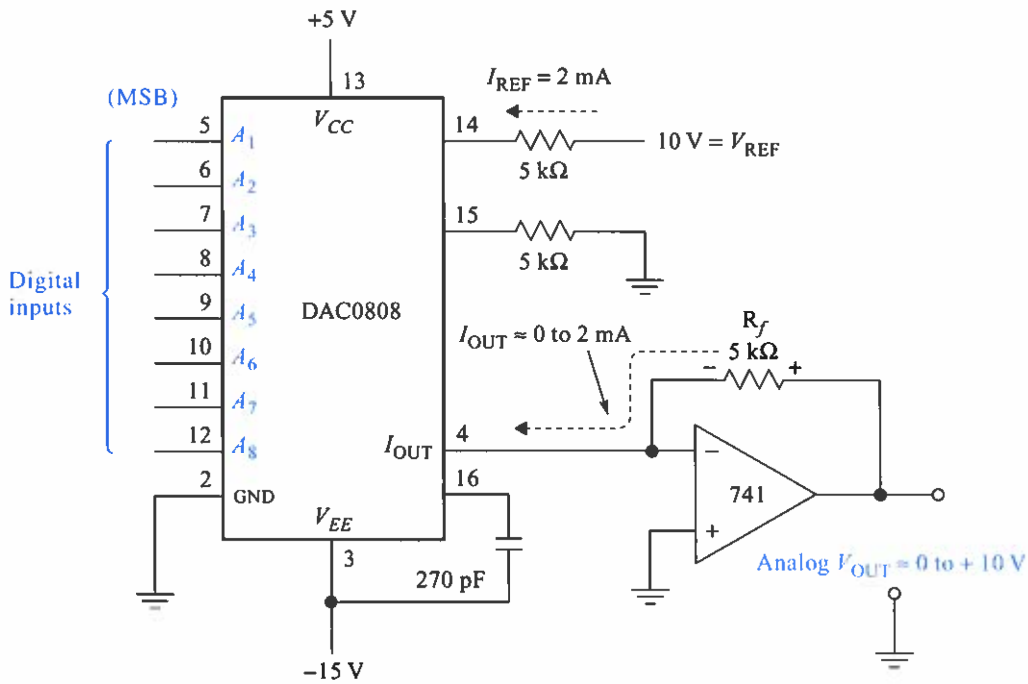


FIGURE 2-22 The DAC0808 and the 741 op amp connected to form a DAC

Normally, resolution is expressed in terms of the number of binary input bits that are converted. A DAC with high resolution requires an accurate reference voltage because any variation can cause an error.

Resolution is obviously an important factor to consider when purchasing a DAC. Also important are its accuracy and operating speed.

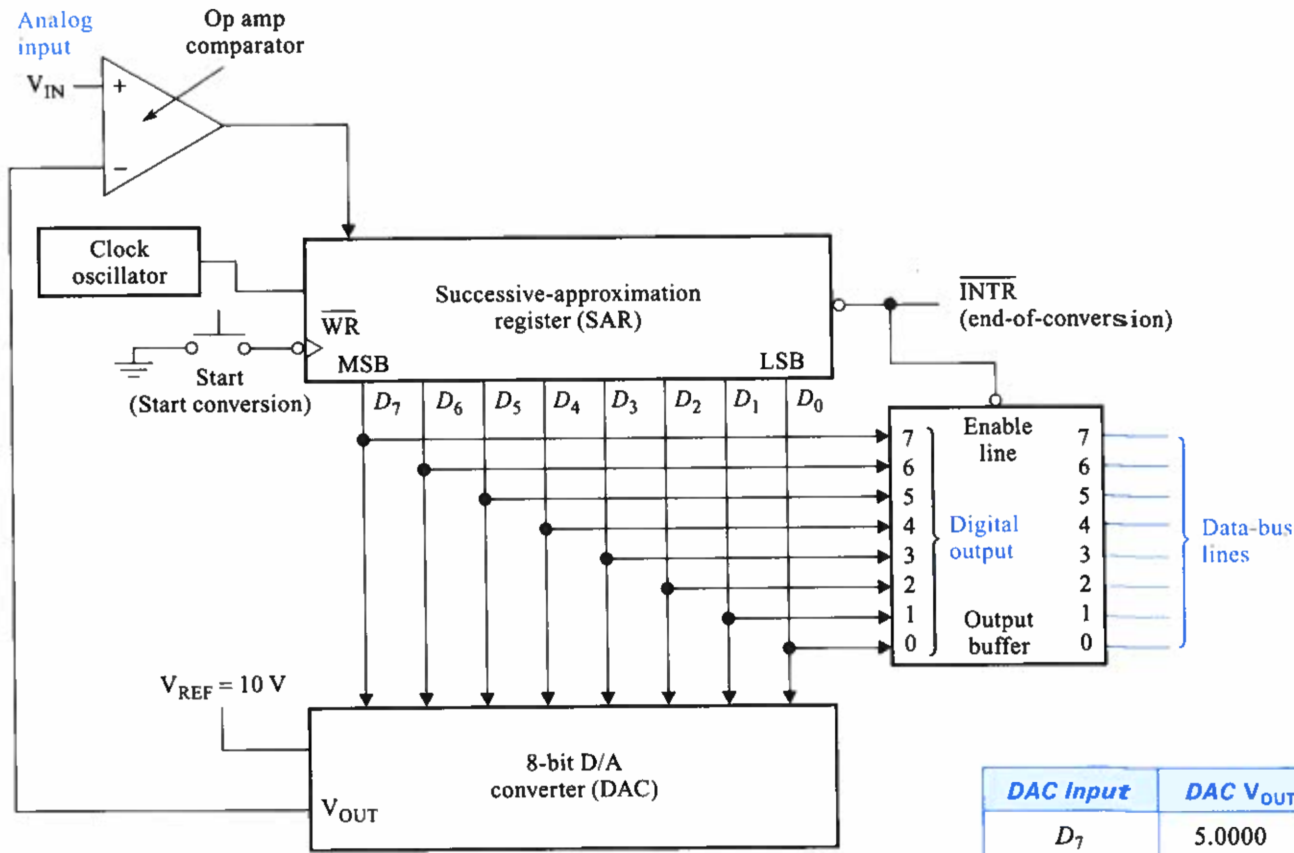
Integrated-Circuit Digital-to-Analog Converter

One popular DAC is the 8-bit DAC0808. The internal components supply proportional currents to its output lead.

Figure 2-22 shows the DAC0808 connected to an external 741 op amp. The current range is dictated by the 10-volt 5-kilohm combination connected to pin 14. The 2 mA flowing through resistor R_f is the maximum amount of current that can flow through output pin 4 (I_{OUT}). When the digital input is $0000\ 0000_2$, the minimum current of 0 mA flows through pin 4. When the digital input is $1111\ 1111_2$, the maximum current of 2 mA flows through pin 4. By using a 5-kilohm feedback resistor (R_f), the analog output voltage at the op amp output ranges from 0–10 volts. The 10 volts is produced when I_{OUT} is 2 mA. If a different analog output voltage range is desired, the gain of the op amp is adjusted by changing resistor R_f to a different value.

2-6 Analog-to-Digital Converters

The analog-to-digital converter (**ADC** or A/D converter) is capable of converting analog input voltages into proportional digital numbers. Analog-to-digital converters that operate at high speeds employ a circuit called a successive-approximation-register (SAR).



(a)

(b)

DAC Input	DAC V_{OUT}
D_7	5.0000
D_6	2.5000
D_5	1.2500
D_4	0.6250
D_3	0.3125
D_2	0.15625
D_1	0.078125
D_0	0.0390625

FIGURE 2-23 Simplified SAR A/D converter

Figure 2-23(a) shows a simplified block diagram of an ADC that uses an SAR. Its eight output lines D_0–D_7 cause the D/A converter to produce different voltages, as shown in Figure 2-23(b). These voltages will result if 10 volts is supplied to the V_{REF} input line. Its operation is as follows:

1. When the START button is pressed, the SAR is reset on the negative edge of the pulse applied to the $\overline{WR}$ input.
2. The conversion is begun on the leading edge of the conversion pulse after the START button is released.
3. When the positive transition of the first clock pulse occurs, the SAR produces a high at its MSB output, D_7. This causes the D/A converter to produce an analog voltage that is one-half its maximum value.
4. If the D/A converter output is higher than the unknown analog voltage (analog V_{IN}), the SAR output returns low. If the D/A converter output is lower than the analog input voltage, the SAR leaves bit 7 high.
5. The second clock pulse causes the next lower bit, D_6, to produce a high. If it causes the D/A converter output to be higher than the analog input, it returns to a low. If not, the SAR leaves D_6 high.
6. This process continues with the remaining six bits, D_5 to D_0.

7. At the end of the process, the SAR contains an 8-bit binary output that causes the D/A converter to produce an analog output equal to the unknown analog input. This occurs at the end of the eighth clock pulse. The 8-bit binary number contained by the SAR represents the analog input present at the eight output lines.
8. At the moment the eight-step conversion process is complete, the End-of-Conversion $\overline{INTR}$ line goes low. Because the ADC outputs are often shared with other devices on a common data-bus line, an 8-bit tri-state buffer is often connected to the digital outputs. When low, the $\overline{INTR}$ signal is used to enable the buffer to pass the digital count of the ADC to the bus lines. When the $\overline{INTR}$ output is high, the buffer outputs go into a high impedance state which allows another device to use the data-bus lines.

EXAMPLE 2-4

Show the waveforms that would occur if the successive-approximation-register A/D converter in Figure 2-23(a) were used to convert a 5.59-volt analog voltage to an equivalent 8-bit digital output.

Solution

See Figure 2-24. The SAR is fast because an 8-bit SAR only requires eight clock pulses to perform the entire process.

Integrated-Circuit Analog-to-Digital Converter

Figure 2-25 shows the block diagram of the ADC0804 analog-to-digital converter IC. The circuit shown is capable of converting the analog voltage into a proportional 8-bit digital output. The analog voltage range to be converted is determined by applying the desired maximum voltage to V_{DC}. For fine tuning, half of the V_{DC} voltage is applied to input $V_{REF/2}$. If necessary, a slight voltage change at $V_{REF/2}$ will then bring the ADC into calibration. By applying 5.12 volts to V_{DC} and 2.56 volts to $V_{REF/2}$, the circuit is capable of converting an analog voltage connected across $V_{IN}(+)$ and $V_{IN}(-)$ ranging from 0 to 5.12 volts. With eight output leads, there are 256 different analog voltage levels that are converted into digital outputs. Therefore, the resolution of this device is 0.39 percent (1/255 = .0039 = 0.39%). With 5.12 volts as the maximum input voltage, each 0.02-volt (5.12 × .0039) increase causes the binary count to increase by 1.

EXAMPLE 2-5

If the binary count produced by the ADC is 01011101_2, what is the analog voltage applied to the input?

Solution

Step 1: Convert the binary number to an equivalent decimal value.

$$01011101_2 = 93_{10}$$

Step 2: Multiply 93 times the resolution.

$$93 \times 0.02 = 1.86\text{V}$$

It is possible to determine the binary output when the resolution and the analog input voltage is known.

EXAMPLE 2-6

If the analog voltage applied to the input is 3.04 volts, what is the binary count at the digital output?

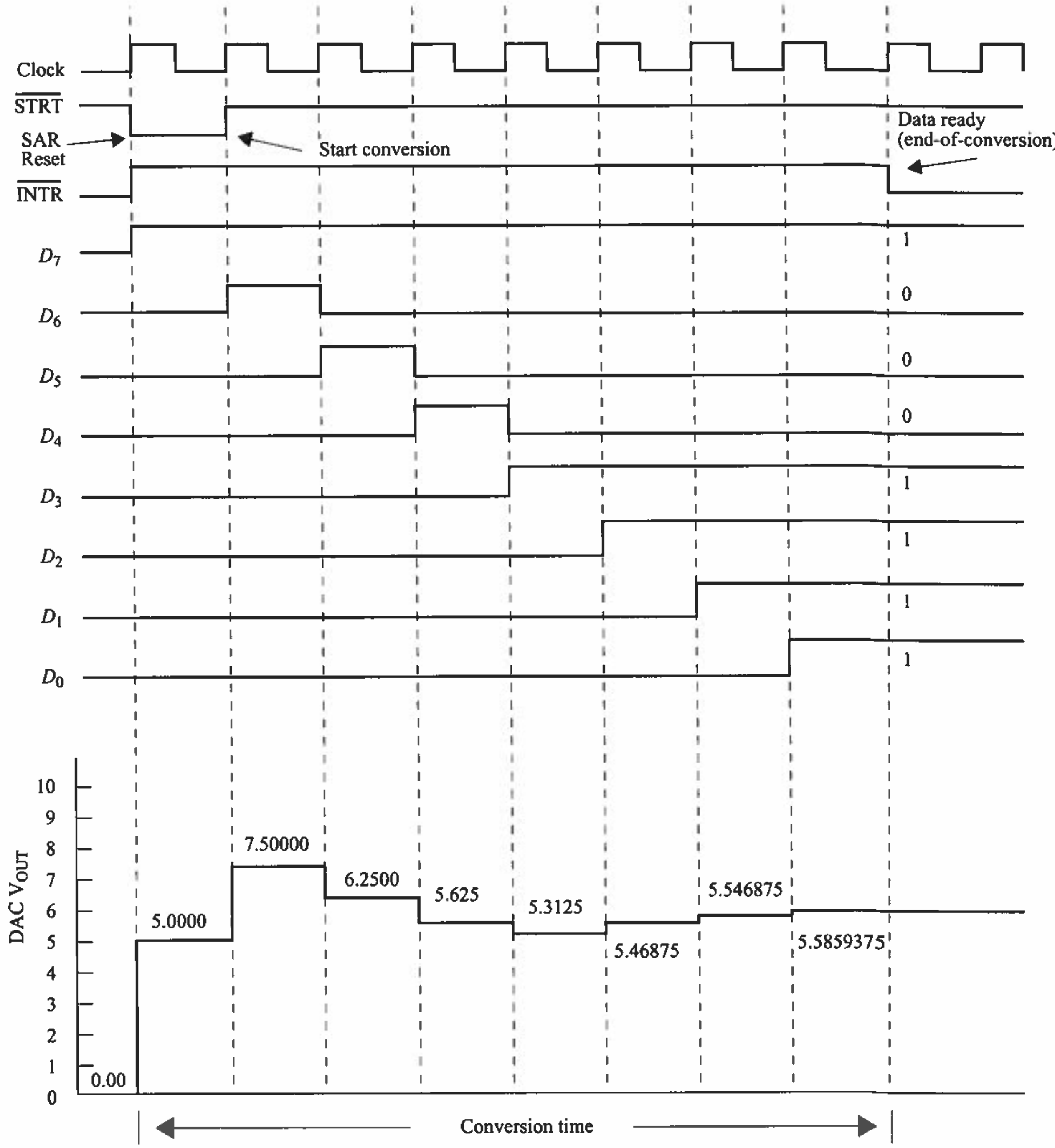


FIGURE 2-24 Timing diagram for a successive-approximation-register ADC

Solution

Step 1: Divide the input voltage by the resolution.

$$3.04/.02 = 152$$

Step 2: Convert the decimal value into the equivalent binary number.

$$152_{10} = 10011000_2$$

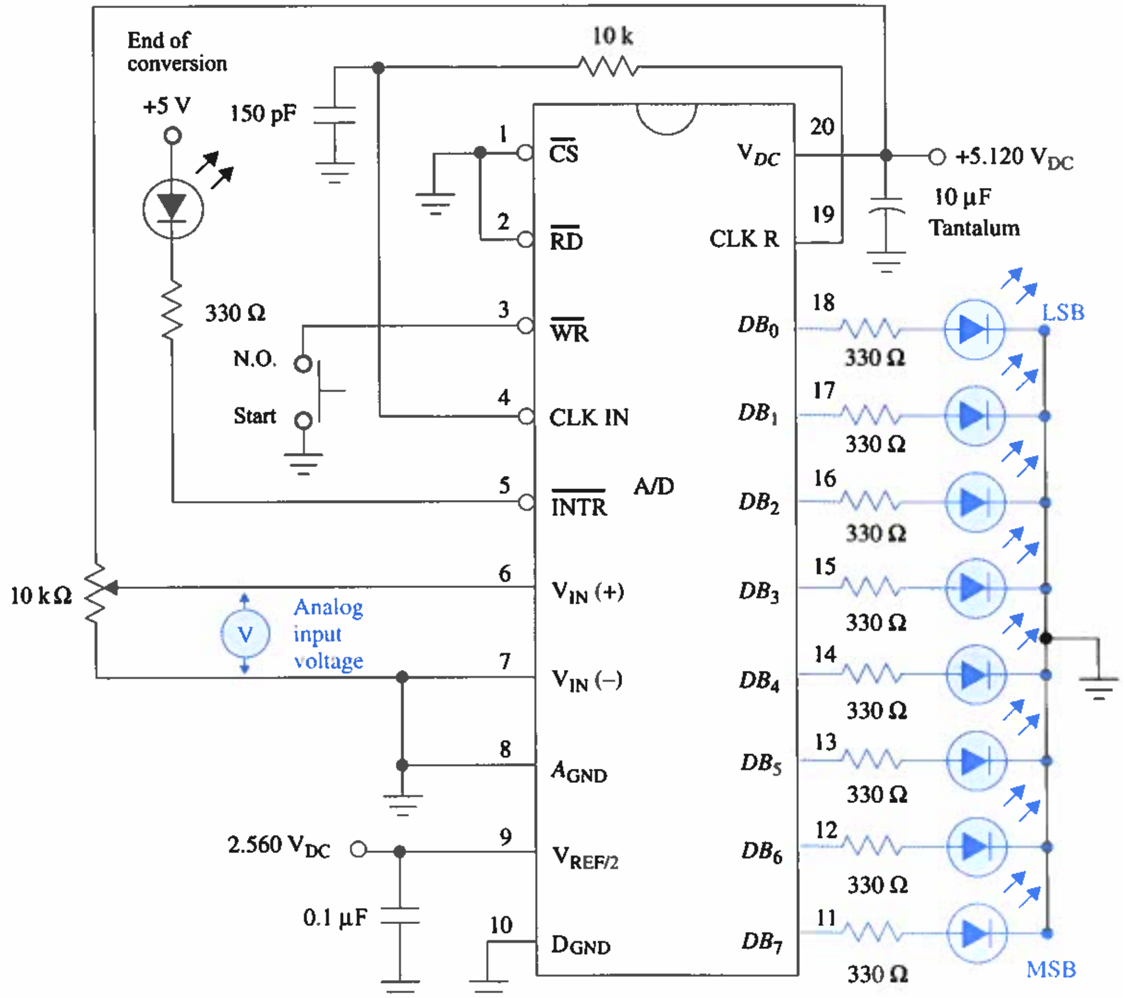


FIGURE 2-25 Block diagram of the ADC0804 analog-to-digital converter

The ADC0804 IC contains an internal clock. To operate, a resistor and capacitor are connected to the CLK *R* and CLK IN inputs. The ADC0804 IC also contains an 8-bit successive approximation register for its conversion process. The SAR is reset on a negative edge of a pulse to the $\overline{\text{WR}}$ input lead by the closure of the START push button. When the push button is released, the pulse applied to the $\overline{\text{WR}}$ input returns high and the conversion process begins. At the end of this process, which takes eight clock pulses, output $\overline{\text{INTR}}$ goes low. The eight outputs that represent the analog input voltage will be present at the active-high output lines DB^0 to DB^7. To continue updating the applied analog input voltage, the $\overline{\text{INTR}}$ pin is connected to the WR input line. By doing so, 5000 to 10,000 conversions can be made per second.

The ADC0804 IC is a CMOS device that is designed to interface directly with some types of microprocessors. Therefore, some of its pins such as $\overline{\text{RD}}$, $\overline{\text{WR}}$, $\overline{\text{CS}}$, and $\overline{\text{INTR}}$ correspond to leads of the similarity-labeled microprocessors.

2-7 Timing Devices

Timing devices are used to produce rectangular signals referred to as square-wave signals. Timing devices may generate either a single pulse or a continuous string of pulses. Single pulses are used to preset data into memory devices or to clear data. These signals are produced by **monostable multivibrators.** Continuous pulses are used as clock signals that are the heartbeat in computer devices. As they are fed through computer-based equipment, all events throughout the computing systems are properly timed and synchronized. These signals are produced by **astable multivibrators.**

A linear IC specifically designed for timing applications is the 555 monolithic IC chip. A pin diagram of this chip is shown in Figure 2-26.

When a minimal number of external resistors and capacitors are connected to various pins of the 555 IC, it operates as an astable or monostable multivibrator. Figure 2-27 shows a schematic diagram of the 555 IC. It consists of the following sections:

Voltage Divider Network. Resistors R_1, R_2, and R_3 are all 5 kohms. They form a voltage divider which biases the inverting (−) input of comparator A at 2/3 the power

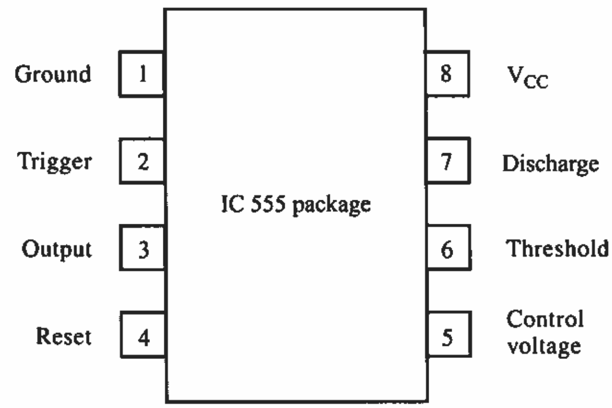


FIGURE 2-26 555 IC package

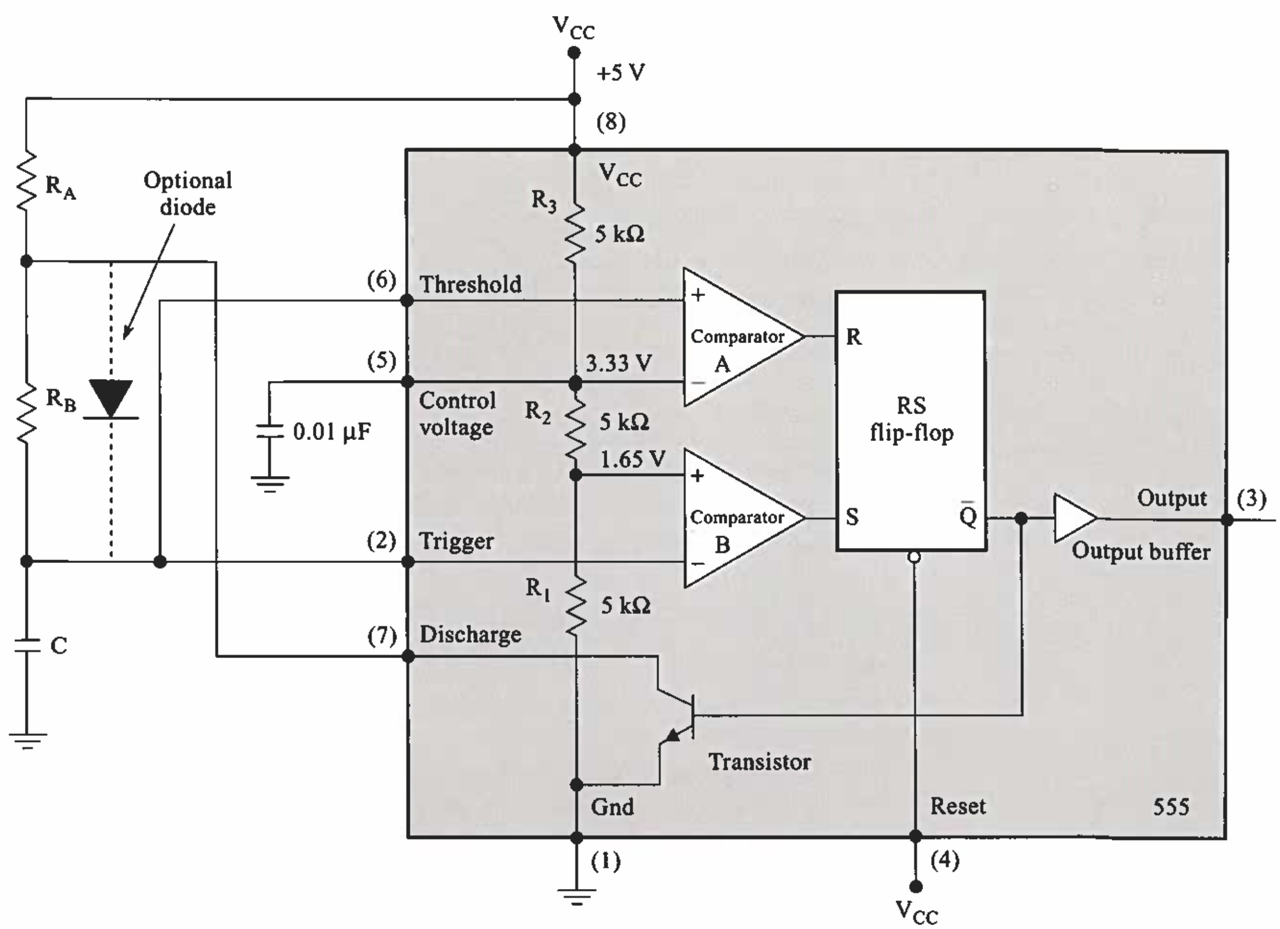


FIGURE 2-27 Schematic diagram of the 555 IC astable timer

supply voltage (3.33 V), and the noninverting (+) input of comparator B at 1/3 the power supply voltage (1.65 V).

Voltage Comparators. Each comparator has one of its inputs connected to an external pin. The noninverting input of comparator A is connected to external pin 6, called the *Threshold terminal.* The inverting input of comparator B is connected to external pin 2, called the *Trigger terminal.* The output of comparator A is Low if the voltage at the threshold terminal is lower than 3.33 volts. The output of comparator B is Low if the voltage at the trigger terminal is greater than 1.65 volts. The logic levels at the comparator outputs control the flip-flop.

R-S Flip-Flop. The output of comparator A is connected to the R input of the flip-flop, and the output of comparator B is connected to the S input. The outputs of the two comparators are never on simultaneously. Only output $\overline{Q}$ of the R-S flip-flop is used. The $\overline{Q}$ lead is connected to the base of the transistor and the input of the output buffer. When the output of comparator A goes High, it causes the flip-flop to reset, generating a High at the $\overline{Q}$ output. When the output of comparator B goes High, it causes the flip-flop to set, generating a Low at output $\overline{Q}$.

Transistor. The NPN transistor operates like a switch. When the $\overline{Q}$ output of the flip-flop is High, the transistor turns on and operates like a closed switch. When the $\overline{Q}$ output is Low, the transistor turns off.

Output Buffer. The function of the output buffer is to produce a high current voltage to provide a sufficient signal for external circuitry. The buffer goes Low when $\overline{Q}$ is High, and goes High when $\overline{Q}$ is Low because it is an inverting amplifier.

555 Astable Multivibrator

The astable multivibrator diagrammed in Figure 2-27 has no stable output state. It is triggered by its own internal circuitry; therefore, it has no input lines. When power is applied, it switches back and forth at a desired rate between two states, producing a square wave at its output. The operation of the astable multivibrator is as follows:

Assume:

- The capacitor is discharged.
- Comparator A output is Low.
- Comparator B output is High.
- Flip-flop $\overline{Q}$ output is Low.
- Transistor is off.

Therefore:

- When power is applied to the circuit, current flows through the RC network of R_A, R_B, and C. When the capacitor charges to 1.66 volts, this potential is felt at the trigger input (2) and causes the comparator B output to go Low.
- When the capacitor charges to 3.34 volts, it is felt at the threshold input (6) and comparator A goes High.
- With a Low at flip-flop input S, and a High at input R, the $\overline{Q}$ output goes High.
- A High at $\overline{Q}$ causes the output line of the output buffer to go Low.
- A High at $\overline{Q}$ turns the transistor on, which allows the capacitor to discharge through the transistor and R_B.
- When the charge on the capacitor goes less than 3.33 volts, the threshold potential causes the comparator A output to go Low.
- When the discharging capacitor goes less than the 1.65 volts, the trigger input causes comparator B to go High.
- When comparator A output is Low and comparator B output is High, the flip-flop $\overline{Q}$ output goes Low.
- A $\overline{Q}$ Low output causes the output line of the output buffer to go High.

- A Low turns the transistor off, which opens the discharge path of the capacitor and starts the charging phase of the next cycle.

The rate at which the IC's internal components turn on and off is determined by the values of the external components connected to the IC.

The frequency of the output can be determined by the following formula:

$$f = \frac{1.44}{(R_A + 2R_B)C}$$

EXAMPLE 2-7

What is the frequency of the astable multivibrator with the following values of external components? $R_A = 4.7\ k\Omega$, $R_B = 270\ \Omega$, and $C = 0.47$ ufd.

Solution

$$f = \frac{1.44}{(R_A + 2R_B)C}$$

$$= \frac{1.44}{(4.7\ k\Omega + 540\ \Omega)0.47\ \text{ufd}}$$

$$= \frac{1.44}{0.0024628}$$

$$= 585\ \text{Hz}$$

Initially, the external capacitor charges through R_A and R_B and then discharges through R_B. These charging and discharging times affect what is called a *duty cycle.* The duty cycle is the ratio of time the output terminal is High to the total time of one cycle. The duty cycle is set precisely by the ratio of these two resistors. The charging time (output buffer is High) is T_1. The discharging time (output buffer is Low) is T_2. The total period of time for one cycle is T. These values are calculated as follows:

$$T_1 = 0.693(R_A + R_B)(C)$$

$$T_2 = 0.693(R_B)(C)$$

$$T = T_1 + T_2 = 0.693(R_A + 2R_B)(C)$$

The duty cycle is:

$$DC = \frac{T_1}{T} \quad \text{or} \quad DC = \frac{R_A + R_B}{R_A + 2R_B}$$

EXAMPLE 2-8

What is the duty cycle of the astable multivibrator with the following values of external components. $R_A = 10\ k\Omega$, $R_B = 4.7\ k\Omega$.

Solution

$$DC = \frac{R_A + R_B}{R_A + 2R_B}$$

$$= \frac{10\ k\Omega + 4.7\ k\Omega}{10\ k\Omega + 9.4\ k\Omega}$$

$$= \frac{14.7\ k\Omega}{19.4\ k\Omega}$$

$$= .76, \text{ or } 76\%$$

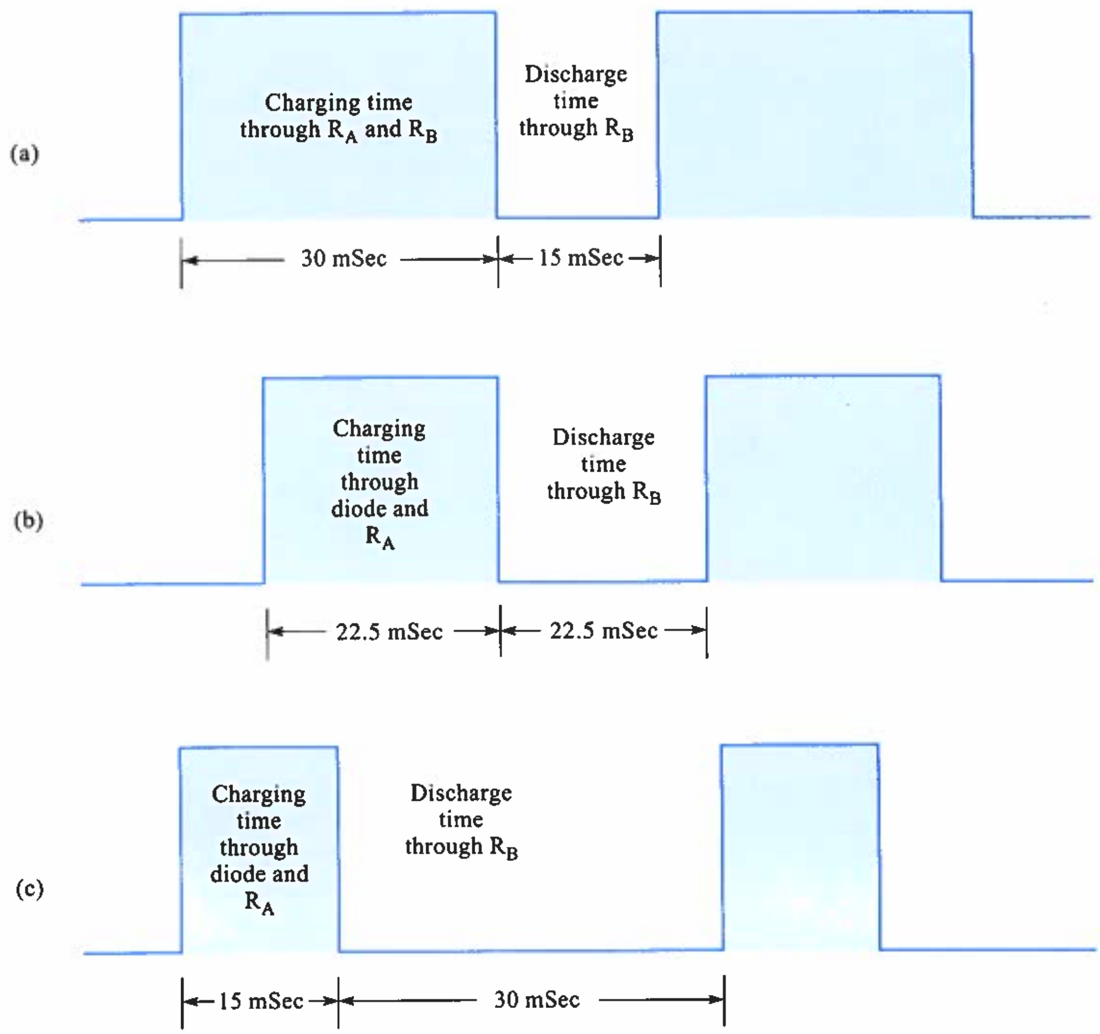


FIGURE 2-28 Waveforms showing duty cycles

Because the capacitor charges up through R_A and R_B and then discharges only through R_B, the duty cycle is always greater than 50 percent, as shown in the top waveform of Figure 2-28(a). However, it may be desirable to have a symmetrical square wave, which means that the time duration of the positive alternation equals that of the negative alternation, as shown in Figure 2-28(b). This would result if the duty cycle is 50 percent. This situation is possible only if the charging and discharging time durations of the capacitor are the same. By making R_A and R_B the same, and placing a diode across R_B with the anode connected to pin 7, and the cathode to pin 6, a symmetrical square wave is possible. The placement of the diode bypasses R_B and allows the capacitor to charge only through R_A. When the capacitor discharges, its current path is blocked by the reverse-biased diode, and only flows through R_B. Therefore, the charge and discharge paths are through resistances of the same value. Depending on the resistance ratios of R_A and R_B, this configuration allows the duty cycle to vary over a range of 5 percent to 95 percent, as shown in Figure 2-28(c).

555 Monostable Multivibrator

The **monostable multivibrator,** also known as a one-shot, is characterized as having only one stable state. Its output is normally 0. When a triggering signal is applied to its input, the output changes from its normal stable state to a logic 1 (unstable state) for a specified length of time before automatically returning to its stable state. The triggering signal comes from either a mechanical switch or from another circuit. The period of time the monostable multivibrator

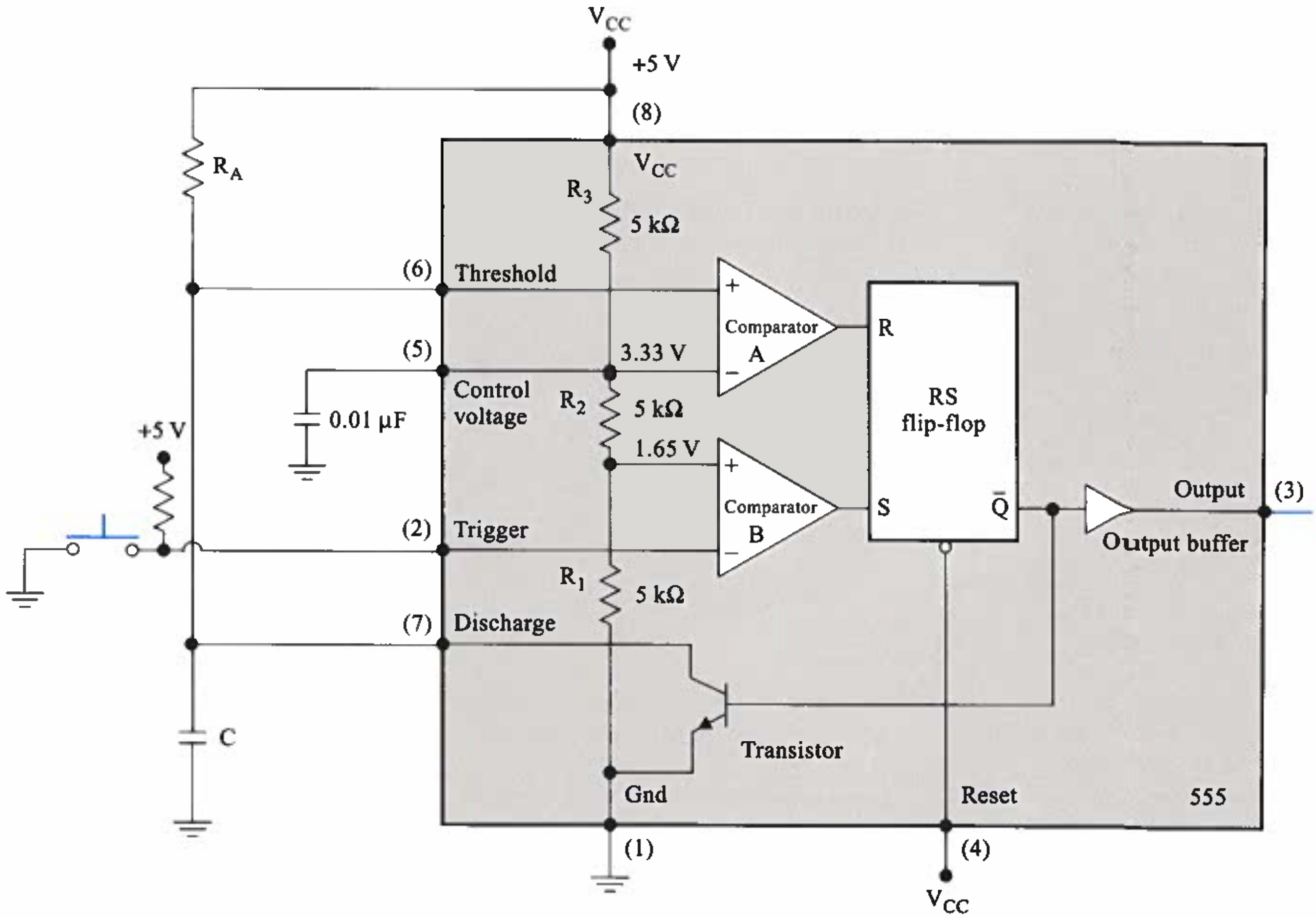


FIGURE 2-29 Schematic diagram of a 555 timer with the external timing components to form a monostable multivibrator

remains in its unstable state is determined by an external RC timing circuit. The output pulse generated can be either longer or shorter than the input pulse.

Figure 2-29 shows the required connections for a 555 IC to operate as a one-shot. Its operation is as follows:

Assume:

- The capacitor is discharged.
- Comparator A output is Low.
- Comparator B output is Low.
- Flip-flop $\overline{Q}$ output is High.
- The transistor is on.
- The output buffer is Low.
- A +5-volt High is applied to the trigger input.

Therefore:

- While the trigger signal is brought from a High to a temporary 0-volt potential by a push button closure, the comparator B output goes High. The comparator B output returns to a Low when the push button is released.
- A Low applied to the flip-flop's R input from comparator A and a temporary High applied to the flip-flop's S input from comparator B cause the flip-flop's $\overline{Q}$ output to go Low.
- A Low at the $\overline{Q}$ output of the flip-flop causes the buffer output to go High.

- A Low at the $\overline{Q}$ output turns off the discharge transistor that enables the capacitor to begin charging up toward $+V_{CC}$.
- When the capacitor charges to 3.34 volts, the comparator A output goes High.
- A High at the output of comparator A and a Low at the output of comparator B causes the RS flip-flop to reset and develop a High at its $\overline{Q}$ lead.
- A High at the $\overline{Q}$ output causes the output buffer to go back to a normal Low state, and the one-shot pulse time duration is complete.
- The High $\overline{Q}$ output turns on the discharge transistor that provides a discharge path for the capacitor.
- When the capacitor is discharged, the one-shot awaits another negative-going pulse at the trigger input.

The capacitor reaches a 3.34-volt charge after 1.1 time constants. This time period determines the width of the output pulse of the one-shot. The time duration of the pulse is expressed in the following formula:

$$T = 1.1\ RC$$

where,

T is in seconds,
R is in ohms,
C is in farads.

EXAMPLE 2-9

What is the duration in which the monostable multivibrator is in its unstable state when the external components have the following values:

$$R = 100\ k\Omega$$
$$C = 47\ ufd$$

Solution

$$T = 1.1\ RC$$
$$= 1.1 \times 100\ k\Omega \times 47\ ufd$$
$$= 5.17\ seconds$$

The one-shot pulse duration can range from microseconds to several minutes.

Problems

1. An inverting op amp circuit has $R_F = 5$ kilohms and $R_{IN} = 1$ kilohm. What is the gain of this circuit?
2. What is the output voltage of the circuit in Figure 2-30?
3. A noninverting op amp with an input resistor of 10 kohms and a feedback resistor of 50 kohms has 0.4 volts applied to its input. What is the output voltage?
4. At the moment an input signal applied to an integrator changes from 0 to +3 volts, it has a __________ (minimum, maximum) gain.
5. When a sawtooth-shaped signal is applied to the input of a differentiator, a __________-shaped signal is produced at the output.
6. The process where the switching threshold on a positive going input signal applied to a Schmitt trigger is higher than the negative-going signal is referred to as __________.
7. Fill in the parenthesis of each of the following equations with $<$, $>$, or $=$ symbols to describe how an op amp comparator operates:
   a. Inverting input voltage (____) noninverting input voltage = positive output voltage.
   b. Inverting input voltage (____) noninverting input voltage = zero output voltage.
   c. Inverting input voltage (____) noninverting input voltage = negative output voltage.

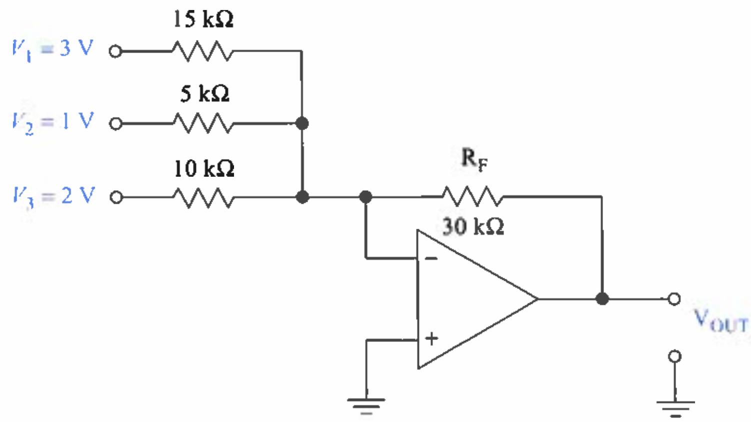


FIGURE 2-30 Circuit for problem 2

8. Assuming the values of all resistors connected to a difference op amp are the same, what is the output voltage when +3 volts are applied to the inverting input and +1 volt is applied to the noninverting input?
9. What three decisions does a magnitude comparator perform when comparing two different binary numbers?
10. Describe the meaning of the term optoisolator.
11. When light strikes the base of a __________ (forward, reverse) biased photoelectric detector, it turns on.
12. DAC resolution is determined by the number of digital __________ lines available.
13. What is the resolution of a DAC with a maximum voltage of 15 volts and five input lines?
14. A 5-bit DAC produce an output of 9.2 volts when the binary number applied to its input is 10111_2. What is the output voltage if the binary number changes to 10101_2?
15. What is the resolution of a 5-bit ADC that has a maximum analog input voltage of +10 volts?
16. An 8-bit "successive-approximation-register" ADC requires how many clock pulses for each conversion?
17. In Figure 2-25, if the output reads 10000000, the analog voltage applied to the input is __________ volts.
18. What is the duty cycle of the astable multivibrator with the following values of external components: R_A = 3.3 kΩ, R_B = 6.8 kΩ.
19. The duty cycle of a square wave is the ratio of time the output terminal is __________ (low, high) to the total time period of one cycle.
20. How can a 555 astable multivibrator be constructed to produce a square wave that ranges from a 5 percent to 95 percent duty cycle?
21. Referring to Figure 2-27, what is the output frequency if R_A = 100 kΩ, R_B = 10 kΩ, and C = 10 μfd?
22. Referring to Figure 2-29, what is the amount of time the one-shot is in the unstable state if R_A = 2 kΩ, and C = 1 μfd?

SECTION 2

The Controller

OUTLINE

Chapter 3 The Controller Operation

Section one introduced key concepts in industrial control, namely, control system classifications and interfacing. It provided an overview of the elements of an industrial control loop and described the operation of discrete components and various integrated circuits.

Section 2 consists of a single chapter, which describes the operation of the "brain" of the industrial control loop: the controller element. It addresses the operational techniques performed by controllers that use descrete components or computer software to perform their functions. Various control modes such as On-Off, PID (proportional-integral-derivative), and time proportioning.

CHAPTER 3

The Controller Operation

OBJECTIVES

At the conclusion of this chapter, you should be able to:

- List the four control modes used by the controller section.

On-Off Control	Proportional-Integral Control
Proportional Control	Proportional-Integral-Derivative Control

- Define the following terms associated with control modes of a closed-loop system:

Hysteresis	Proportional Band	Proportional Gain
Differential Gap	Stable/Unstable	Offset
PID	Steady-State Error	Deadband

- Describe the operation of each type of mode control function.
- Explain the operation of the operational amplifier circuitry that performs each of the three PID mode functions.
- List a practical application of a PID and a time-proportioning control system.
- Describe the operation of time-proportioning control.

INTRODUCTION

The controller is an element of the closed-loop system that processes information needed to perform the decision-making function. The controller can be considered the brain that enables automated systems to operate without human intervention.

The input applied to the controller is the error signal, which is proportional to the difference between the desired setpoint and the feedback signal. The controller calculates changes needed in the controlled variable to compensate for disturbances that upset the process, or changes in the setpoint. The controller responds to these changes by producing an output signal that drives the actuator to alter the controlled variable until the error signal is reduced toward zero.

The controller may be as simple as a spring-balanced mechanical lever or as complicated as a computer. It may control one process or several simultaneously. It may be analog, digital, or a combination of both.

3-1 Control Modes

Figure 3-1 illustrates the operation of the controller. The input applied to the controller is called the error signal. It represents the difference between the setpoint signal and the feedback signal. The input error signal is expressed by the following formula:

$$\text{Error Signal } e(t) = \text{Setpoint} - \text{Feedback Signal}$$

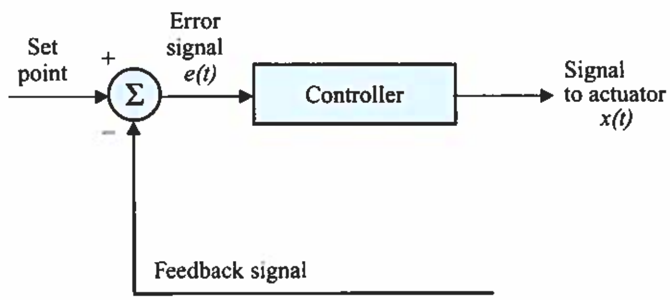


FIGURE 3-1 Controller representation

The error signal is not constant; it changes through time. Therefore (t) is used with symbol e in the equation.

The controller output signal is expressed as $x(t)$. Because the controller output also changes with time, (t) is used with the output symbol x. The time required for the controller to respond to the error signal depends on the control mode used.

There are four control modes of operation that are commonly performed by the controller section of a closed-loop system:

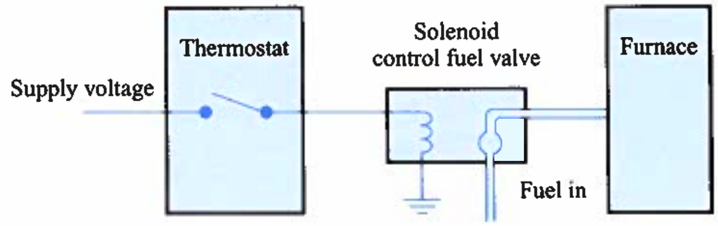
1. On-Off
2. Proportional
3. Proportional-Integral
4. Proportional-Integral-Derivative

All four modes of control respond to error signals. They differ in the speed and accuracy with which they eliminate the error between the setpoint and the controlled variable.

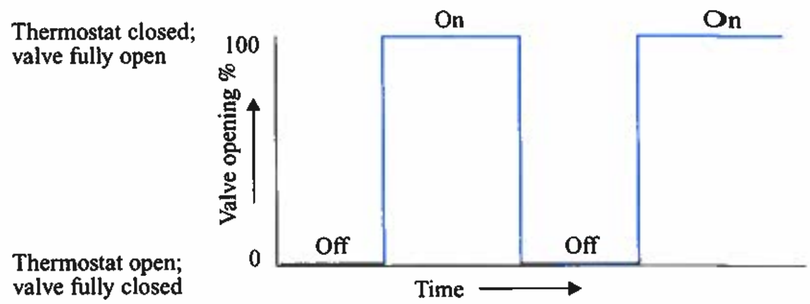
3-2 On-Off Control

The **On-Off control** mode is the most basic type of control system. Its output has only two states, usually fully on and fully off. One state is used when the controlled variable (e.g., temperature, fluid level, voltage) is above the desired value (setpoint). The other state is used when the controlled variable is below the setpoint. The On-Off controller is also referred to as the two-position, or bang-bang, control.

The home heating system shown in Figure 3-2 illustrates this mode of control. The thermostat is the measurement device. When the room temperature (controlled variable) falls below the setting (setpoint), the thermostat closes a switch that is connected to a fuel valve in the furnace, as shown in Figure 3-2(a). With the switch closed, the valve is fully opened. The furnace turns on and begins to generate heat. When the room temperature rises above the setting, the thermostat opens the switch connected to the furnace fuel valve. An open switch closes the fuel valve to extinguish the flame. With the furnace off, the temperature in the room begins to fall. When the temperature has gone low enough, the furnace turns back on.



(a) Home heating system



(b) Graph illustrating operation of thermostat and furnace fuel valve

FIGURE 3-2 On-Off controller

Since the controlled variable must deviate from the setpoint to cause control action, the process response will continually cycle. The cycling occurs because of two factors:

1. Process disturbances cause the output to deviate from the setpoint.
2. The corrective action of the On-Off controller cannot adjust the output to exactly match the process demand. Instead, by being either fully on or fully off, the actuator's response is too large to return the process to the setpoint. The temperature is said to oscillate as it continually rises above and below the setpoint, as graphically shown in Figure 3-3.

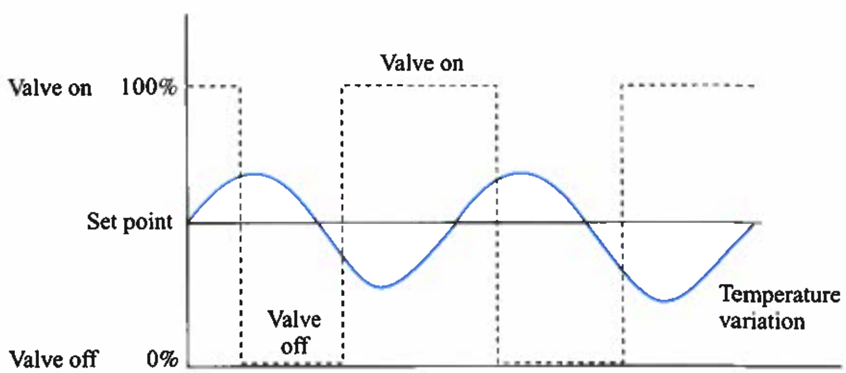


FIGURE 3-3 Graph illustrating temperature oscillation above and below setpoint as fuel valve is opened and closed

The inherent cycle condition is detrimental to most final correcting devices, such as the fuel valve, pumps, relays, etc. By turning the output on and off so frequently, the rapid oscillation wears equipment and shortens its life. This condition is often referred to as **short cycling.**

To prevent rapid cycling, the time between the oscillations can be lengthened by adding an On-Off **differential gap** to the controller function. Also referred to as the **deadband,** the differential gap forces the controlled variable to move above or below the setpoint by a specified amount before the controlled action will change again. Figure 3-4 illustrates the differential gap function added to the thermostat device. The temperature must rise 2 degrees above the setpoint before the furnace turns off. To turn the furnace back on, the temperature must fall 2 degrees below the setpoint. Differential gap is defined as the smallest change in the controlled variable that causes the value to shift from on to off, or off to on. Therefore, the differential gap for the thermostat is 4 degrees.

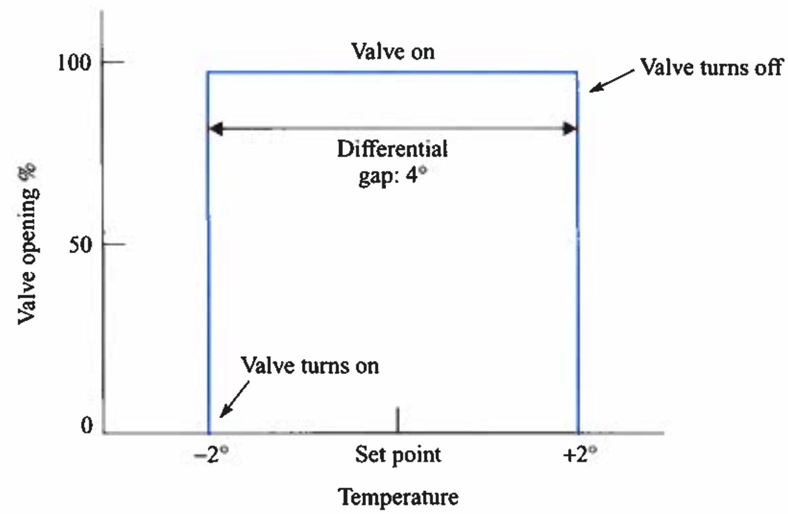


FIGURE 3-4 Differential gap of a thermostat

The differential gap is also expressed as a percentage of the full range of the controlling device. For example, the temperature range on a typical home thermostat is between 40 and 90 degrees. Therefore, the full range is 50 degrees (90 − 40 = 50). A temperature variance of 4 degrees represents 8 percent of full control range, because

$$\% \text{ Differential Gap (Deadband)} = \frac{\text{Differential Gap}}{\text{Total Control Range}}$$

$$= 4/50$$

$$= 0.08 \text{ or } 8\%$$

The graph in Figure 3-5(a) illustrates the operation of the thermostat, the fuel valve in the furnace, and the resulting room temperature. It shows that the room temperature does not respond instantly after the fuel valve is turned on or off. For instance, after the thermostat turns the fuel valve off, the furnace and ducts contain enough heat so that the temperature in the room will not immediately begin to fall. Likewise, the temperature in the room does not rise as soon as the furnace turns on. A certain amount of time passes before the heat generated inside the furnace travels to the location of the thermostat. This lagging effect of the temperature behind the thermostat switching action is called **hysteresis.** Figure 3-5(b) shows the effects of narrowing the differential gap. The narrow gap causes rapid cycling with a small deviation from setpoint. The wider differential shown in Figure 3-5(a) causes less frequent cycling, but at the expense of greater deviation from the setpoint. A compromise is made between frequency of cycling and amplitude.

Because the On-Off control mode is simple, inexpensive, and inherently reliable, it is the most common type of feedback system. On-Off controllers are widely used in applications that can tolerate the cycling and deviation from setpoint. For example, they control thermostatic furnaces, refrigerators, and solenoids to open or close flow valves that pass liquids to a tank. They would never be used to control precision devices, such as a robot.

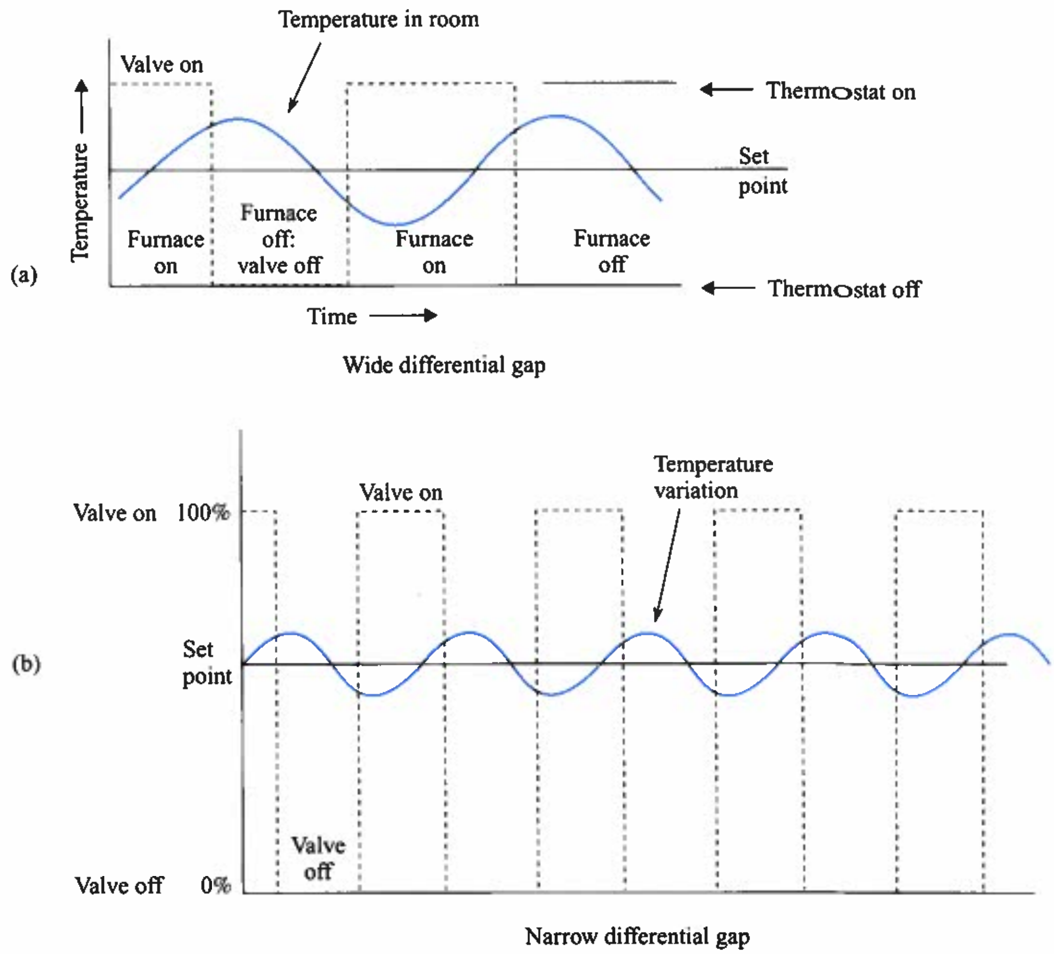


FIGURE 3-5 Comparison of systems with wide and narrow differential gaps

3-3 Proportional Control

Some situations require tighter control of the process variable than On-Off control can provide. **Proportional control** provides better control because its output operates linearly anywhere between fully on and fully off. As its name implies, its output changes proportionally to the input error signal. The greater the error, the more the output responds. This action returns the controlled variable to the desired setpoint value without the rapid cycling of On-Off control.

To illustrate the operation of proportional control, the operation of a furnace is again used. To obtain this type of control, two modifications must be made to an On-Off system. First, the On-Off switch in the thermostat is replaced by a thermistor in a bridge network. The output of the bridge produces a variable voltage in response to temperature changes. Second, the solenoid-type fuel valve in the furnace must be replaced by a proportional valve. The proportional valve opens proportionally to the input voltage from the bridge. The larger the voltage, the more fuel it supplies so that a higher temperature is produced.

Figure 3-6(a) shows the proportional control furnace system. The graph in Figure 3-6(b) plots the percentage of the proportional valve opening versus room temperature. The temperature of 70 degrees is the setpoint for the system. At a 70-degree room temperature, the proportional valve is 50 percent open. At this point, the bridge is balanced and a 0-volt feedback signal is produced. The positive voltage error signal produced by the summing op amp causes the proportional valve to be half open when the setpoint of −5 volts is not offset by the feedback signal. If the temperature drops below 70 degrees, the resistance of the thermistor increases. As a result, the voltage at the inverting input of the difference op amp becomes greater than the voltage at the noninverting input. The feedback signal produced by the difference op amp

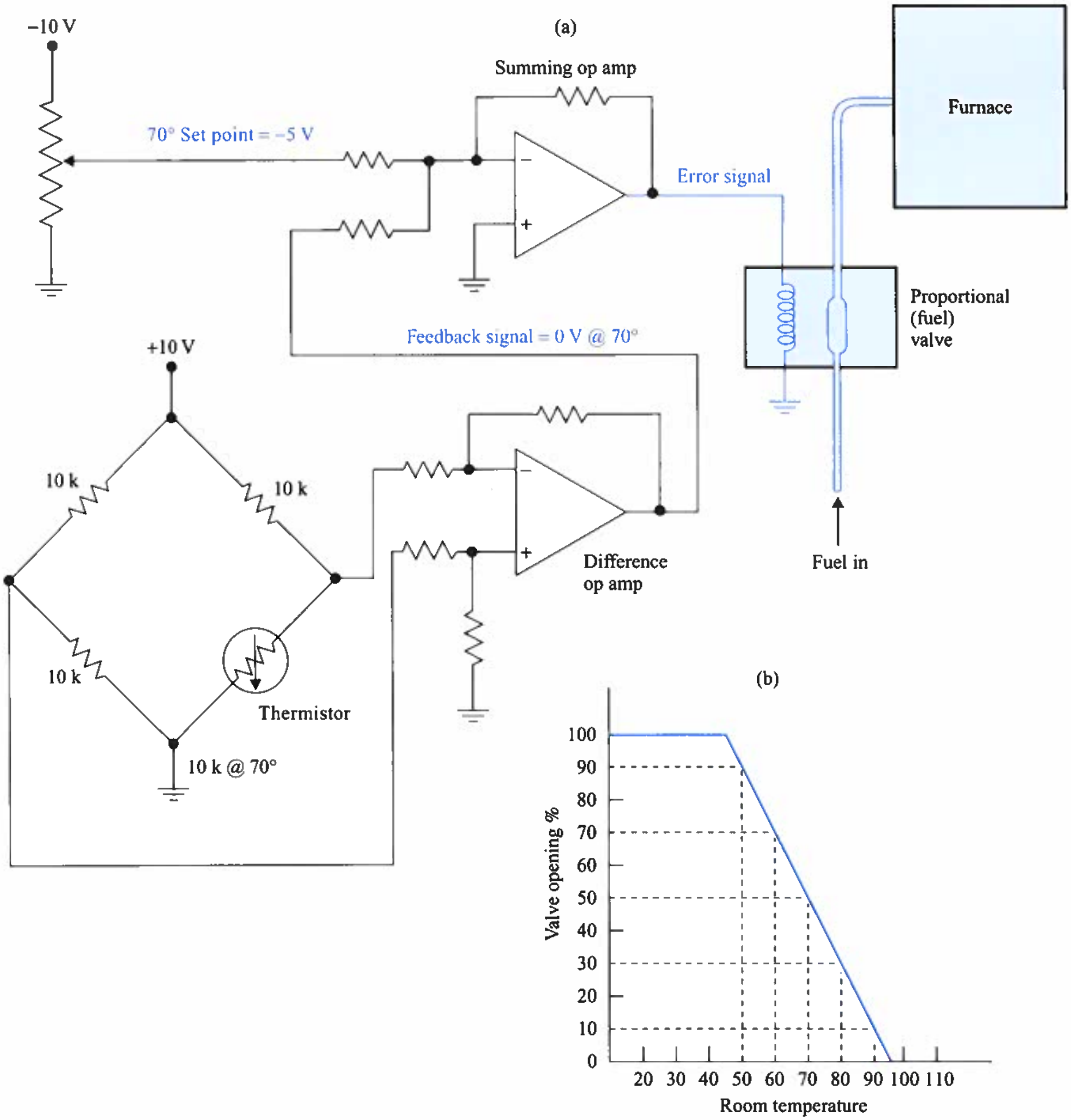


FIGURE 3-6 Proportional control heating system

becomes a negative voltage that is added to the negative setpoint voltage at the summing op amp. Therefore, as the error signal produced by the summing op amp goes more positive, the proportional valve opens more than 50 percent. For example, if the room temperature suddenly drops to 60 degrees, the error signal goes higher and causes the valve to open from 50 percent to 70 percent. The room temperature rises back to its setpoint. If the temperature rises above 70 degrees, the thermistor resistance decreases, causing the voltage at the inverting input to become less than the noninverting input at the difference op amp. Therefore, a positive voltage feedback signal is produced that cancels the negative setpoint voltage at the summing op amp. The canceling effect produces a less positive error signal, causing the proportional valve to be less than 50 percent open. As the valve closes to less than 50 percent, the room temperature decreases back toward the setpoint.

Controller Amplification

The controller has the capability of amplifying the amount at which its output changes in proportion to the change applied to its input. Controllers typically have a way in which the magnitude of the amplification can be adjusted. Amplification by a proportional controller is referred to as either **proportional gain,** or **proportional band.** The example of the furnace can be used to describe the difference between them.

The thermistor is the sensor, the summing op amp functions as both the comparator and the controller, and the fuel valve is the actuator. The graph in Figure 3-6(b) shows that the full operating temperature range over which the valve can be controlled is 50 degrees (95 – 45 = 50). The desired setpoint temperature of 70 degrees is exactly in the middle of the span. If the temperature drops to 45 degrees, the proportional valve fully opens. When the temperature rises to 95 degrees, the valve becomes fully closed. Within the 50-degree temperature span, the valve response is proportional to the temperature change.

Proportional Gain

Gain is the ratio of change in output to change in input, as described mathematically by the following formula:

$$\text{Gain} = \frac{\text{Percentage of Output Change}}{\text{Percentage of Input Change}}$$

In the furnace example, the input to the controller is a feedback signal that represents the temperature. The output of the controller is applied to the fuel valve, which controls the flow of gas to the furnace. Whenever the temperature changes by 1 degree, or 2 percent of the span, the valve opening varies by 2 percent of its span. According to the formula, the gain is 1.

$$\text{Gain} = \frac{2\%\ \text{Output Change}}{2\%\ \text{Input Change}} = 1$$

By increasing the gain of the controller to 2, a temperature change of 1 degree (2 percent of the span) will cause the valve to vary by 4 percent of its span. The result is that the controlled variable is restored to a desired value more quickly.

Proportional Band

Amplification is also expressed as *proportional band (PB).* Proportional band is defined as the percentage change in the controlled variable that causes the final control element to go through 100 percent of its range. The proportional band can be determined mathematically by using the following formula:

$$\text{PB} = \frac{\text{Controlled Variable \% Change}}{\text{Final Control Element \% Change}} \times 100$$

The width of the proportional band setting on a controller determines how much controlled variable change is required to cause a given amount of movement by the final control element. For example, to cause a final control element to move through 100 percent of its range, a controller with a proportional band setting of 100 requires that the controlled variable change twice as much as it does in one having a proportional band setting of 50.

In the furnace example, assume that the proportional band setting, which causes the operation shown on the graph in Figure 3-6(b), is 100. Whenever the temperature (controlled variable) changes by 1 degree, or 2 percent of the span, the valve opening varies the final control element by 2 percent of its span. By reducing the proportional band setting to 50, a temperature change of 1 degree (2 percent of the span) will cause the valve to vary by 4 percent of its span.

In a system that has a narrow proportional band, the response to a disturbance is rapid. The temperature is adjusted to the setpoint quickly. The response to a system with a wider proportional band will take longer.

It would appear that the system with the narrow proportional band is better because the setpoint temperature would be restored more quickly. However, the characteristic of a narrow proportional band is that a system has a tendency to oscillate. When the system responds quickly, it tends to overshoot the setpoint. The system tries to correct itself by shifting the valve in the opposite direction. However, the system overshoots again in the opposite direction. The oscillations normally die out, at which time the system becomes **stable.** If the proportional band is too small, oscillations will not stop. A proportional band of zero percent will cause the system to operate almost the same as the On-Off control. When the system continues to oscillate, it is **unstable.**

The size of the proportional band is simply the inverse of the proportional gain. The following formulas show how to convert between gain and proportional band values:

Note: Proportional band is in percent.

$$PB = \frac{1}{Gain} \times 100 \quad \text{and} \quad Gain = \frac{1}{PB} \times 100$$

EXAMPLE 3-1

Calculate the gain of the process if the PB setting is at 25 percent.

Solution

$$\begin{aligned} Gain &= \frac{1}{PB} \times 100 \\ &= \frac{1}{25} \times 100 \\ &= 4 \end{aligned}$$

EXAMPLE 3-2

Calculate the PB setting if the gain of the process is 8.

Solution

$$\begin{aligned} PB &= \frac{1}{Gain} \times 100 \\ &= \frac{1}{8} \times 100 \\ &= .125 \times 100 \\ &= 12.5\% \end{aligned}$$

Steady-State Error

The proportional controller is tuned so that the setpoint causes the proportional valve to open 50 percent with a given load. The 50 percent figure is desirable because the controller has equal amounts of corrective action from the setpoint to the maximum and minimum temperature settings. When the temperature produced by the furnace is at the 70-degree setpoint, the voltage supplied to the proportional valve is 50 percent.

If the load changes, the 50 percent valve position can no longer maintain the same temperature. Figure 3-7 illustrates what action then occurs. Suppose a disturbance causes the temperature to drop. A more positive error signal voltage is produced. The condition causes

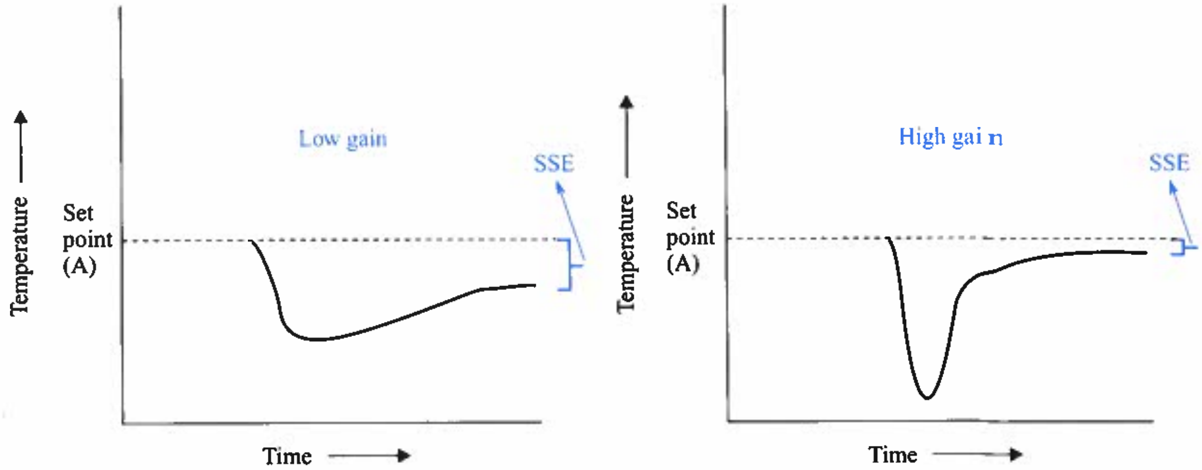


FIGURE 3-7 Relationship between gain and steady-state error

the proportional valve to open more than 50 percent. As the temperature rises, the thermistor resistance decreases and the proportional valve starts to close. If the disturbance continues for a long time, the proportional valve cannot return to the 50 percent open position. Instead, it must remain open more than 50 percent to offset the disturbance. For the valve to remain open above 50 percent, the error signal must be slightly more positive. Thus, the actual measured temperature could never climb to the 70-degree setpoint. Instead, it may stop at approximately 69.9 degrees in order to maintain the error voltage necessary to keep the valve open slightly more than 50 percent. The difference between the setpoint and the measured value is called **steady-state error,** or **offset.**

The example of steady-state error in the heating system is similar to that found in many process control applications. Some process control systems allow some degree of steady-state errors. In other systems—especially motion control applications—proportional control does not provide the necessary level of control. In a position type of motion control application, steady-state error cannot exist because precision is required.

Figure 3-8 shows the schematic diagram for a proportional position control robotic system. The output of the system is connected to the arm of a robot. The arm is attached mechanically to the wiper of a potentiometer. As the robot's arm moves, the output voltage of the pot at the wiper varies. The potentiometer is the feedback device that supplies the negative feedback signal in the system. The voltage produced indicates the position of the arm and is applied to the inverting input of an op amp. The command setpoint signal is supplied by a computer. Since a computer's output signal is digital, a D/A converter (DAC) is needed to change the value to an equivalent analog voltage. The output of the D/A converter is connected to the noninverting input of the op amp. The op amp used is a difference type that functions as the comparator. Its function is to compare the command (setpoint) signal with the feedback signal, and produce an appropriate error signal.

The output of the difference op amp is connected to an inverting op amp which amplifies the error signal. This is called a proportional op amp because its gain is proportional to the ratio of the resistor values for R_{IN} and R_f. Since the output power of a standard op amp is seldom high enough to drive a motor, the error signal is further amplified by a power amplifier. The output of the inverting power amp is connected to the motor that drives the robot's arm.

When the computer digital output is zero, the potentiometer will be zero volts, and the robot arm will be in the lowest position. Suppose the computer supplies a new position command to move the arm upward. The computer data and the resulting voltage of the D/A converter are shown in Figure 3-9. The computer outputs a series of numbers that increment until a value is reached that represents the desired position. The analog output voltage of the D/A converter ramps upward in small steps in a positive direction. The voltage change stops when the computer stops incrementing. This signal is compared to the feedback signal from the potentiometer by the difference op amp. Since the feedback signal lags behind the setpoint signal (because it does not respond immediately), a positive error signal voltage is produced by the

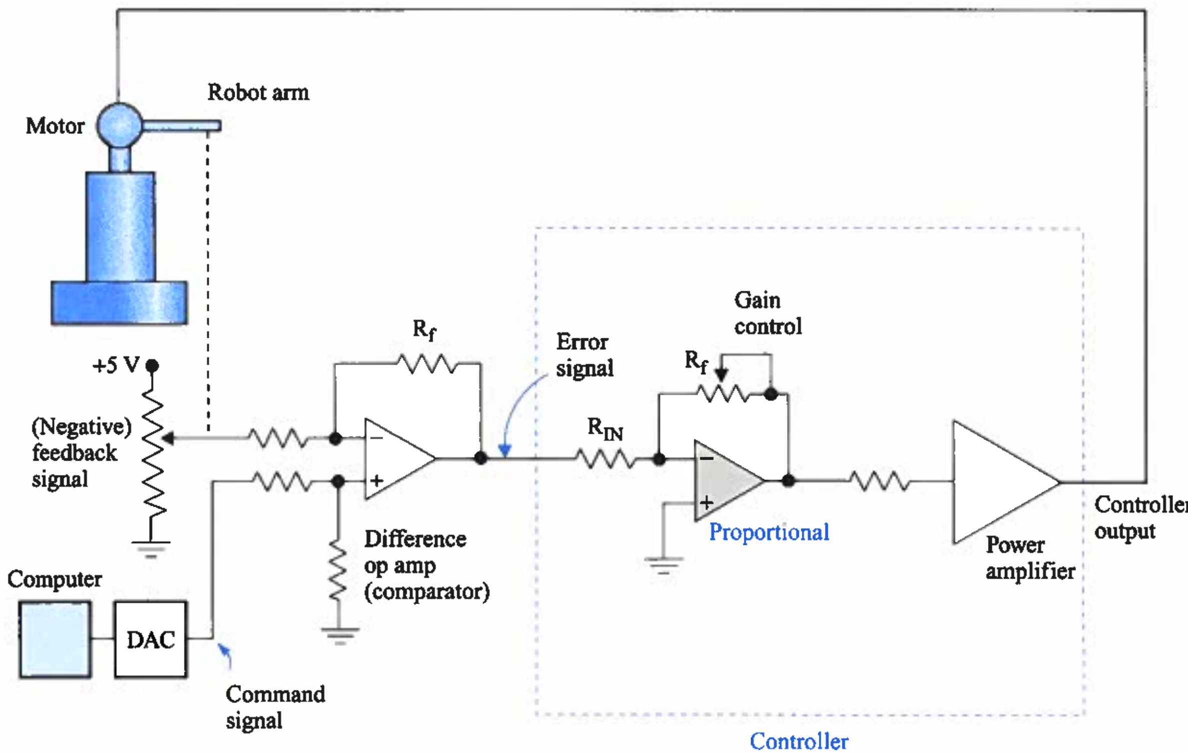
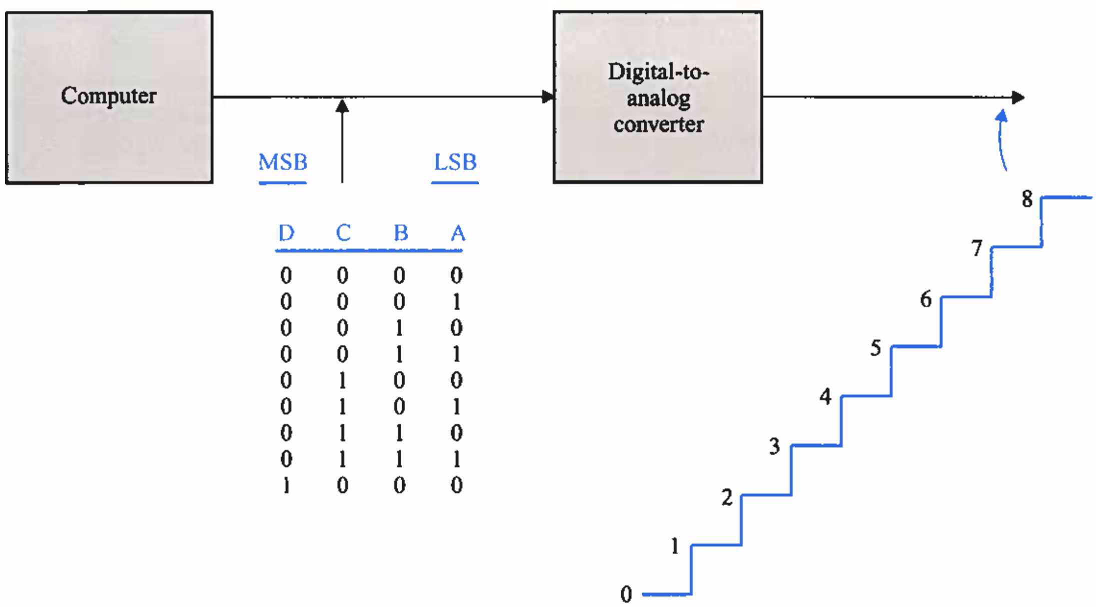


FIGURE 3-8 Proportional mode control system



D	C	B	A
0	0	0	0
0	0	0	1
0	0	1	0
0	0	1	1
0	1	0	0
0	1	0	1
0	1	1	0
0	1	1	1
1	0	0	0

FIGURE 3-9 Computer command output signal converted to a proportional analog voltage

difference op amp. The error signal is amplified by the proportional op amp and is also inverted to a negative voltage. The output of the proportional op amp is further amplified by the power amp and is also inverted to a positive voltage. With a positive voltage applied to the motor, the arm moves upward. The arm stops when it reaches the command position. At that position, the voltage of the potentiometer will equal the voltage of the D/A converter. This condition causes the comparator output to go to zero volts, which stops the motor from turning the arm.

A closed-loop proportional motion control system is unlikely to have precise accuracy. The arm might never reach the desired position because the closer it approaches the location,

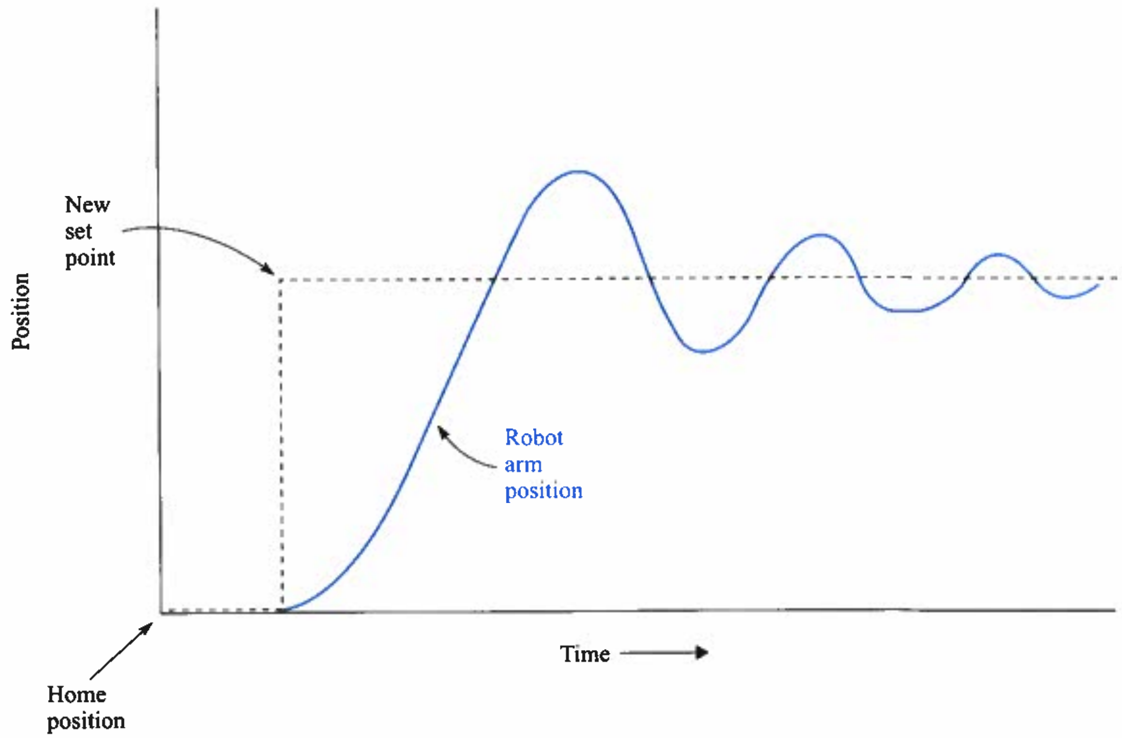


FIGURE 3-10 Instability of a proportional mode control system when gain is too high

the closer the voltage on the wiper comes to the command signal voltage. Therefore the output voltage applied to the difference op amp becomes very small and causes the motor to slow down. Eventually the mechanical friction of the robot arm cannot be overcome by the small amount of current that flows through the motor from the power amp. It falls short of its desired position, and a residual condition of steady-state error exists.

To reduce offset, the proportional band can be made smaller by increasing the gain of the proportional operational amplifier. This adjustment will also speed response to the command signal. However, the proportional band can be narrowed only so far before *instability* occurs. Instability exists when the device being positioned oscillates because of overshooting. The system will try to correct the overshoot error by reversing the direction of the arm. The arm oscillates above and below the position before it dampens out and stops, as illustrated by the graph in Figure 3-10.

The friction of the load is not the only cause of steady-state error. Offset depends on three factors:

1. Load or demand on the process
2. The low gain or wide proportional band of the controller
3. The setpoint at which the controller is set

Changes in any of these three factors can result in some offset. To overcome offset, the control mode known as **integral control** is used.

3-4 Proportional-Integral Control

The **integral** (or *reset*) mode of control is designed to eliminate the offset inherent in proportional mode control. It develops a control signal that depends on the absolute value of the offset. The integral mode does not function by itself. It is used along with the proportional control mode in the controller section of a closed-loop system.

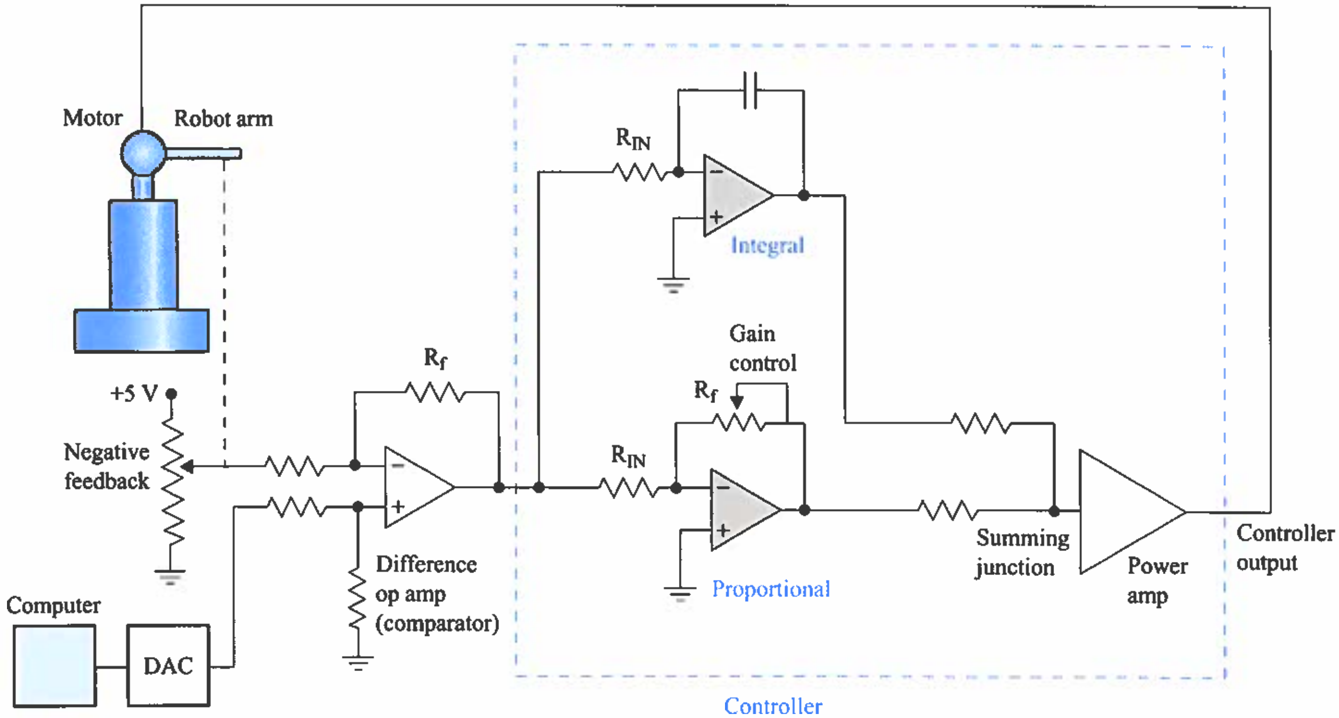


FIGURE 3-11 Proportional-integral mode control system

When an error signal first appears, the controller is tuned so that the proportional control signal returns the process to the desired control point. This proportional control signal is immediate and fast acting. If a deviation between the setpoint and controlled variable is present after the operation of the proportional control mode is completed, an additional corrective signal is required, which is supplied by the integral control mode function. A small corrective action is developed slowly to reduce the deviation to zero only after it is certain that there is a definite steady-state error.

The operation of the integral mode of control is illustrated in the robotic closed-loop system shown in Figure 3-11. It shows the same circuitry as the proportional-only controller, with an additional amplifier that performs the integral action. This second op amp is called an *integrator.*

The integrator resembles an inverting op amp. The difference is that the feedback resistor is replaced by a capacitor. At the first instant a DC voltage is applied to its input, the capacitor operates like a short circuit. Recall that the gain of an inverting op amp is dependent on the ratio of the feedback resistance (R_f) and the input resistance (R_{IN}): Gain = R_f/R_{IN}. Therefore, since the capacitor initially provides low impedance in the feedback loop, the gain of the integrator is very low. The output voltage is also low. However, as the capacitor begins to charge, the current charging the capacitor reduces. Its impedance increases until it is fully charged, at which time it acts like an open switch. The result is that the R_F/R_{IN} ratio increases, the gain of the op amp increases, and the output voltage reaches saturation. The magnitude of the integrator output is proportional to the input voltage and the length of time the voltage is applied.

The operation of an integrator is further illustrated in Figure 3-12. This shows a graph that compares the input voltage with the output voltage. At T_1, a positive DC voltage is applied to the inverting input of the integrator. Its inverted output voltage increases in a negative direction until saturation is reached at T_2.

Suppose the computer sends out a command signal for the robot to move. The proportional function of the controller immediately responds to the setpoint change and drives the motor. The robot arm moves in the direction commanded by the computer, but stops just short of the desired position. The proportional mode has completed its response to the command setpoint change. Since the arm is out of position and does not achieve the desired

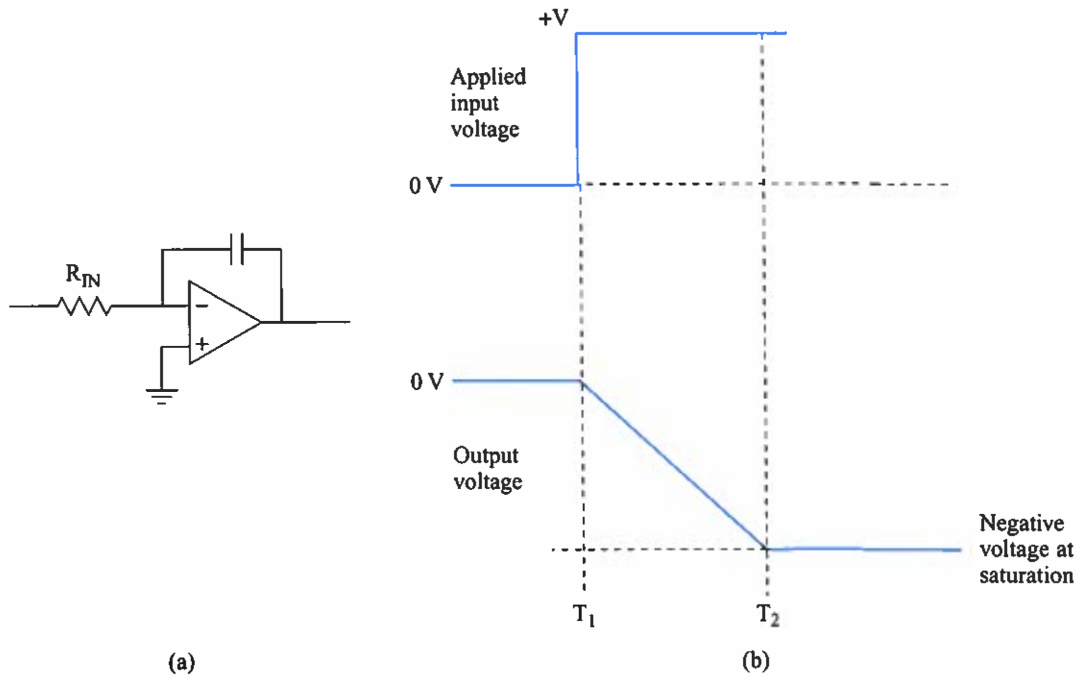


FIGURE 3-12 Operation of an integrator operational amplifier: (a) schematic diagram; (b) waveform diagram

location, the setpoint voltage and the feedback voltage are not the same. The result is that a steady-state error is present at the difference op amp output. This voltage is not sufficient to drive the robot arm the remaining distance. At this point the integral control mode takes over.

The steady-state error is also fed to the integrator op amp. The longer the error exists, the greater the output voltage of the integrator op amp becomes. The increasing integrator error signal is summed with the small amplified offset voltage of the proportional amplifier output. In time, the power amp receives enough input energy to turn the motor shaft until the robot arm attains the desired position. The steady-state error is then eliminated. Since the integral action continues to reset the amplifier gain until the process variable equals the setpoint value, it is also referred to as the *reset* mode of control. Although the two names are synonymous, reset is the older term.

The proportional-integral control mode is used in applications where load disturbances occur frequently and setpoint changes are infrequent. It is also used when load changes are slow, to allow enough time to elapse before it is necessary for the integral function to aid the proportional operation.

3-5 Proportional-Integral-Derivative Control

It is usually desirable to move the robotic arm quickly from one position to another. However, rapid movements are not possible using the proportional mode without excessive gain. If the gain setting of a proportional amplifier is too high, an instability condition develops where overshoot and subsequent oscillations occur. To reduce the overshoot and bring the controlled variable to the setpoint rapidly, a control mode called **derivative** or *rate* control is used.

The term **derivative** refers to the rate of change. A derivative controller produces an output that is proportional to the rate that the error signal changes. If the error signal is changing very rapidly, the derivative output is large. When the error signal is changing slowly, the derivative output is small. If the error signal is stable, the derivative output is zero.

The function of the derivative controller is to provide a proportional correction to a changing error signal. For example, if the error signal gap increases, the derivative mode control gives a boost to the system to stop the error from increasing any further. The faster the error signal increases, the larger the boost. When the error signal gap decreases, the derivative mode control provides braking action. The faster the error gap closes, the stronger the braking action. The braking action reduces overshoot and dampens out any oscillations of the controlled variable.

In Figure 3-13(a), the derivative function is performed by a differentiator op amp circuit. Like the integrator op amp, the differentiator op amp resembles an inverting op amp. The difference is that the input resistor is replaced by a capacitor. Figure 3-13(b) provides a graph that compares the input voltage with the output voltage. If the voltage applied to the inverting input of the differentiator is a constant DC voltage, the output is zero volts, as shown during time period W. If the input changes slowly at a constant rate, the output will be a small steady DC voltage, as shown during time period X. Time period Y shows that if

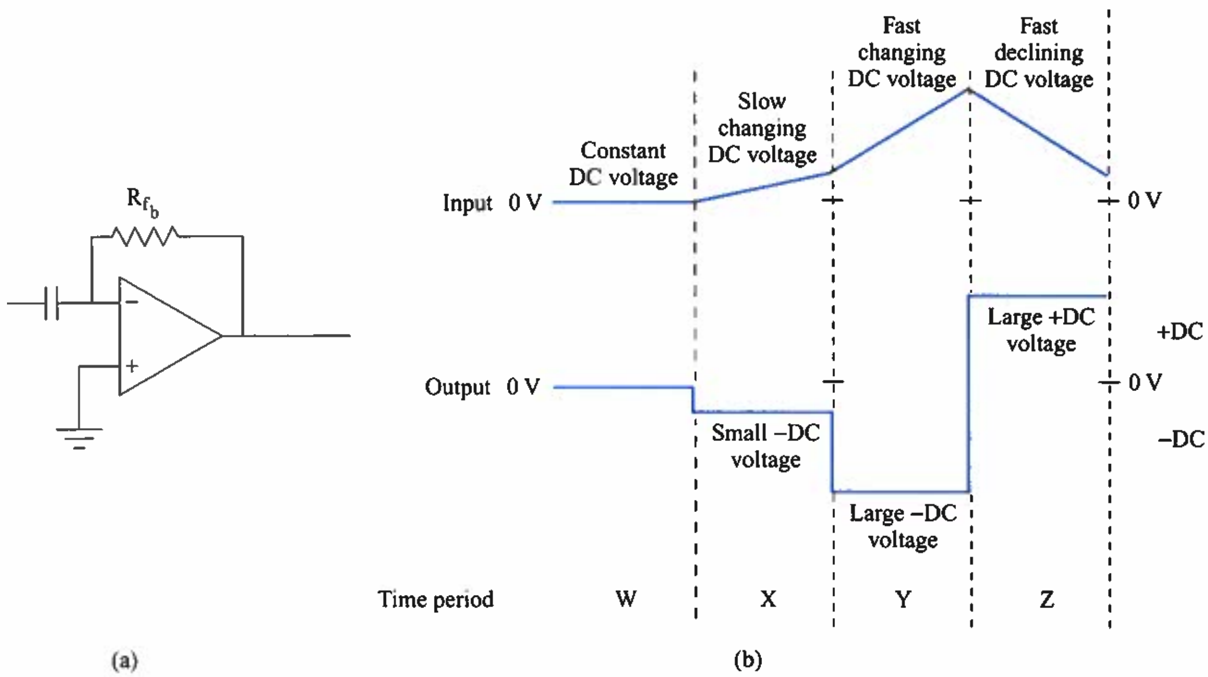


FIGURE 3-13 Operation of a differentiator operational amplifier

the input voltage rises at a rate that is constant, but more rapidly, the differentiator output amplitude will be higher. Time period Z shows that if the input voltage decreases at the same rate, the differentiator will produce an equal output voltage of opposite polarity.

Figure 3-14 shows a robotic control system that contains proportional, integral, and derivative (PID) circuits. Figure 3-15 graphically shows the operation of the PID mode control system. Suppose an application requires that the robot arm move quickly from one position to another. The computer outputs a rapidly-incrementing series of numbers. The analog output waveform of the D/A converter shown between points A and D rises quickly at a steady rate.

The analog signal is fed to the noninverting input of the difference op amp. Since the arm of the robot initially does not move, the output of the difference amplifier starts to rise and develop an error signal. As the error is fed to the input of the proportional amp, it is further amplified by the summing power amp. This action causes the motor to drive the robot arm toward the desired position. As it does, a voltage from the potentiometer, which is the feedback signal, begins to rise, as shown soon after time period A begins. However, the amplitude of the error signal continues to grow in the positive direction, as shown between points A and B. This happens because the stationary inertia of the robot arm has to be overcome, causing it to move slowly at the start.

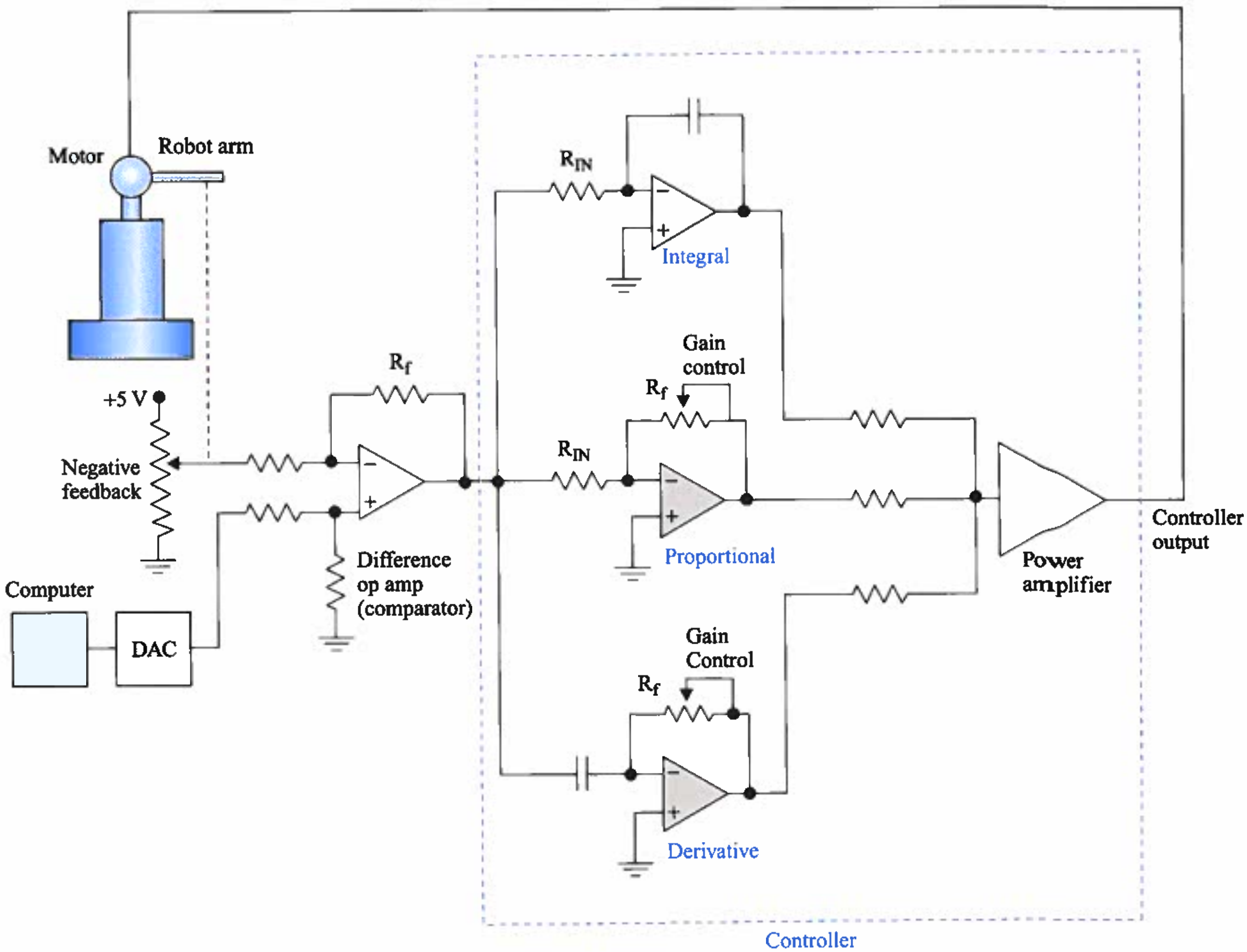


FIGURE 3-14 Proportional-integral-derivative mode control system

Therefore the measured variable from the feedback pot does not change as fast as the command signal from the computer.

The output of the difference op amp is also feeding the derivative amplifier. As the error signal voltage increases its amplitude, as shown between points A and B, a negative voltage is created by the derivative network. The derivative voltage is added to the proportional voltage by the summing power amp. The combined voltages cause the power amp output to increase, which makes the robot arm move faster. Eventually it moves fast enough that the measured variable is changing as fast as the command setpoint signal, as shown at time period C. This boost by the derivative function prevents the error signal from increasing any further.

Between points C and D, the error signal does not change. The output of the derivative amp goes to zero and the proportional function operates alone.

When the command signal from the computer reaches the value that represents the desired position, it stops changing. The output voltage of the D/A converter also stops increasing, as shown at time period D. Since the arm has not yet reached the desired position, the setpoint and measured variable are unequal. Therefore the difference amp continues to produce a voltage, causing the arm to continue moving. Because the error signal decreases in amplitude, as shown between time periods D and E, a positive voltage is produced by the differentiator op amp. This voltage is subtracted from the proportional output by the summing power amp. Since the combined voltages cancel, the power amp output decreases. The result is that the motor causes the arm to slow down enough so it does not overshoot.

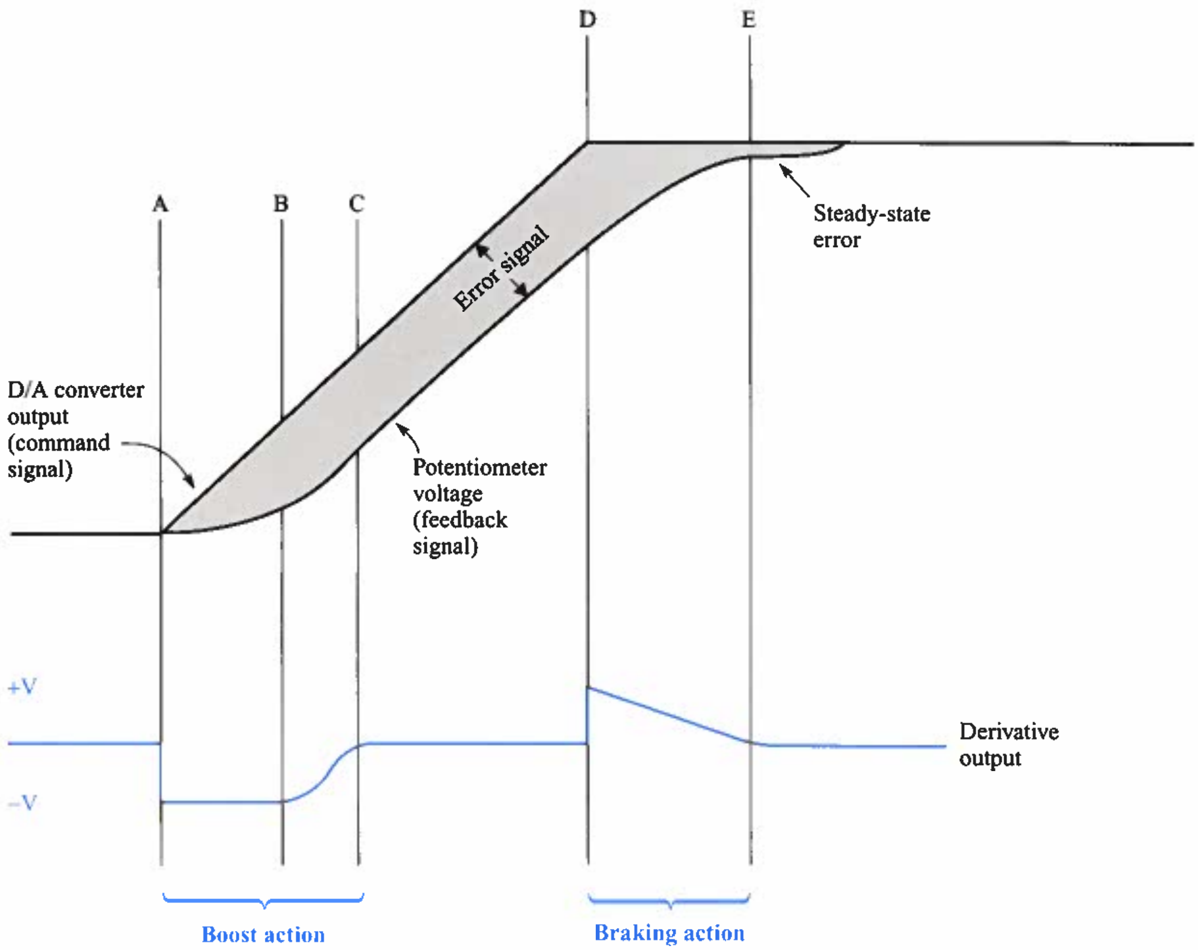


FIGURE 3-15 A graphical representation of a proportional-integral-derivative robotic control system

As the arm nears the desired position, the error signal stops changing and approaches zero. The result is that the proportional and derivative outputs go to zero. Since the setpoint and measured variable are not exactly equal, as shown in part E, a steady-state error exists and the integral op amp takes over to cause the arm to move the remaining distance.

Whenever there is a large setpoint change, the controlled variable will usually lag behind and cause a rapid change of the error signal. Because the derivative controller detects this trend, it responds by compensating for large system changes before they fully develop. Therefore, derivative control is sometimes referred to as *anticipatory* or *predictive* control. Because derivative control tends to reduce system oscillation, the proportional gain can be set at higher values to further increase the speed of response of the controller to system disturbances.

The derivative mode is used only when the controlled variable lags behind a setpoint change and an error signal develops. In the robot example, which is a motion control application, the operation is relatively fast. However, there is a lagging condition that exists because the arm position cannot respond as quickly as the command signal. Therefore, the derivative mode is used by the controller to minimize the error signal that develops from this condition. The derivative mode is often used in a slow-acting process control application, such as regulating the temperature of a liquid in a large tank. If a new setpoint setting is made, the static inertia of the liquid does not allow the temperature to immediately change. Therefore, a lagging condition develops. An example where derivative control would not be used is in an airflow control application. Whenever a new setpoint setting is made, a flow control valve changes and immediately alters the flow rate of the air. Since the response of the system is very fast, a lagging condition does not develop and the derivative control action is not required.

Derivative-mode control is never used alone. It is usually combined with the proportional and integral modes for systems that cannot tolerate offset error and require a high degree of stability. This type of system—which combines the advantages of proportional, integral, and derivative action—is known as a three-mode **PID** controller. PID controllers are best suited for systems that need to react quickly to large disturbances. They are also recommended in systems where load changes frequently occur.

Derivative control is rarely combined with proportional control only. When it is, proportional-derivative action is used in applications where lag times vary and offset error is tolerated.

To obtain the best possible PID control for a particular application, the gain settings for each mode must initially be made. These settings are different for each system. While the system is actually running, *tuning* adjustments are often made to the gain settings to attain optimal performance. Gain adjustments can be performed by trial and error, or automatically by autotune controllers.

In a conventional PID system, the process being controlled is seldom performed by op amp circuits. Instead, these three modes are performed by computer software packages that calculate a set of differential equations. When a setpoint change or disturbance occurs, feedback devices send signals that cause the numerical values of the mathematical equations to change. Calculations are made to produce a solution that tells the PID controller how to adjust the system parameters to meet the new requirements.

PID control is an industrial standard well understood by many control engineers. It is a popular control technique that has been proven through many years of use. PID control can presently be performed with a personal computer or a programmable controller. PID controllers can be purchased as prebuilt, preprogrammed assemblies.

3-6 Time-Proportioning Control

A common method of controlling a DC voltage actuator device, such as a heating element or a DC motor, is to vary the DC voltage of an amplifier that drives it. This method is called the proportional mode because the magnitude at which the actuator is driven is proportional to the amplitude of the applied voltage. For example, by doubling the applied voltage produced by an amplifier the temperature of the heating element is doubled if the gain is 1.

Another way of controlling an actuator is to use an operation called **time proportioning.** Also called the PWM (Pulse Width Modulation) technique, time proportioning is a method in which the amplifier output is switched alternately to fully on and fully off. Changing the ratio of signal-on to signal-off varies the average voltage produced. Figure 3-16 illustrates various time-proportioning output signals that are in the form of a square wave. The square wave is at +10 volts when the amplifier is on, and 0 volts when it is off. The ratio of the time the square wave is on to the total time period of one cycle is called the *duty cycle.*

If the duty cycle is 25 percent, as shown in part (a), the on-time occurs for 25 percent of the time, and the off-time occurs for 75 percent of the time.

The average DC voltage produced, which affects how much power is applied to the actuator, can be determined by multiplying the duty cycle times the on-state DC amplitude of the square wave.

EXAMPLE 3-3

What is the average voltage at a 25 percent duty cycle when the on-state DC amplitude of the square wave is +10 volts.

Solution

$$\text{Average Voltage} = \text{Duty Cycle} \times \text{On-State DC Voltage}$$

$$= .25 \text{ x} + 10 \text{ V}$$

$$= 2.5_{AVE} \text{ DC volts}$$

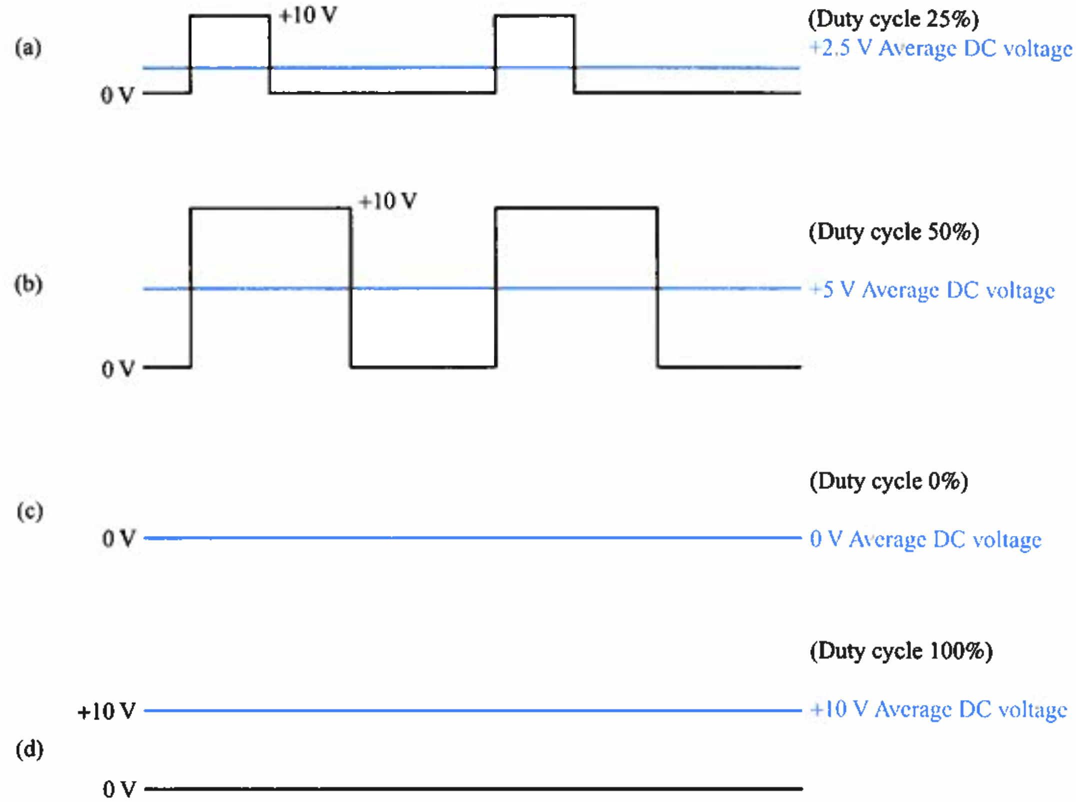


FIGURE 3-16 Waveforms of average DC voltages at different duty cycles: (a) 25 percent duty cycle; (b) 50 percent duty cycle; (c) 0 percent duty cycle; (d) 100 percent duty cycle

When the duty cycle is 50, as shown in Figure 3-16(b), the on-time/off-time ratio is 50 percent, so the average voltage is 5 volts. If the duty cycle is 0 percent, the amplifier is not turned on, so the average voltage is 0 volts, as shown in part (c). At a duty cycle of 100 percent, the amplifier is always on, and the average DC voltage is +10 volts, as shown in part (d).

3-7 Time-Proportioning Circuit

A voltage-level detector op amp, as shown in Figure 3-17, can be used as a time-proportioning circuit. The output of the op amp is zero volts at any moment the noninverting input is less than the inverting input. When the voltage at the noninverting input is greater than the voltage at the inverting input, the op amp goes into saturation and produces +10 volts.

A 0- to +10-volt peak-to-peak sawtooth signal is applied to the inverting (–) input of the op amp. A 0- to +10-volt signal is applied to the noninverting (+) input of the op amp by varying the wiper arm of a potentiometer. When the wiper arm is at the 0-volt ground position, the sawtooth at the (–) input is always equal to or greater than the voltage at the (+) input. Therefore, the output of the op amp is at a constant 0-volt potential, as shown in Figure 3-17(b).

When the wiper arm is in the middle position, a +5-volt potential is applied to the (+) input. The sawtooth potential applied to the (–) input does not become greater than the (+) input until it goes above +5 volts, halfway up the ascending portion of the waveform, and remains that way until it drops below +5 volts halfway down the descending portion. As a result, the op amp produces a square wave with a 50 percent duty cycle, as shown in Figure 3-17(c). The resulting average DC voltage is +5 volts ($.5 \times 10\text{ V} = 5\text{ V}$). When the wiper arm is positioned at the top, 10 volts is applied to the (+) input. The voltage applied to the (–) input is never greater than the (+) input, so the op amp output is always +10 volts, as shown in Figure 3-17(d).

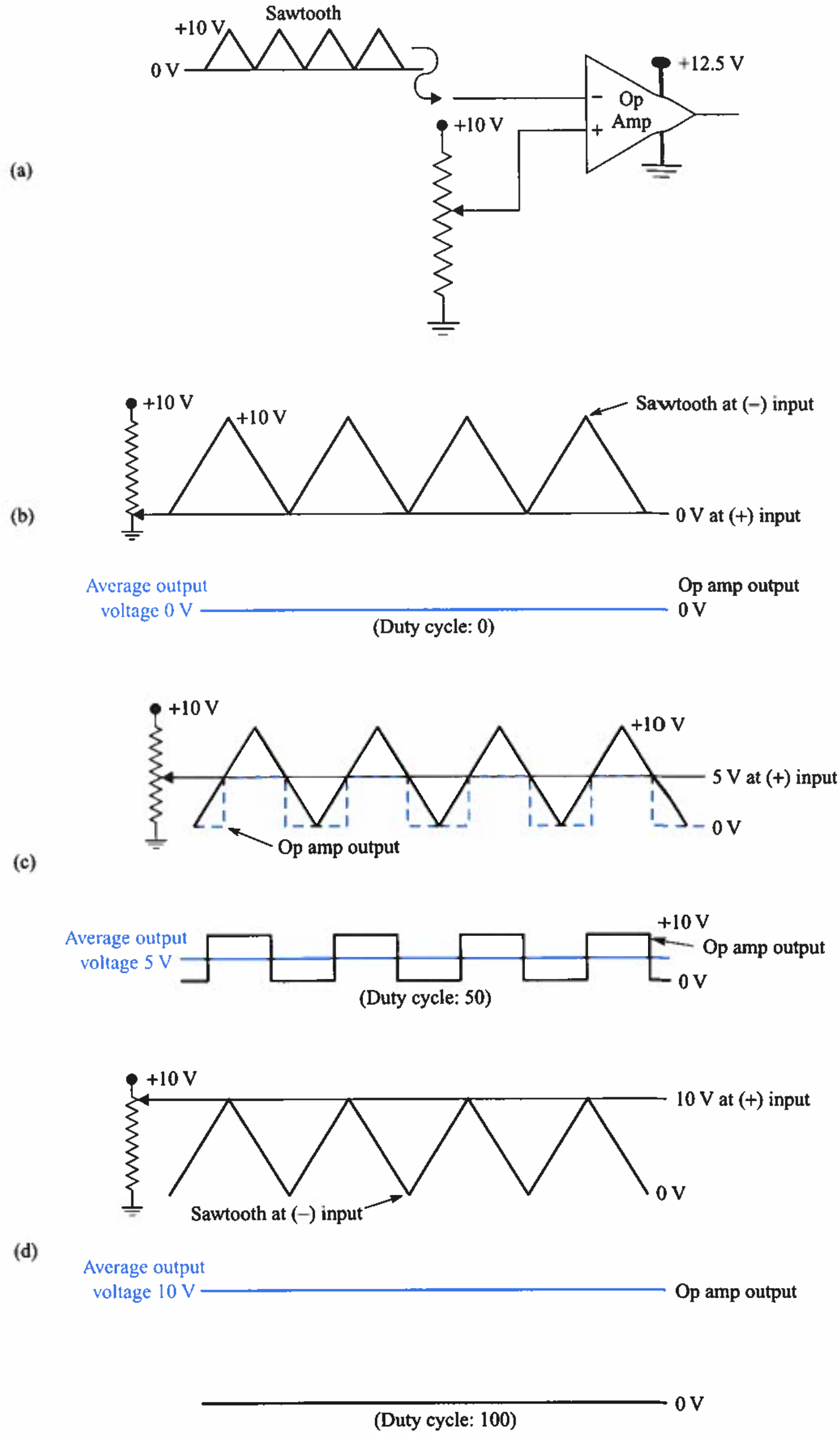
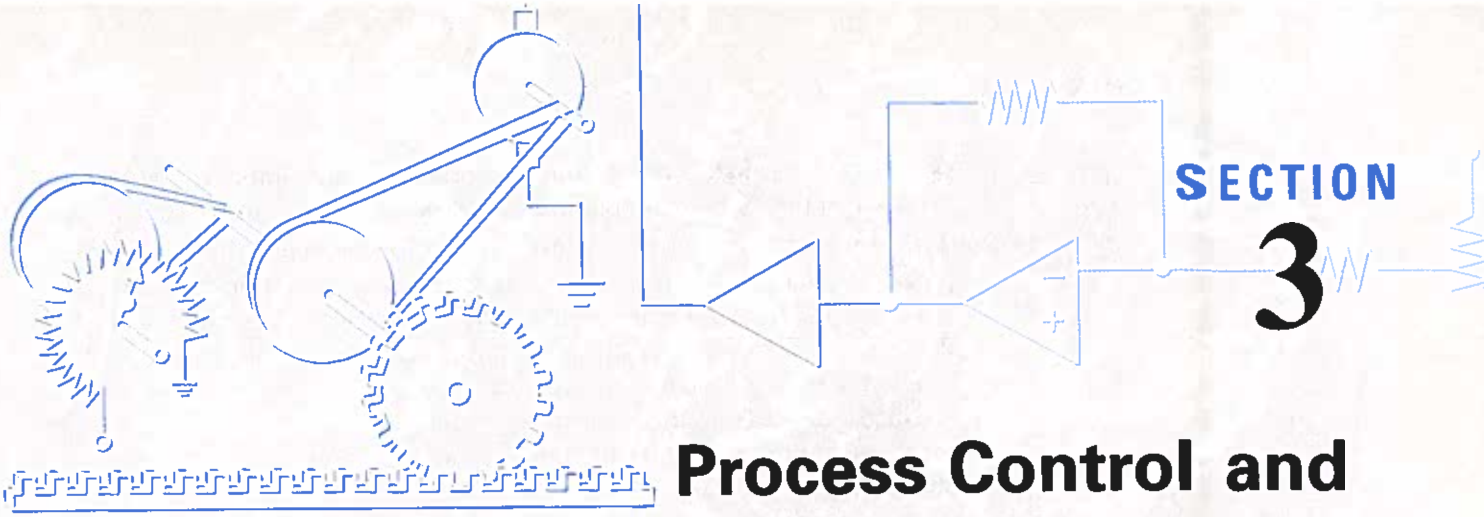


FIGURE 3-17 (a) Time-proportioning circuit; (b) 0 percent duty cycle; (c) 50 percent duty cycle; (d) 100 percent duty cycle

Problems

1. Which section of the closed-loop system performs the four control modes?
2. In an On-Off heating system an error signal is produced when the measured temperature is __________ (above, below) the setpoint.
3. List two factors that cause the controlled variable to deviate from the setpoint in an On-Off system.
4. By __________ (increasing, decreasing) the On-Off differential gap, the cycle time is lengthened.
5. Calculate the differential gap percentage if a full temperature control range is 80 degrees and the differential gap is 8 degrees.
6. If the output of the controller changes by 6 percent when the signal applied to its input changes by 2 percent, the gain is __________.
7. If the full temperature range of a proportional control heating system is from 35 to 95 degrees, and its proportional band is 30 degrees, find the percent of the system's proportional band.
8. The lagging effect of the controlled variable behind the error signal is called ____.
   a. time delay
   b. hysteresis
   c. lag time
   d. all of the above
9. T/F By narrowing the proportional band, a closed-loop system may oscillate.
10. A system that oscillates is referred to as being ____.
    a. stable
    b. unstable
11. Steady-state error is also referred to as __________.
12. Offset is reduced by ____.
    a. increasing the gain of the system
    b. narrowing the proportional band
    c. either A or B
13. T/F A setpoint change can also produce offset.
14. The ____ mode is designed to eliminate offset.
    a. proportional
    b. integral
    c. derivative
15. If the gain of a system is 4, the proportional band is __________.
16. The longer time duration that a steady-state exists, the ____ the integral action becomes.
    a. less
    b. greater
17. Another term for integral is ____.
    a. rate
    b. reset
18. Proportional-integral control is used in which of the following applications: ____
    a. Where load disturbance occurs frequently and setpoint changes are infrequent.
    b. Where load disturbances occur frequently and setpoint changes are frequent.
    c. Where load changes are slow.
    d. Where load changes are fast.
19. The magnitude of the integral output is proportional to the ____.
    a. applied input voltage
    b. length of time the error signal exists
    c. both a and b
20. The term *derivative* means __________ of change.
21. T/F A derivative controller produces an output that is proportional to the amplitude of the error signal.
22. The output of the derivative function __________ (adds to, subtracts from) the output of the proportional output when the error signal is getting larger.
23. The output of the derivative function __________ (adds to, subtracts from) the proportional output when the error signal is getting smaller.
24. As the rate of change of an error signal at the controller's output increases, the derivative signal ____.
    a. increases
    b. decreases
25. The derivative function gives the actuator a ____ action.
    a. boost
    b. braking
    c. both A and B
26. T/F In a PID system, after the derivative function is complete and the proportional signal is ineffective, the integral function is performed.
27. List which type of operational amplifier performs the following PID mode functions:
    Proportional:
    Integral:
    Derivative:
28. A PID system that is properly tuned provides which of the following characteristics? ____
    a. Quick response
    b. No overshoot
    c. No offset
    d. All of the above
29. The term *duty cycle* refers to the amount of time a signal is ____ compared to the period of one complete cycle.
    a. on
    b. off
30. When the voltage applied to the _____ input is greater than the_____, the voltage level detector op amp produces a positive saturation voltage at its output.
    a. inverting
    b. noninverting
31. A square wave that is 20 volts at its on-state and 0 volts at its off-state will produce an average DC voltage of _____ when its duty cycle is 75.
    a. 7.5 V
    b. 10 V
    c. 15 V
32. If the proportional band is 40 percent, what is the gain?



SECTION 3

Process Control and Instrumentation

OUTLINE

Chapter 4	Pressure Systems
Chapter 5	Temperature Control
Chapter 6	Flow Control
Chapter 7	Level Control Systems
Chapter 8	Analytical Instrumentation
Chapter 9	Industrial Process Techniques and Instrumentation
Chapter 10	Instrumentation Symbology
Chapter 11	Process Control Methods
Chapter 12	Instrument Calibration and Controller Tuning

The branch of control engineering that involves the regulation of variables, which affect products as they are being manufactured, is known as **process control.** Specifically, these variables, called *process variables,* include pressure, temperature, flow, levels, and the product composition of gases, liquids, and solids. The term *process* refers to the manipulation of variables by production equipment to alter raw materials until they reach a desired condition. The number and types of variables being manipulated depends upon the product being manufactured. Products produced in process industries include chemicals, refined petroleum, treated food stuffs, paper, plastics, and metals. Process control engineering is also involved in the public service fields that provide water purification, waste water treatment, and electrical power production.

During the early years of industrial manufacturing, the process variables were controlled manually. Today, the same operations are performed by automated systems that require only minimal human intervention. The hardware used in an automated system is called **instrumentation** equipment.

An instrument used in process control directly performs one or more of the following three functions:

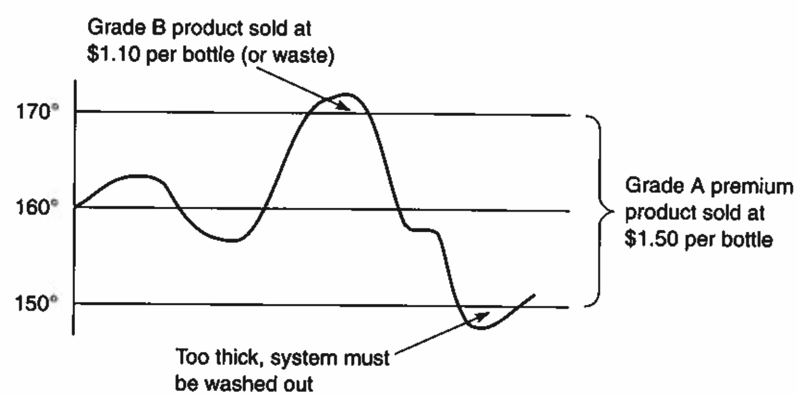
Measurement During the manufacturing process, it is often necessary to monitor the existence or magnitude of process variables. Measuring instruments are the eyes of the automated system function. The measurements may be read and used in real time for control purposes, or stored as data for use at a later time.

Control Another function of an instrumentation device is to ensure that a process variable is maintained at a specific value or within specific limits. For example, if a disturbance causes the controlled variable to deviate from the setpoint, the controller must call for a corrective action. The control section is the brain of the automated system, which compares the setpoint to a feedback signal from the measuring device. In response, it provides an appropriate signal to the output actuator device, which makes any necessary changes.

Manipulation The final control element is the actuator, or muscle, of an automated system. Its function is to manipulate energy or flow of materials at a desired quantity or rate.

Process control is one of two branches of control engineering that use automation to produce a product. The other branch is referred to as *servo control,* or **servomechanisms.** A servomechanism is a machine that controls mechanical position or motion. Examples of servo machines are robotic welders, machine tool equipment, printing presses, packaging equipment, and electronic parts insertion machines, which place components onto a printed circuit board. The primary difference between these branches is the control method that is required. In process control, emphasis is placed on sustaining a constant controlled variable, such as temperature or pressure. The reference point (setpoint) is seldom changed. It may remain constant for several days. The objective of the system is to provide regulation when the controlled variable fluctuates due to a disturbance. Alterations of the controlled variable and the system reaction to correct a change are typically slow. In servo control, the setpoint is constantly changing. The emphasis of the system is to follow the changes in the desired input signal as closely as possible. Variations of the setpoint are typically very rapid. This does not mean that process control systems are never subjected to reference point changes or that servo systems never encounter disturbances. Both systems must be capable of responding to either disturbances or reference point changes.

An example of an automated process control system is a production machine that manufactures catsup. The primary objective of the process is to make premium quality catsup at $2.50 a bottle. This goal is achieved when the temperature of the ingredients to be cooked is within 10 degrees above or below 160 degrees. If the temperature of the cooking vat rises above 170 degrees, as shown graphically in the illustration below, the catsup will have less viscosity and be watered down. The product no longer meets quality control standards for the premium line. It will either



Catsup viscosity

be sold as a class B product and the price will be reduced to $1.90 a bottle, or it will be discarded as waste. In either case the profit will be reduced. If the cooking temperature of the vat decreases below 150 degrees, the viscosity of the catsup will reduce and it will become thicker. In this situation, the valves in the outlet pipes will become clogged and the production line will be shut down while the system is washed out.

Through the continuous control of systems and processes, automated production provides the advantages of better product consistency, more precise tolerances, and reduced waste. The improved efficiency it offers cuts energy cost, which increases profit and minimizes conservation concerns.

This section of the book consists of nine chapters that provide information on the operation of process control and instrumentation equipment. Chapters 4 through 8 define the properties and characteristics of the process variables: pressure, temperature, flow, level, and product composition. They also describe various types of instrumentation equipment used for measuring and manipulating the variable to maintain a desired condition. Chapter 9 has two major parts: the first part describes various types of manufacturing methods used in process control; the second part identifies various types of instrumentation devices used throughout a closed loop. Chapter 10 provides coverage on how to use common Process and Instrumentation Drawings (P&ID) diagrams. Chapter 11 describes various control techniques used in automated process control, including the characteristics of each one. Chapter 12 provides information about calibration and controller tuning procedures.

CHAPTER 4

Pressure Systems

OBJECTIVES

At the conclusion of this chapter, you should be able to:

- Define pressure.
- Define fluid.
- Given force and area, calculate the pressure exerted by a fluid.
- Identify five factors that affect the pressure exerted by a liquid.
- Calculate pressure by using specific gravity and depth values for a liquid in a container.
- Identify three factors that affect the pressure exerted by a gas.
- List the reference value for gauge, absolute, and vacuum pressures.
- Convert psia to psig, and psig to psia.
- Calculate differential pressure.
- Identify the difference between direct and indirect measurements.
- Describe the operation of the following nonelectrical measuring devices:

Barometer	Bourdon tube	Bellows
Manometer	Diaphragm	Capsular

- Describe the operation of the following electronic pressure sensors:

Semiconductor Strain Gauge	Traverse Voltage Strain Gauge	Variable Capacitor Pressure Detector

- Explain the operation of the following pressure systems:

Hydroelectric	Vacuum	Static distribution
Pneumatic	Steam	

INTRODUCTION

Many products manufactured in industry result from a process that involves **pressure.** In fact, the number of pressure gauges and pressure controls in most plants is greater than all the other instruments used for different types of processes combined.

Pressure is defined as force exerted by a **fluid** over a unit of surface area. Different forms of fluids include liquids, gases, steam, and air. They are the medium used to transfer energy from one location to another within a confined network of pipes, tubing, and vessels. Various mechanical devices control the fluids that ultimately provide the power to perform some type of work. Pressures that fluids exert in industrial systems range from a near-vacuum level to 10,000 psig and above.

Various industrial applications involve increasing or decreasing the pressure exerted by a fluid. Reasons for increasing pressure in a process system are:

1. To perform work with a machine such as a hydraulic-powered press or a pneumatic air drill.
2. To move fluids through pipes or to a higher elevation by overcoming friction and gravity.
3. To transform a fluid into a desired physical state. For example, a nitrogen gas will become a liquid when the pressure is high enough.

Reasons for decreasing pressure in a process system are:

1. To perform work, such as lifting and moving sheets of paper in a printing press operation.
2. To draw liquid into a vessel. Lowering the pressure inside a container helps to fill it with a liquid.
3. Changing the physical state of a fluid, such as causing a liquid to vaporize.

To perform these various operations, it is often necessary to control the pressure accurately. Closed-loop systems that perform this function can maintain the pressure at some specific value, or within a required range.

Several reasons to accurately measure and control pressure are:

1. To ensure that the pressure does not become too great and create an explosion, which could cause injury or damage to equipment. A controlled system will either set off an alarm or shut down the equipment responsible for the deviation.
2. To ensure quality of products that must be processed at specific pressures and temperatures.
3. To maximize efficiency by preventing pumps or compressors from wasting energy by raising or lowering pressures more than is needed to produce the desired result.

4-1 Pressure Laws

Pressure is measured as force per unit area. In the English system, force is measured in pounds, and unit area for pressure measurements is the square inch. Therefore, pressure is commonly expressed in terms of pounds per square inch, or *psi.* The formula for pressure is:

$$\text{Pressure (P)} = \frac{\text{Force (F)}}{\text{Area (A)}}$$

4-2 Properties of a Liquid

The molecules of a liquid are closely attracted to each other, which is why most substances in this state are incompressible. Its molecules are constantly moving, slipping and sliding past one another. This enables liquids to flow and take the shape of a container. The ability of a liquid to accomplish this action is related to a property called **viscosity.**

Liquids exert a pressure, which is affected by several factors: height, weight, temperature, atmospheric pressure, and mechanical machines.

Height

The height of the liquid affects the pressure it exerts. The term *head* is commonly used to describe the height of a liquid above the measurement point. Head is given in inches, feet, or other units of distance.

Weight

Another factor that affects liquid pressure is its weight. Different liquids have different weights due to their **density.** Density is defined as the weight of a certain volume of liquid, expressed in pounds per unit volume.

Hydrostatic Pressure

By multiplying the height of the liquid by its density, the pressure, called **hydrostatic pressure,** can be calculated.

$$\text{Pressure} = \text{Height} \times \text{Density}$$

For example, the head of water inside a tank can be determined by measuring the height and obtaining the weight density of water. Figure 4-1 shows a tank with a water level of 15 feet. The weight of one square inch of water one foot high is 0.433 lb. The hydrostatic pressure is computed by the following calculation:

$$\text{Hydrostatic Pressure (head)} = 15 \text{ feet} \times 0.433 \text{ psi/ft} = 6.495 \text{ psi}$$

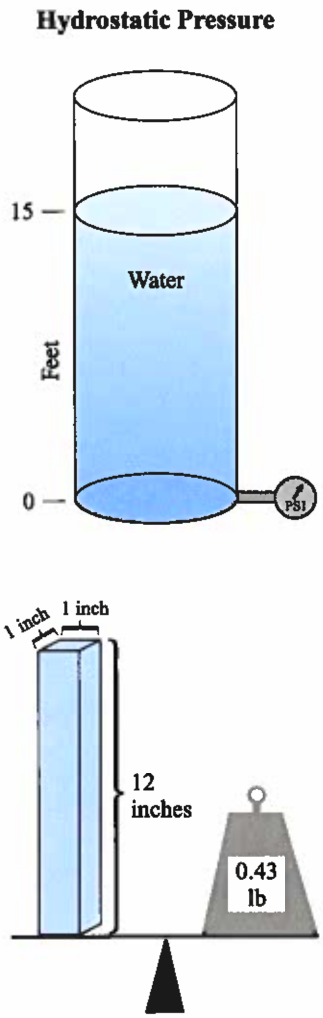


FIGURE 4-1 Hydrostatic pressure is developed by the weight of a column of liquid

Specific Gravity

If a liquid other than water is in the container, calculations may be made for its **specific gravity** (S.G.). Specific gravity of a liquid indicates how much lighter or heavier it is compared to water at 60 degrees Fahrenheit. This relationship is calculated by dividing the weight of a specific volume of liquid by the weight of the same volume of water. Because water is used as a standard, its specific gravity is 1.0. If a liquid is lighter than water, its specific gravity will be less than 1.0. An example is ethyl alcohol, with an S.G. of 0.79. A liquid heavier than water has a specific gravity number greater than 1.0. An example is mercury with an S.G. value of 13.57. Therefore, the hydrostatic pressure of 10 feet of mercury is determined by the following calculations:

Step 1: Determine the hydrostatic pressure of a one-foot column of mercury using its specific gravity value and the weight of an equivalent height of water.

$$\begin{aligned}\text{Mercury Pressure (Density)} &= 13.57 \text{ (S.G.)} \times 0.433 \text{ psi/ft (Water)} \\ &= 5.876 \text{ psi}\end{aligned}$$

Step 2: Multiply the hydrostatic pressure of a one-foot column of mercury times the level of the mercury.

$$\begin{aligned}\text{Pressure} &= 5.876 \text{ psi/ft} \times 10 \text{ ft} \\ &= 58.76 \text{ psi}\end{aligned}$$

Temperature

The temperature of a liquid affects the pressure it exerts. Increasing the temperature expands the liquid (i.e., its molecules move farther apart) and reduces its density. If the liquid is in an open vessel, the hydrostatic pressure remains the same, because the density reduces at the same rate at which the level rises; the decrease in density and the increase in volume cancel each other to keep the weight of the liquid constant. However, if the liquid is confined in a closed vessel, as shown in Figure 4-2, the pressure rises. As the temperature of the vapor inside the vessel increases, the vapor pressure also increases. The pressure due to the vapor is transmitted through the liquid and adds to the pressure due to the weight of the liquid itself.

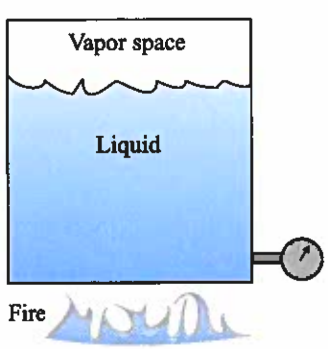


FIGURE 4-2 The heated vapor presses down on the liquid

Atmospheric Pressure

The earth is surrounded by its atmosphere, a layer of air approximately 100 miles thick that is pressed against the earth's surface by gravity. Under normal conditions, the weight of a one-square-inch column of air from the top of the layer to sea level is 14.7 psi. At an elevation higher than sea level, such as Mexico City (altitude 7,800 feet), the atmospheric pressure is only 11.1 psi, because the column of air above the earth's surface at that location is shorter. Figure 4-3 illustrates the difference in hydrostatic pressure between liquids in Boston and Mexico City.

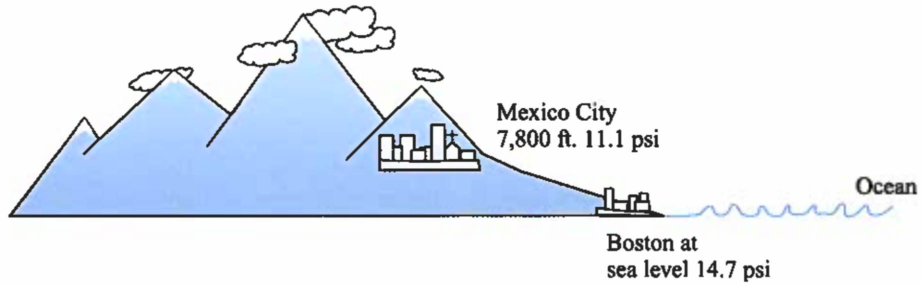


FIGURE 4-3 The higher elevations produce less atmospheric pressure

The pressure from the atmosphere also will exert a force on a liquid in an open vessel. Atmospheric weather conditions also affect the hydrostatic reading of the liquid in an open vessel. The reading will decrease if a low pressure front has moved into the region.

Mechanical Machines

The pressure of a liquid can be changed by a mechanical machine. For example, pumps are used to move liquids. If the liquid is moved out of an enclosed space, the pressure reduces. When the liquid is pumped into a confined area, the pressure increases.

4-3 Properties of a Gas

Gases are another type of fluid used in industrial process applications. A gas can be air from the atmosphere, vapor, or steam.

Unlike molecules of solids and liquids, which remain attracted to one another, gas molecules remain separate. They are also constantly moving at a very rapid speed, crashing both into each other and into nearby surfaces. The molecular energy of the gas causes it to take the shape and fill the volume of its container. Unless the gas is confined in a container, it will disperse. Most of the volume occupied by a gas is space. If the space was eliminated, the gas molecules would be in contact with one another and become a solid or liquid.

Because of their high degree of molecular activity, gases take the shape of their container and exert equal pressure in all directions on its walls. The factors that affect this pressure are temperature of the gas, volume of the container, and air removal from the container.

Temperature of the Gas

In a gas, the molecules are constantly moving. In a confined vessel, billions of molecules collide each second. A pressure gauge placed in a gas container will interpret these collisions as a single pressure. As the temperature of the gas increases, its molecules move faster and collide more frequently in a given span of time. The result is that the pressure increases proportionately with the rise in temperature.

When the temperature of a gas, which is not confined in a sealed container, is increased, the gas will expand proportionately and the pressure will remain constant.

Volume of the Gas Container

When the area of the enclosed container is decreased, the space between the gas molecules is reduced. This action is called **compression.** By decreasing the space between the molecules, a proportionately greater number of collisions will occur in a given span of time, resulting in a higher pressure. The temperature of the gas will also increase. Compressed gas is stored in a confined tank at a higher pressure than atmosphere. The pressure also increases as an additional amount of gas is pumped into the system. Compression can be accomplished by a mechanical compressor, as shown in Figure 4-4. This device is a cylindrical container with a close-fitting piston and a seal. This piston is driven in a reciprocating manner by a crankshaft connected to a motor. An inlet port allows air in from the atmosphere. The piston pushes the air out of the exhaust port into an enclosed system with a fixed volume.

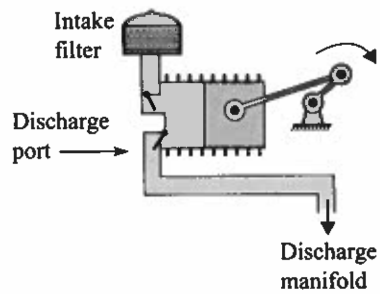


FIGURE 4-4 Single-stage one-cylinder compressor

Gas Removal from a Container

If any gas is removed from a sealed container, its pressure will become less than the atmospheric pressure surrounding the vessel. Any reduction of pressure compared to the atmospheric pressure is a partial **vacuum.** If the gas is completely removed, a full vacuum exists.

The vacuum is created by a pump, as shown in Figure 4-5. It operates on the same principle as the compressor. The difference is that the intake port is connected to the enclosed system, and the discharged air is pumped out of the exhausted port into the atmosphere. Most systems require only a partial vacuum to perform the desired operation.

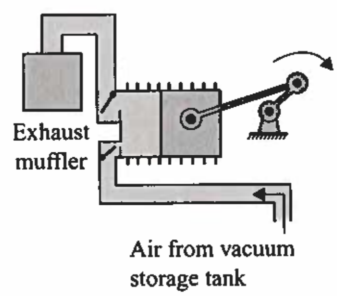


FIGURE 4-5 Single-stage one-cylinder vacuum pump

4-4 Pressure Measurement Scales

Pressure measurements always show the measured pressure as compared to a reference pressure. There are four basic scales, each distinguished by the reference pressure used. Instruments that measure pressure use one of these scales: *gauge pressure, absolute pressure, differential pressure, vacuum pressure,* or *inches of water column.*

Gauge Pressure Scale

Instruments that utilize the **gauge pressure** scale use atmospheric pressure as the reference point. If the sensing element is exposed to the atmosphere, the measurement scale records zero. The units of measurement are recorded in *psig* (pounds per square inch, gauge).

Gauge pressure is either positive or negative, depending upon its level above or below the atmospheric pressure reference. A gauge pressure instrument will read +30 psi when measuring an inflated tire with 30 pounds per square inch of air pressure. This value indicates a positive pressure of 30 psi above atmospheric pressure. A negative gauge pressure indicates a pressure in pounds per square inch below atmospheric pressure. A negative pressure of −14.7 psi indicates a full vacuum. A gauge pressure scale that makes a positive reading only is shown in Figure 4-6(a). A compound gauge pressure scale, which makes both positive and negative readings, is shown in Figure 4-6(b).

Absolute Pressure Scale

Instruments that use the **absolute pressure** scale are referenced to absolute zero, or the complete absence of pressure. Since it is not possible to have a pressure less than a vacuum, absolute pressure readings are only positive values. If the sensing element is exposed to the atmosphere at sea level, the measurement scale will read 14.7 pounds per square inch. The units of measurement are recorded in *psia* (pounds per square inch, absolute).

Absolute pressure readings are generally more accurate than gauge readings. The reference of gauge pressure instruments is not consistent: atmospheric pressure fluctuates with weather changes and altitude. With absolute pressure instruments, the reference point is consistent. A pure vacuum is the same at sea level as it is on top of Mt. Everest. An absolute pressure scale is shown in Figure 4-7.

To convert gauge to absolute pressure, simply add atmospheric pressure to the psig pressure value. To convert absolute to gauge, subtract atmospheric pressure from the psia measurement. The diagram in Figure 4-8 shows a comparison of both gauges when measuring pressures under various conditions.

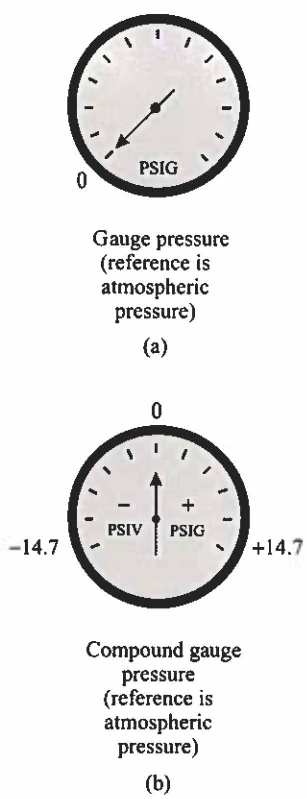


FIGURE 4-6 Gauge pressure measurement scales

FIGURE 4-7 Absolute pressure measurement scale with a vacuum reading of zero as the reference

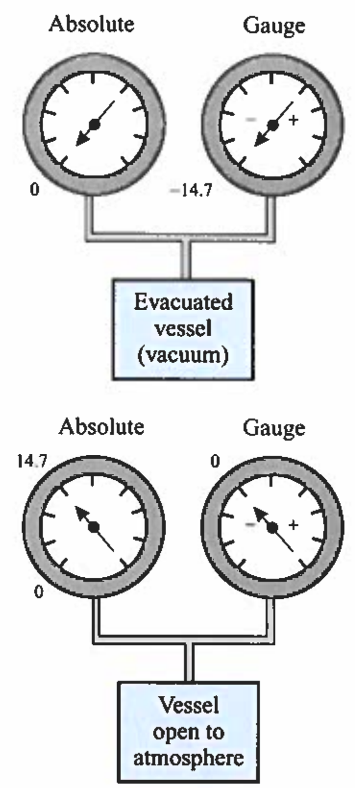


FIGURE 4-8 Comparison of readings by absolute and gauge measurement scales at a vacuum and at atmospheric pressure

EXAMPLE 4-1

A gauge reading of 30 psig is taken. What will an absolute pressure instrument read under the same conditions?

Solution

$$\begin{aligned}\text{Absolute Pressure} &= \text{Gauge Reading} + 14.7\\ &= 30 + 14.7\\ &= 44.7 \text{ psia}\end{aligned}$$

EXAMPLE 4-2

An absolute reading of 60 psia is taken. What will a gauge pressure instrument read under the same conditions?

Solution

$$\begin{aligned}\text{Gauge Pressure} &= \text{Absolute Reading} - 14.7\\ &= 60 - 14.7\\ &= 45.3 \text{ psig}\end{aligned}$$

Inches of Water Column

When making low pressure readings, such as those that are a fraction of a pound, the engineering unit of measurement is in *inches of water column*, or *inches of H_2O*. This unit of measurement refers to how many inches of water in a vertical column will create the pressure. The result is that larger numbers can be used in measurements and in calculations.

Inches in H_2O is commonly used in air flow applications, such as measuring the flow rate of a gas through an orifice plate in a pipe. A differential pressure that forms across the plate is very small. So this unit of measurement is used. Inches in H_2O measurements are also commonly used in HVAC (Heating, Ventilation, Air Conditioning) systems because the air pressures are very small.

If a pressure in pounds per square inches (psi) is known, it can be converted into H_2O engineering units by simply multiplying the reading in psi by the constant 27.71.

EXAMPLE 4-3

Determine the inches in H_2O value if a measurement of 1.8 psi is made.

Solution

$$1.8 \times 27.71 = 50$$

Differential Pressure Scale

Pressure readings are also measured in units of **differential pressure,** given in *psid* (pounds per square inch, differential), or ΔP. Differential pressure is used to express the difference in pressure between two measured pressures. It can be determined by subtracting the lower reading from the higher reading. The calculation must be made by using values from the same type of measurement scale.

Vacuum Pressure Scale

Instruments that measure a vacuum use a scale that begins at atmospheric pressure, just as gauge pressure, but works its way down to a vacuum. In the United States, the most common vacuum scale is listed in units of inches of mercury (*in Hg*), as shown in Figure 4-9. The gauge reads zero when measuring atmospheric pressure, and 29.92 in Hg when measuring a complete vacuum. This unit of measurement is based on a barometer tube that uses mercury to indicate atmospheric pressure. The operation of this device is described in the next section. Figure 4-10 shows a graphic comparison of the different pressure scales.

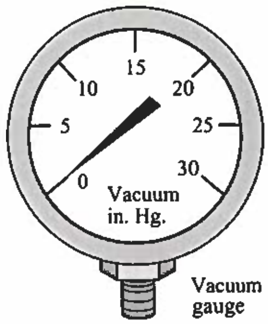


FIGURE 4-9 A vacuum pressure measurement scale

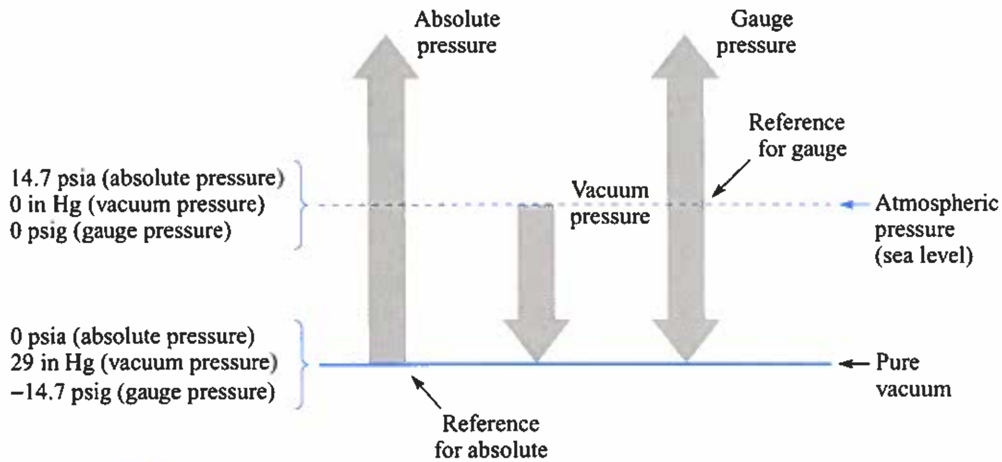


FIGURE 4-10 Comparison of different pressure scales

4-5 Pressure Measurement Instruments

Many manufacturing operations require that specific conditions exist. For example, to combine a powder and a liquid in preparation for a food-blending operation, a pressure condition within a few pounds may be required. Pressure above or below the required range can ruin the food. Excessive pressure in a system can rupture equipment or cause an explosion.

Measuring instruments are used to monitor pressure conditions so that corrective action can be taken if necessary. The forces created by the pressure produce a deflection, a distortion, or some change in volume or dimension of the instrument's sensing element. The physical alteration of the element provides the movement that is necessary to indicate the pressure reading.

Measuring instruments that detect pressure, temperature, level, and flow conditions are classified by whether they make the measurements *directly* or *indirectly*. For example, the level of liquid in a tank can be measured directly with a dipstick. When measurements are taken indirectly, some variable other than the liquid is read. For example, by making an indirect measurement of a tank's weight, the level of its contents can be determined. This method is also referred to as an **inferred measurement.** The weight is used to *infer* a level measurement.

Both nonelectrical measuring devices and electronic sensors used to measure pressure are described below.

4-6 Nonelectrical Pressure Sensors

Nonelectrical pressure sensors fall into two categories: liquid column gauges and mechanical gauges.

Liquid Column Gauges

As previously stated, it is possible to measure pressure by monitoring the height of liquid in a column. For example, a pressure of 0.433 psi will support a 12-inch column of water.

This method, called head pressure, is very simple and accurate. For this reason, it is often used to calibrate other types of pressure gauges or instruments.

The operation of this measuring device is based on the same principle as the barometer that measures atmospheric pressure, shown in Figure 4-11. It consists of a glass tube filled with mercury that is sealed at one end and open at the other end. Mercury starts to drain out of the tube when it is positioned vertically with its open end inserted into a dish of mercury. When there is enough atmospheric pressure exerted on the mercury in the dish to support the mercury in the tube, it will stop draining. The gap that forms above the mercury is a vacuum. Changes in pressure cause the mercury in the tube to rise or fall. The larger the pressure, the higher the mercury will rise. A scale on the side of the glass tube allows the height of the liquid to be read directly. At sea level, 14.7 psi of atmospheric pressure will support 29.92 inches of mercury.

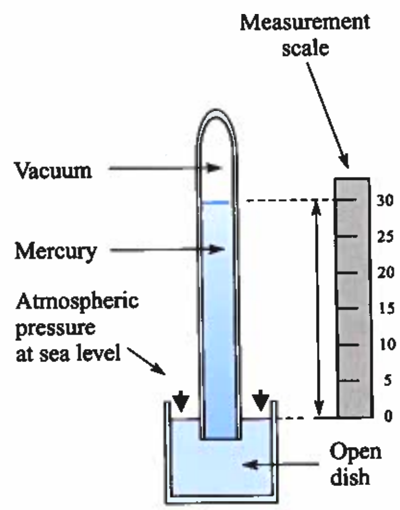


FIGURE 4-11 A barometer reading of 29.92 inches of mercury at sea level

In addition to being affected by pressure, the level of the liquid is also influenced by its density. Because it takes less pressure to support liquids lighter than mercury, water is often used in liquid column gauges to measure very low pressures, vapors, pressures below atmospheric, or a vacuum. Mercury is typically used to detect and indicate **higher** pressures. Liquid column devices that use water as the medium should never be exposed to temperatures below freezing.

Manometer

The most common liquid column device used to measure pressures is the manometer. It consists of a glass tube bent in the shape of a U so that there are two columns. Each column is exposed to a different pressure source. To determine the amount of pressure, read the rise of liquid in one column and the drop in the other, and add them together. There are several types of manometers used to measure various types of pressure.

Gauge Pressure

A manometer that measures gauge pressure uses one column as a reference. The end of the reference tube is open so that it is exposed to atmospheric pressure. The other column is connected to the process being measured. The pressure measurement is taken by reading the difference in height of the two columns on the scale. If the level in the reference column is higher than the liquid in the measurement column, a positive value above atmospheric pressure is read. The opposite situation indicates a negative value below atmospheric pressure. The maximum negative pressure reading indicates a vacuum. Figure 4-12 shows a U-shaped manometer and how a gauge pressure manometer measures both positive and negative readings.

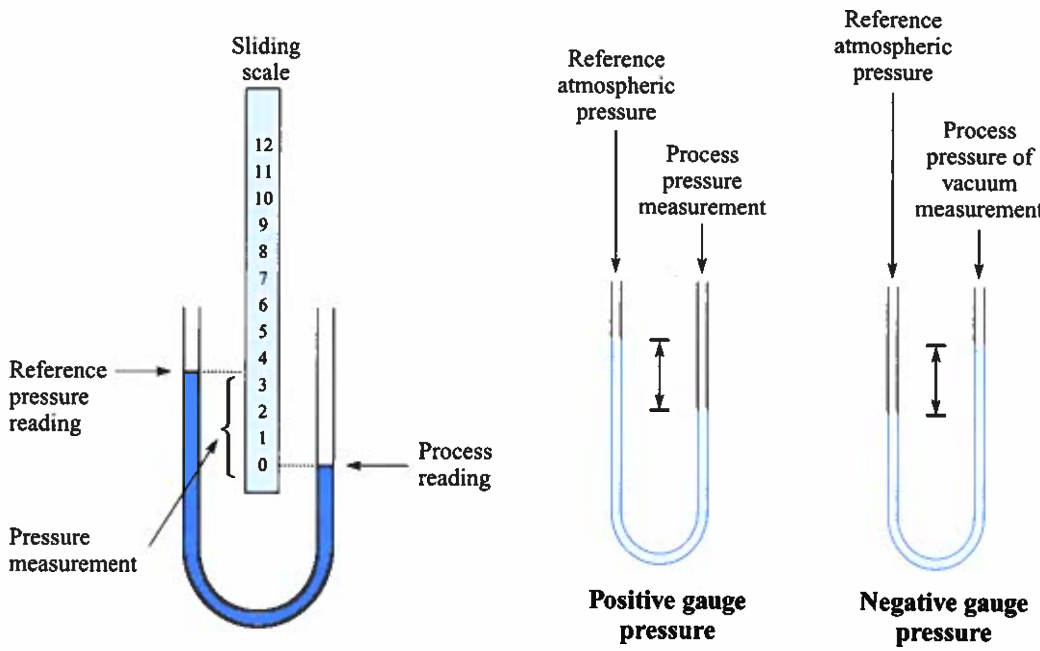


FIGURE 4-12 Gauge pressure manometer

The formula for measuring gauge pressure with a manometer is

Gauge Pressure (psig) = Total Deflection (inches) × Liquid Constant (psi)

EXAMPLE 4-4

The liquid in the reference column of a manometer rises 3 inches and the liquid in the pressure column lowers 3 inches. If mercury is used as the liquid, what is the gauge pressure being measured? *Mercury has a constant of .491 psi per inch.*

Solution

Gauge Pressure = Total Deflection × Mercury Constant
= 6 inches × .491
= 2.946 psig

Absolute Pressure A manometer that measures absolute pressure of a vacuum has a reference column with the end of the tube sealed. The closed end creates a vacuum and allows an evacuation space to form. The other column is connected to the measured pressure. If a high pressure exists, it will push the level in the measured column downward and the level in the reference column upward, thus creating a large level difference between both columns. If a vacuum is measured, the levels in both columns will be the same. Figure 4-13 shows how an absolute pressure manometer makes measurements of a vacuum (Figure 4-13(a)) and a positive pressure (Figure 4-13(b)).

Differential Pressure The manometer can also be used to measure differential pressure. Simply connect the open ends of each column to the two pressure sources being compared, as shown in Figure 4-14. The level differences of the liquid provide the pressure reading.

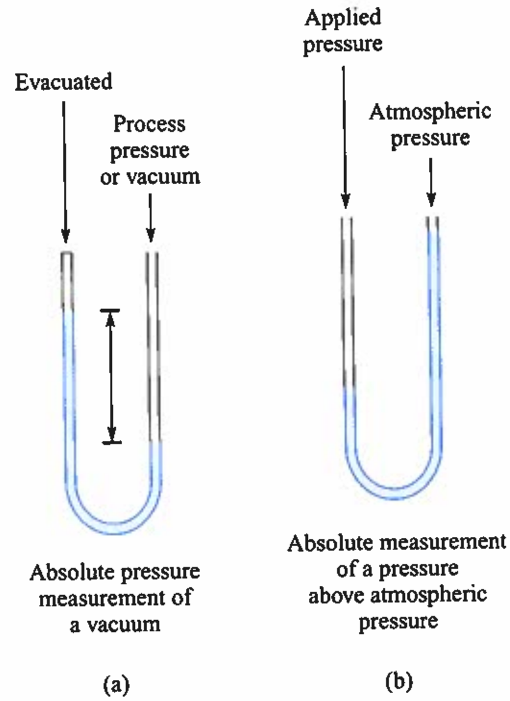


FIGURE 4-13 An absolute pressure manometer

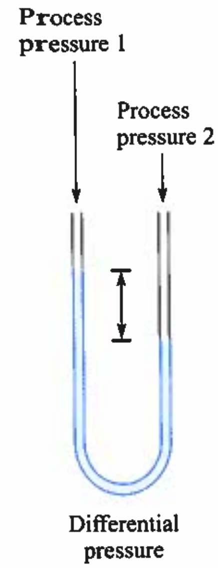


FIGURE 4-14 A differential pressure manometer

The formula used to calculate differential pressure by a manometer is:

$$\text{Differential Pressure (DP)} = (\text{Column 2 Movement} - \text{Column 1 Movement})\ \text{Liquid Constant}$$

EXAMPLE 4-5

The liquid in column 2 of a manometer rises $2\frac{1}{4}$ inches and the liquid in column 1 lowers $2\frac{1}{4}$ inches. If mercury is used as the liquid, what is the differential pressure being measured?

Solution

$$\begin{aligned} \text{DP} &= (\text{Pressure 2} - \text{Pressure 1})\ \text{Mercury Constant} \\ &= 4.5\ \text{inches} \times .491 \\ &= 2.21\ \text{psid} \end{aligned}$$

Mechanical Gauges

Because of their durability, mechanical pressure gauges are often preferred over liquid-filled glass gauges. They are also inexpensive and reliably accurate. Mechanical gauges are constructed by using two major parts, a sensing element and an indicator. The element is elastic and changes form when exposed to pressure. The element is mechanically connected to an indicator device, such as a needle-shaped pointer. As the pressure changes, the element's shape changes and moves the pointer over a scale to indicate a reading.

There are several types of mechanical gauges. They differ primarily by the type of device each uses as the sensing element.

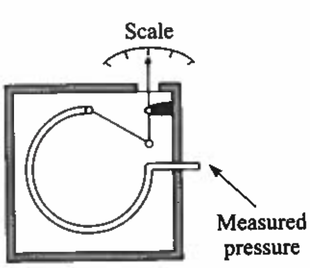


FIGURE 4-15 A Bourdon tube gauge

Bourdon Tube Gauge

The Bourdon tube gauge illustrated in Figure 4-15 shows a C-shaped metal tube as the element. The tube is hollow, sealed at one end, and open at the other end. The open end is exposed to the pressure being measured. An increase in process pressure creates a higher pressure inside the tube, while the pressure outside the tube remains the same. This increase in differential pressure causes the coil to unwind. As it becomes straighter, the needle coupled to the tube will move toward the right of the scale to indicate a higher pressure reading. A decrease in measured pressure reduces the differential pressure between the inside and outside of the tube. The tube returns toward its original shape, and the needle moves to the left.

Bourdon tubes are available to measure pressure ranges from 0–15 psi and from 0–6000 psi. They are made from a variety of materials to provide compatibility with the measured fluids.

Diaphragm Gauge

The diaphragm gauge in Figure 4-16(a) measures absolute pressure. It uses a flat flexible material that bends or flexes when exposed to pressure. One side of the diaphragm is connected to the process being measured and the other side is exposed to a vacuum, which is the reference pressure. The diaphragm element bends toward the side that has the lowest pressure and pushes against an opposing spring. Also referred to as a *load spring,* its strength determines the range and sensitivity of the instrument. The spring also helps to return the element to its original shape as the pressure is reduced. The diaphragm element is mechanically connected to a pointer that indicates the pressure reading.

Figure 4-16(b) shows a gauge pressure measuring device. One side of the diaphragm is exposed to atmospheric pressure as a reference. The other side of the element senses the process pressure. The element is pushed toward the side with the least pressure. Figure 4-16(c) shows a differential pressure measuring device. The differential pressure gauge does not have a reference. It only measures the difference between two pressures. The construction of the differential gauge is identical to the gauge device. Each side of the element is connected to one of the two pressures being measured. Instead of having a meter face with a gauge scale, a differential scale is used.

For low pressure readings, a nonmetallic element such as teflon is used, often without an opposing spring. Because of its resiliency, it is able to distort when lower pressures are

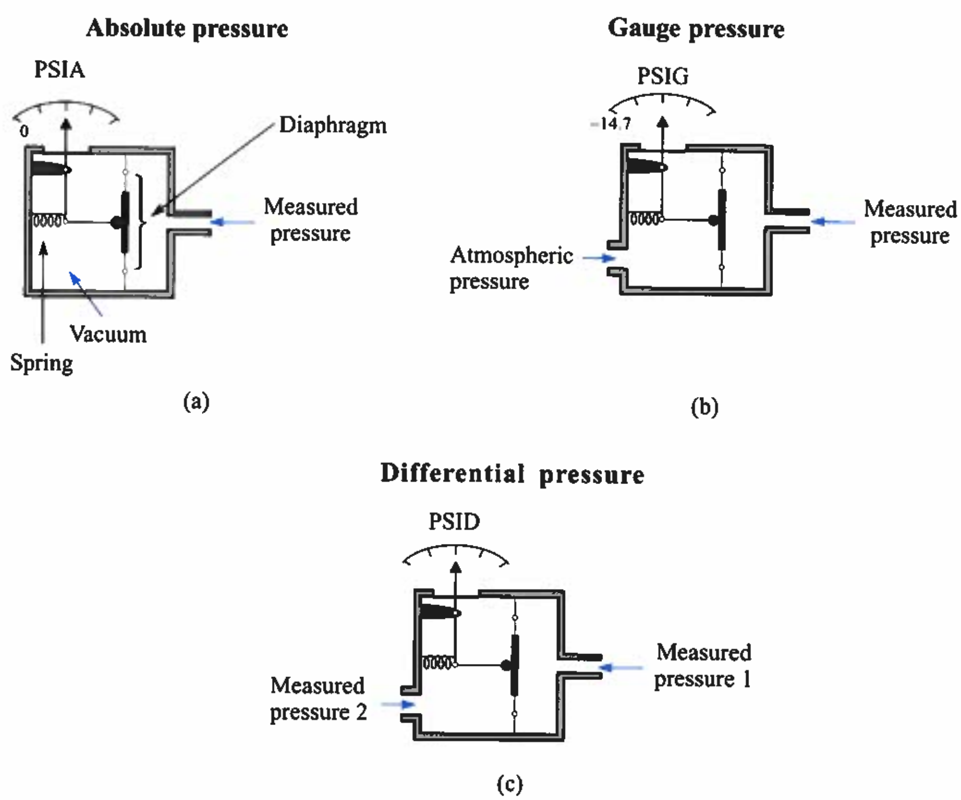


FIGURE 4-16 The diaphragm mechanical pressure gauge

applied. Metal elements are not as flexible, but bend enough when measuring high pressure. Because metals tend to withstand exposure to harmful elements, they are used in environments that are corrosive and where the temperatures are high. Diaphragm gauges sense pressure from 30 inches Hg vacuum to 6000 psig.

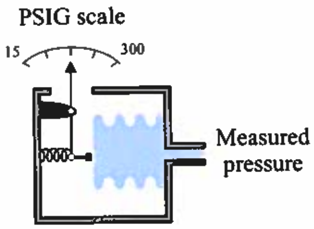


FIGURE 4-17 A bellows pressure gauge

Bellows Gauge

Flat diaphragm elements have a limited range of motion and produce nonlinear readings. By using sensing devices with pleated walls, the flexibility and movement increase. An elastic element that resembles an accordion bellows is shown in Figure 4-17. When applying the measurement pressure to the inside of the element, it expands and causes a larger needle deflection than the flat element. The bellows material may be brass, phosphor bronze, or stainless steel, depending on required range, sensitivity, corrosion resistance, and cost. An opposing spring is employed to control range and sensitivity. Bellows instruments measure pressures that range from 30 inches Hg vacuum up to 500 psig.

4-7 Electronic Pressure Sensors

New advancements in electronic technology have resulted in the development of electronic sensors to measure pressure. These devices are more accurate, more reliable, and less expensive than many of the mechanical measuring instruments they are replacing.

Semiconductor Strain Gauges

The strain gauge is used to detect the strain on a body caused by force. This device is typically constructed with a Wheatstone bridge arrangement. It is shown in both schematic and exploded views in Figure 4-18. The four resistive elements that make up the bridge network are made of piezoelectric semiconductors. The elements are bonded to a pressure-sensitive diaphragm. A pressure change causes the elements to expand. A compressive strain on the diaphragm will cause the element to contract. The distortion of the elements produces a differential resistance change, which is measured by applying a constant excitation voltage to the bridge. The diaphragm deflection is an analog output voltage up to 250 millivolts proportional to pressure. Without pressure the bridge output is 0 volts because the four elements are balanced.

The formula $R + \Delta R$ and $R - \Delta R$ represents the elements' actual resistance value with pressure applied to the diaphragm. The R represents the resistor value without pressure applied to the diaphragm. The ΔR represents the change in resistance due to an applied pressure. When pressure is applied, all four resistors' elements change the same amount. The elements are mechanically connected to the diaphragm so that two of them compress while the other two expand. The result is that the resistance of two elements increases, and the resistance of the other two decreases.

Variable resistors R_1 and R_2 are trim pots. They are used to externally balance the resistance of any element changes due to component aging. The thermistor connected across R_3 is used to temperature compensate the bridge network when the ambient temperature changes. The output voltage is applied to an amplifier and to the transducer's internal or external conditioning circuits. The sensitivity of semiconductor strain gauges is 100 times that of wire strain gauges. Silicon has very good elasticity, which makes it an ideal material for receiving an applied force. Since it is a perfect crystal, it does not become permanently stretched. Instead, it returns to its original shape after the force is removed.

For better temperature ranges and stability, semiconductor elements are epoxy bonded onto stainless steel diaphragms.

Transverse Voltage Strain Gauge

The transverse voltage strain gauge is a new configuration developed by Motorola. Figure 4-19 shows the top view of the sensor element. Current passes through a semiconductor piezoresistor from pins 1 to 3. Pressure that stresses the diaphragm is applied at a right angle to

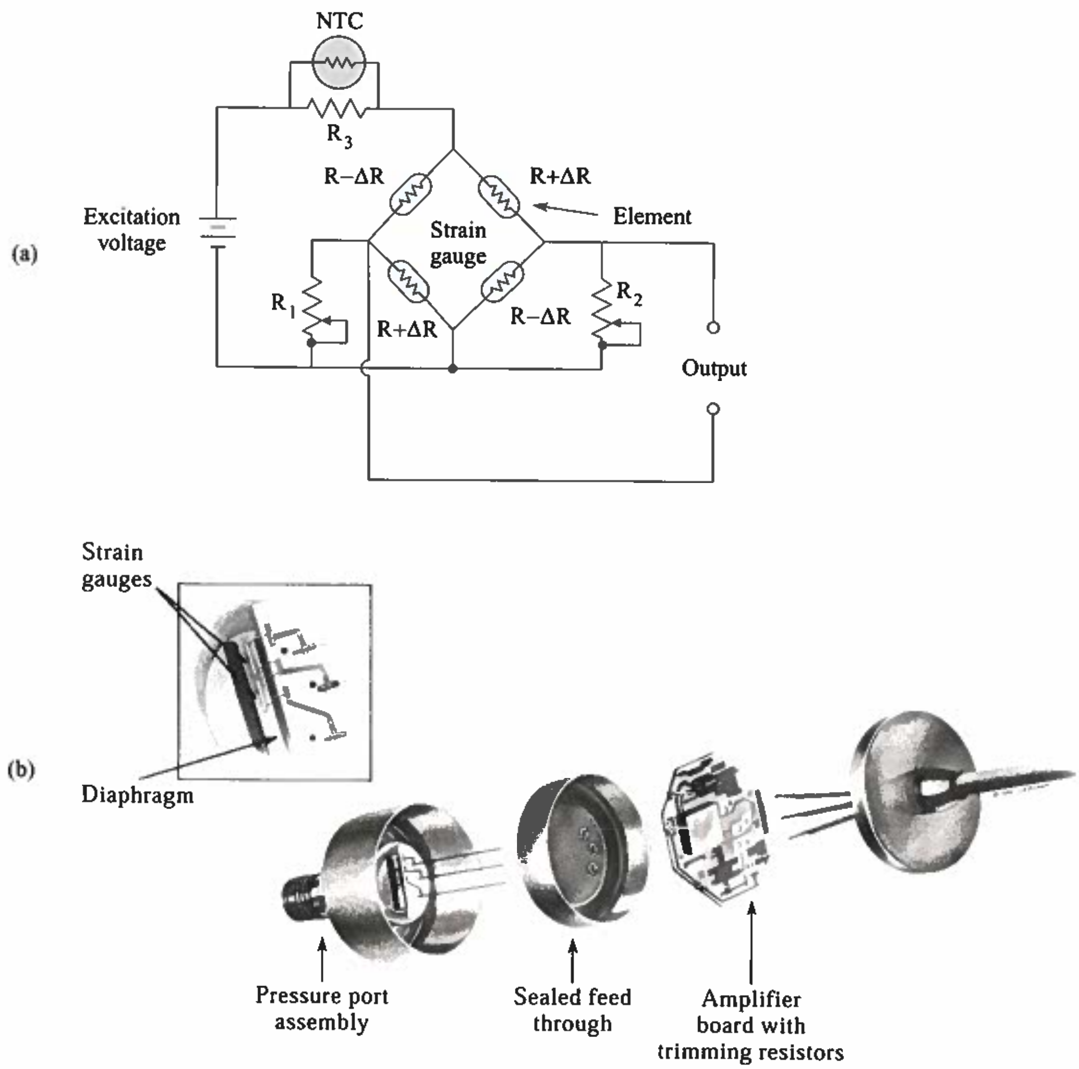


FIGURE 4-18 A semiconductor strain gauge configuration (Courtesy of Data Instruments)

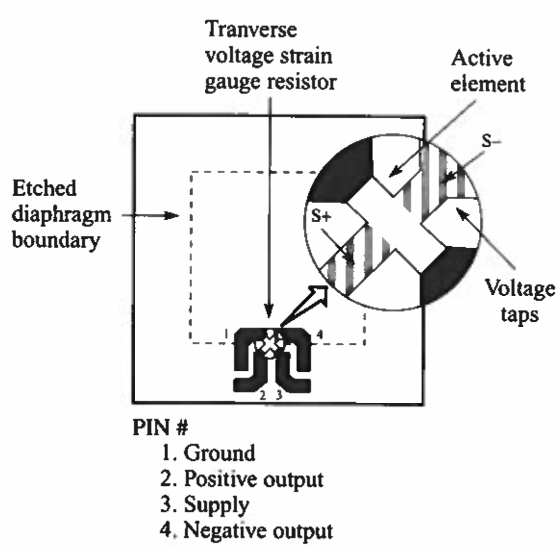


FIGURE 4-19 Transverse voltage strain gauge (Courtesy of Motorola)

current flow. The deflection of the diaphragm causes the resistor element to bend. As it does, a transverse electric field is developed that is sensed as voltages at pins 2 and 4, which are located at the midpoint of the resistor.

The advantage of this type of strain gauge is that it uses only one element. A single element eliminates the need to closely match the four stress- and temperature-sensitive resistors of a Wheatstone bridge design. It also simplifies the additional circuitry necessary to accomplish calibration and temperature compensation.

Variable Capacitor Pressure Detector

The **variable capacitor pressure detector** uses two conductive plates oriented adjacent to each other and separated by air. Shown in Figure 4-20, one plate is fixed and the other plate is positioned by an elastic element, such as a bellows. It works on the principle that the capacitor's value is changed by varying the distance between the plates. As the measured pressure varies, it changes the shape of the element and causes the plate to move either closer to or farther away from the fixed plate. The change in capacitance is translated electronically into a control signal that represents the measured pressure.

The entire capacitor sensor is sealed in a capsule with the diaphragm exposed to the process pressure. These transducers are economical, small, rugged, vibration resistant, and accurate to within 0.2 percent throughout their entire range. These features make them well-suited for many applications, and they are one of the most widely used pressure transducers in the process industry.

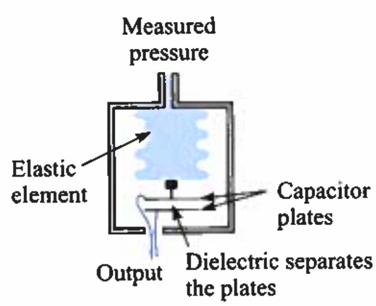


FIGURE 4-20 Variable capacitor pressure detector

4-8 Pressure Control Systems

The most common types of industrial process systems that employ pressure are hydraulic, pneumatic, vacuum, static, and steam pressure distribution systems.

Hydraulic Systems

Many types of machinery used in the manufacturing industry are powered by hydraulic pressure. Most types of hydraulic systems recirculate an oil-based fluid, as shown in Figure 4-21. The illustration shows a double-acting hydraulic system that controls a punch press.

The figure shows a motor-driven rotary pump as the energy source of the system. It converts electrical energy into mechanical energy. With each revolution of the pump, a fixed amount of hydraulic fluid enters the inlet port from the reservoir. The liquid is set into motion by being forced through the outlet port into the system through transmission pipes or flexible tubing. This outlet port is called the pressure line. The hydraulic fluid is in the state of ready operation as it circulates throughout the system.

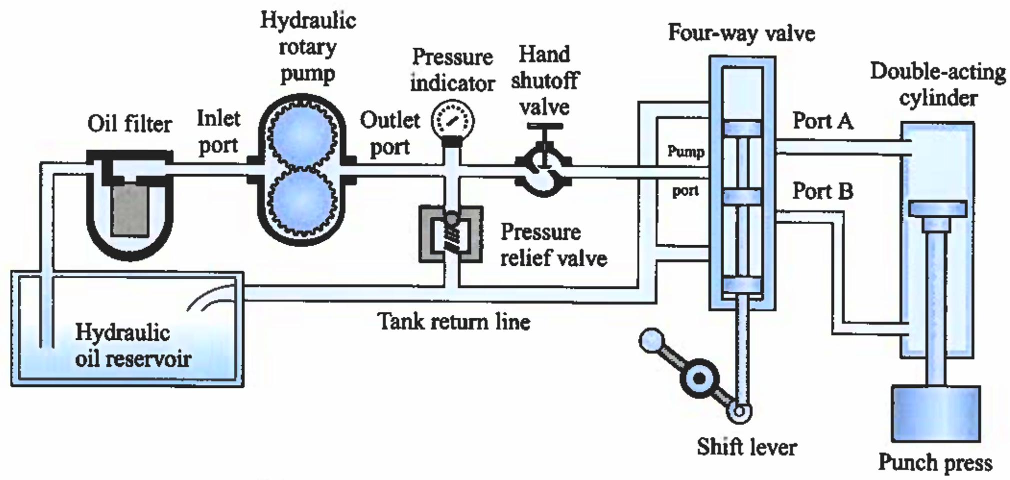


FIGURE 4-21 Hydraulic system

A filter in the feedline is placed between the reservoir and pump. In this position, it removes any dirt particles or contaminants from the oil before it enters the system. Its purpose is to extend the life of the system.

As fluid flows through the system, it encounters resistance due to friction from surface areas of the transmission lines and from various components. The pressure is developed as fluid is forced against the surface areas. Indicator instruments such as pressure gauges and flowmeters are placed throughout the system to show different operating conditions, or to monitor the components in order to show they are functioning properly.

The mechanical control of the hydraulic system is achieved by a number of components, such as directional valves, flow control valves, and regulators. They provide either full or partial control of system fluid.

The directional control valve, or four-way valve, alters the directional flow path of the fluid. It consists of a valve body with four internal passages and a sliding spool that connects and disconnects the passages. When the spool is moved to the extreme bottom position, the pump port is connected to Port A, and the tank return line is connected to Port B. Pressurized fluid enters the cylinder at Port A and fluid is forced out of Port B into the return lines, causing the rod to extend. When the spool is in the extreme top position, the pump port is connected to Port B and the tank return line to Port A. Fluid enters Port B and exits Port A, causing the rod to retract.

The double-acting cylinder is used to control a punch press and it serves as the load device of the system. It performs work by changing the mechanical energy of hydraulic fluid into linear motion that moves the ram of the press. Ports are located at each end of the cylinder body through which fluid can enter and exit, thus allowing the piston rod to move in two directions.

The hand shutoff is a flow control valve. By turning the knob, the amount of fluid flow in both directions can be adjusted between maximum flow and no flow. When the valve is fully open, maximum fluid will flow; when fully closed, no fluid will flow.

A pressure relief valve is connected between the pump output port and the reservoir. It consists of a valve body and a spool that is biased by a spring. When the pressure at the pump end of the spool opposite the spring is high enough, the spool is pushed open. A path is created for flow between the pump and tank. The purpose of the relief valve is to prevent excessive pressure from building up in the system. This function is accomplished by providing a route for the fluid between the pump and tank when the flow paths downstream are blocked. This situation would occur under the following conditions: the cylinder is fully extended or retracted, the flow control valve is fully closed, or the four-way directional control valve is in a position that blocks flow to and from the cylinder.

Pneumatic Systems

One of the major applications of pneumatic pressure systems is on mass production assembly lines. The compressed air of these systems provides the power for industrial processes that require high forces or high-impact blows to produce products.

Figure 4-22 illustrates a pneumatic system that operates a hand tool. An air compressor unit serves as the energy source of the system. It forces surrounding air into a tank under pressure. The tank where the compressed air is stored serves as a reservoir until it is eventually distributed into the system when needed. In an industrial setting, the compressor is driven by an electric motor. Portable pneumatic systems use internal combustion engines. The compressor forces the air into the tank, stopping when the pressure reaches a certain level. The pressure must be maintained during system operation. As the air is used, the pressure drops. If it falls below a predetermined level, the compressor turns on until enough air is replaced.

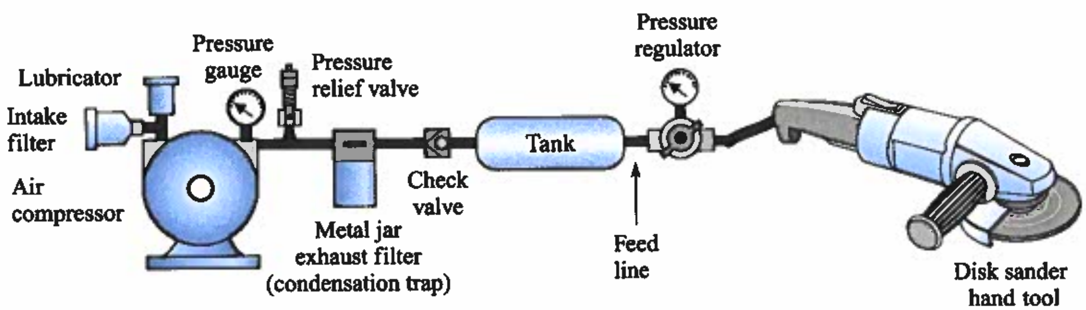


FIGURE 4-22 A pneumatic system that drives a rotary actuator

A feedline from the tank provides air for distribution throughout the plant. Solid pipes, tubing, and flexible hoses are used to transmit pressure in the system. The air is not recirculated and returned to the tank. Instead, it is released from the system back into the atmosphere.

Before the air enters the compressor, it must first be conditioned. Conditioning involves the removal of dirt by an air intake filter, the removal of moisture by a condensation trap, and the injection of a fine oil mist to provide lubrication for moving parts. Figure 4-22 shows the filter and lubricator at the inlet of the compressor and a metal jar exhaust that collects moisture from oil vapors produced by the lubricator. The pressure gauge monitors system pressure. The pressure relief valve vents air into the atmosphere if the pressure in the system becomes excessive. The check valve prevents high air pressure from returning to the compressor from the tank due to backflow. The tank is a reservoir that holds pressurized air for intermittent usage. The pressure regulator is a variable pressure valve that operates by restricting and blocking flow to the working portion of the circuit. The actuating speed of the load can be regulated to different speeds by adjusting the flow control setting of the valve.

The load of the system that performs work is a rotary actuator that is capable of variable speed control. This type of load device would be used in industrial applications such as buffing, drilling, grinding, and mixing. Pneumatic load devices are also designed to produce linear motion to perform work. For example, a double-acting cylinder is used in industrial applications such as hoisting, elevating, pile driving, and clamping.

The pneumatic system operation is monitored by pressure indicators placed at strategic locations. Their readings provide information on system operation and troubleshooting.

Vacuum Systems

Any enclosed space containing air or other gas at a pressure lower than atmospheric pressure is defined as a *vacuum*. Just as with compressed air, a vacuum condition can be utilized to perform various types of work applications.

Figure 4-23 shows a diagram of an On-Off cycling vacuum system. All of the components and pipes are enclosed and isolated from the outside atmosphere. A vacuum pump removes air from the system. A storage tank is used to accumulate vacuum for on-demand power needs. The vacuum pressure in the tank is monitored by a measuring sensor. If the vacuum pressure is not great enough, the sensor develops a signal that turns the pump on. The vacuum pressure lowers when actuator devices pull air into the system as they perform work, or from any leaks that may develop in the system. When the sensor detects that the vacuum pressure has reached a preset level, its output signal changes and turns off the pump. The usual range between the turn-on and turn-off points is about 5 to 15 Hg inches. The reason for using a reservoir tank is that it permits On-Off operation, which allows the vacuum pump time to cool down.

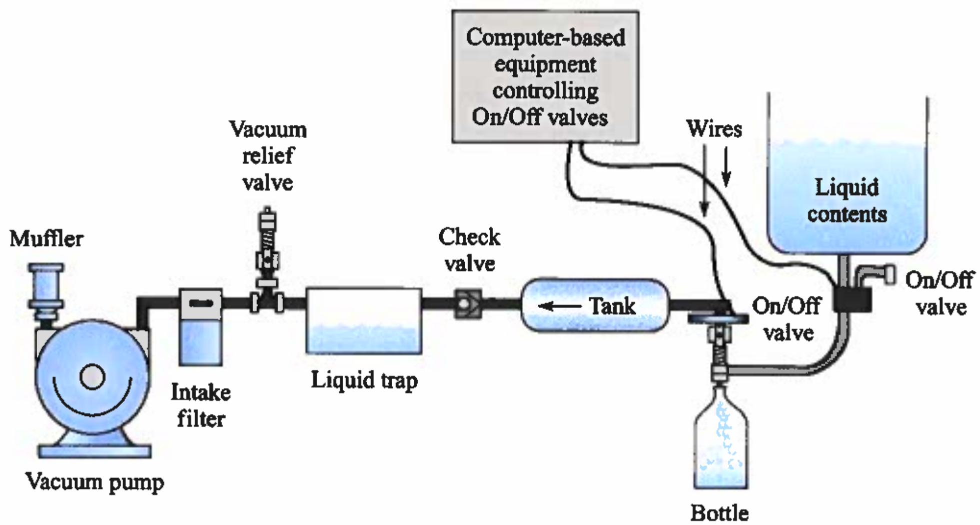


FIGURE 4-23 A vacuum system used to fill bottles with liquid

A vacuum relief valve provides protection from an excessive vacuum condition. The check valve installed between the vacuum pump and tank allows airflow out of the tank. This one-directional component prevents the backflow of air into the tank. An intake filter is used to prevent foreign particles such as dust or sand from entering the pump mechanism. A bottle-like tank called a liquid trap uses gravity to prevent liquid materials from being sucked into the pump.

The vacuum system performs work by creating a pressure differential between the airtight surfaces of the equipment. As controlled actuators open vents, the outside air creates a mechanical force as it is sucked into the system. This force is able to produce different types of work operations.

The actuator in this system is an injector device that fills a bottle with liquid. A vacuum tube is placed in the center of a drain tap. At the moment liquid is dispensed into the container, the vacuum tube is activated to suck air out of the bottle. The filling operation is much faster because the liquid is literally forced into the bottle, rather than filling because of gravity.

Static Pressure Systems

Static pressure systems are also referred to as *hydrostatic*. They are used for industrial applications where fluids are distributed during the manufacturing process. These fluids can include liquids, gases, or solids (such as powders) that flow. Specifically, hydrostatic systems are used for batch processing applications such as mixing or blending operations that occur for a limited period of time.

The pressure developed is the result of the fluid source elevated above the working section of the system. The fluid is usually held in a storage tank where it is stored until it is needed. The depth and density of the fluid develop a force at the bottom of the tank called *static head.* When the fluid is released, this pressure is required for the distribution of fluids to locations throughout the system.

The variety of control components used in the static system is limited to flow control/shutoff valves. Since cylinders or other types of actuators are not used, there are no-load components that perform work. Instead, the load is the resistance of the entire system and the only work function that exists is the result of heat generated due to friction. The operation of the system is monitored by strategically placed pressure and flow measurement instruments.

A batch process static pressure system that manufactures soft drinks of different flavors is illustrated in Figure 6-1 in the chapter on flow control. Ingredients are stored in elevated containers. As the ingredients are needed, valves open to allow drainage into a mixing tank.

Steam Pressure Systems

Steam pressure is used in industry for a variety of purposes. It is used as a heat source for food processing, chemical processing, refining, or simply for warming the plant facility. Steam pressure is also used to perform some types of work, such as driving a turbine to generate electricity. Steam pressure is developed by applying heat to water. Water is transformed into a vapor, which creates a pressure as it expands throughout the system.

The energy source of the steam pressure system is a boiler. The water tube boiler design illustrated in Figure 4-24 is a very popular method of developing steam pressure. Tubes that contain water are placed inside a sealed metal chamber that is heated by a furnace unit. The

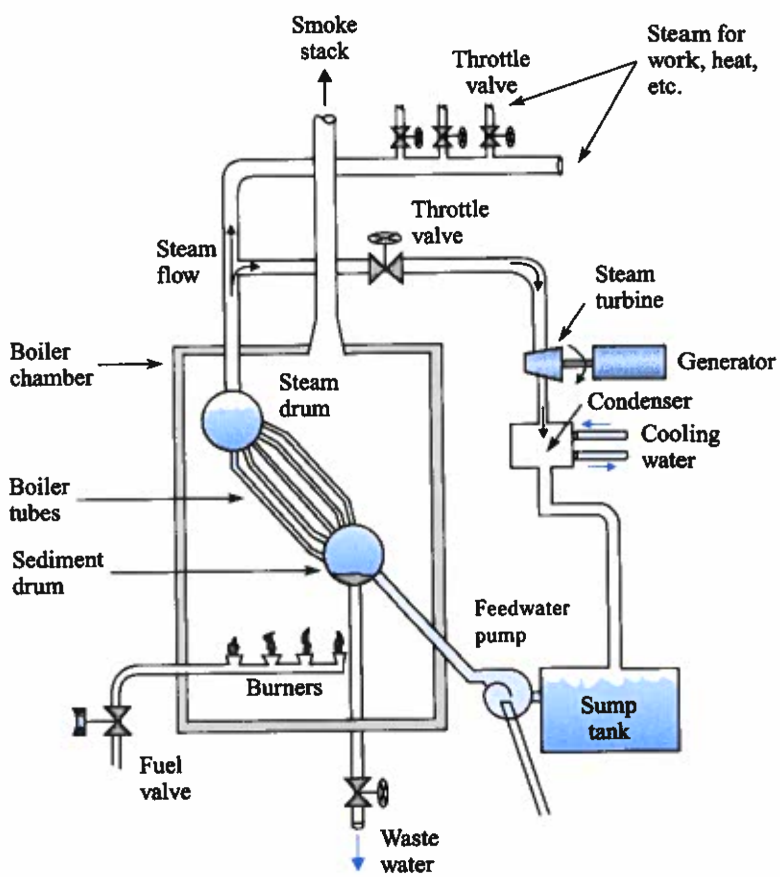


FIGURE 4-24 Steam boiler

tubes are exposed to high temperatures by the surrounding air inside the chamber. Electricity or fossil fuel such as coal, oil, or natural gas is the energy source for the furnace.

As the water inside the tubes is heated, it changes into pressurized steam which is then forced through pipes and tubes that serve as transmission lines. As the steam flows throughout the system during the production process, its pressure and flow are controlled by directional and flow control valves. Pressure gauges monitor the steam at strategic locations and may provide proportional electrical signals as input data to control equipment for automation purposes. The pressure in a steam system can be described as *head pressure*.

In some systems, the steam is recirculated. After passing through the actuator section, it is condensed back into water before returning to the boiler to be used again.

Problems

1. Which of the following are defined as fluid? ____.
   a. Liquid
   b. Gas
   c. Steam
   d. Air
   e. All of the above
2. To perform work such as a hydraulic press or pneumatic air drill, pressure must be __________ (increased, decreased).
3. To lift individual sheets from a stack of papers, pressure is ____.
   a. increased
   b. decreased
4. Liquids __________ (are, are not) compressible.
5. Water has __________ (more, less) density than an equal volume of mercury.
6. Pressure is measured as a force per unit of ____.
   a. area
   b. volume
   c. time
   d. mass
7. A decrease in pressure will change some types of ____ into a ____.
   a. gas(es)
   b. liquid(s)
8. The hydrostatic pressure of one square inch of water 100 feet deep is how many psi? If the liquid is ethyl alcohol instead of water, the hydrostatic pressure is how many psi?
9. A decrease in temperature causes the head pressure of a liquid in a confined container to ____.
   a. increase
   b. decrease
10. The head pressure of one liquid gallon in Mexico City is ____ the pressure of an identical open vessel in Miami.
    a. less than
    b. greater than
    c. the same as
11. Suppose a liquid at 60 degrees Fahrenheit has a specific gravity of 6.28. If the measured pressure at the bottom of the tank in which it is stored is 51.3 psi, what is the height of the liquid?
12. A liquid with a specific gravity is less than 1 is ____ than water.
    a. lighter
    b. heavier
13. A temperature rise ____ the density of a gas.
    a. increases
    b. decreases
    c. has no affect on
14. The pressure exerted by a gas in an open container will ____ when its temperature rises.
    a. increase
    b. decrease
    c. stay the same
15. A condition where air is forced into a confined container is called ____.
    a. compression
    b. a vacuum
16. As air is removed from a confined container, the inside pressure __________ (increases, decreases).
17. List the reference points of the following pressure scales:
    __________ Gauge
    __________ Absolute
18. Convert an absolute pressure of 64.7 psia to gauge pressure.
19. At sea level, 14.7 psi of atmospheric pressure will support __________ inches of mercury in a glass tube.
20. Of the two columns in a U-shaped manometer, the one with the lowest level of liquid has the ____ pressure applied to it.
    a. lowest
    b. highest
21. What is the gauge pressure measured by a manometer using mercury if the reference column rises 1.5 inches and the pressure column lowers 1.5 inches?
22. What are the inches in H_2O value if a measurement of 6.8 psi is made?
23. A (lower, higher) __________ pressure detected by a Bourdon tube causes the coil to unwind.
24. Describe the purpose of variable resistors R_1 and R_2 in Figure 4-18.
25. Identify the output terminals of the transverse voltage strain gauge in Figure 4-19.
26. What is the power source of a hydraulic system?
27. What is the power source of a pneumatic system?
28. Air is pumped __________ (out of, into) the storage tank of a vacuum system.
29. What is the power source of a static pressure system?
30. What is the energy source of a steam pressure system?

CHAPTER

5

Temperature Control

OBJECTIVES

At the conclusion of this chapter, you should be able to:

- Define thermal energy.
- Explain the law of thermodynamics.
- List the three category types of heat transfer.
- Describe the operation of the following heat sources of thermal energy:

Blast Furnace	Arc
Electronic Heat Element	Resistance Induction

- Describe the operation of a cold thermal energy source (refrigeration system).
- Define temperature.
- Identify the Fahrenheit and Celsius scales and convert specific values from one scale to another.
- List several reasons for monitoring temperatures in process control applications.
- Define BTUs.
- Describe the principle of operation of the following temperature indicator devices:

Crayons	Pellets	Liquid Crystals
Paints	Labels	

- Describe the principle of operation for the following mechanical temperature measurement instruments:

Bulb Thermometer	Bimetallic Thermometer

- Describe the principle of operation for the following electrical measurement instruments:

Thermocouple	Thermistor
Resistance Temperature Detectors (RTDs)	Radiation Thermometry

INTRODUCTION

Many products manufactured today are the result of a process that involves temperature control. High temperatures may be used to soften metals before they are formed into a desired shape or to melt plastic in an injection molding machine. Low temperatures are necessary to preserve dairy products in the food processing industry. Manufacturing processes that are affected by temperature are referred to as *thermal systems*.

5-1 Fundamentals of Temperature

Scientific theory states that molecules of matter are in continuous motion due to kinetic energy. Molecular movement creates heat known as **thermal energy.** Thermal energy is measured in temperature. Suppose one end of an object is exposed to the elevated temperature of a flame. The object's molecules in contact with the flame will move faster and create heat. The heat transfers from the heated area to the cooler areas throughout the object. Thermal equilibrium is attained when the object's temperature reaches the elevated temperature. Thermal movement from hot to cold is called **thermodynamics.** Each type of matter has an ignition point, at which a chemical reaction (called a fire) causes it to burn. When a cold theoretical temperature (called absolute zero) is reached, the molecular movement stops and no heat is generated.

5-2 Thermal Control Systems

Thermal systems supply thermal energy from a source, provide a path for its distribution, and convert the energy into some kind of work.

Temperature control is maintained at a desired level either manually by a human operator or automatically. In an automated system, the thermal energy is regulated by a controller. The control function is accomplished by altering the flow of thermal energy from the energy source to the load device that performs the work. There are two types of control methods: On-Off and proportional. The On-Off controller directs energy from the source when the load device's temperature falls below a certain level and stops the flow of energy to the load device when the desired temperature has been reached. An example is a home heating system. The proportional control method provides only the amount of energy from the source that the load needs. Both types of controllers respond to the temperature difference between the setpoint and the measured value.

5-3 Thermodynamic Transfer

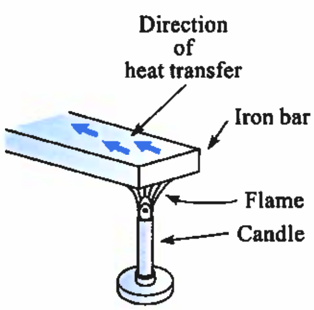


FIGURE 5-1 The heat conduction principle

The transmission path of thermodynamic transfer can be through materials that are solids, liquids, gases, or a vacuum. The process by which heat is transferred by a solid is called **conduction.** Figure 5-1 shows an example of conduction. One end of a metal bar is placed over an open flame heat source. The molecules over the flame move more rapidly. The increased molecular velocity causes collisions with neighboring molecules, which in turn causes them to move faster. This action continues until the molecular movement throughout the bar has increased. The best solid material thermal conductors are metals. Some types of nonmetal solids are insulators.

Since most fluids are poor conductors of heat, very little thermodynamic transfer takes place through the process of conductance. The transfer of heat through fluids such as liquids and gases takes place through a process called **convection.** When a container of fluid is placed above a heat source, the bottom layer begins to expand. The warmer fluid becomes less dense than the fluid above it and therefore moves to the top of the container. The cooler fluid—which is heavier—goes to the bottom. In this manner, heat is transferred through the constant movement of circulating currents, as shown in Figure 5-2.

Thermal energy can also be transferred through a vacuum by a process called **radiation.** In theory, bundles of energy are radiated away from atoms in the heat source as wavelike patterns that travel at the speed of light. Radiated heat transfer also takes place through air. A prime example is the sun, which radiates heat through the vacuum of space and through the earth's atmosphere, as shown in Figure 5-3.

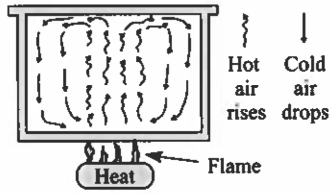


FIGURE 5-2 The heat convection principle

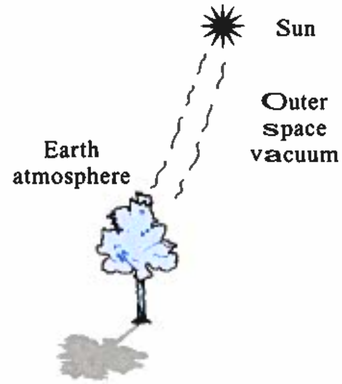


FIGURE 5-3 The heat radiation principle

5-4 Thermal Energy Source

Thermal energy is primarily produced by a change in the state of matter. For example, when a fuel such as coal is combined with oxygen at a high enough temperature, it ignites into a chemical reaction called a fire. As it burns, it changes into another material called carbon dioxide. The combining of carbon and oxygen causes heat to be released. Thermal energy is also released by matter changing form. For example, when a liquid changes to a gas, evaporation occurs and the gas becomes colder than when it was in liquid form. When a gas is converted to a liquid by being compressed, the liquid becomes warmer than when it was a gas.

This section describes several common types of thermal energy sources used in industrial applications. This study will include hot and cold temperature systems.

Industrial Furnaces

The most common heat source for many manufacturing operations is the furnace. It is usually built of metal and brick, because these materials will withstand high temperatures. The shapes of industrial furnaces vary, but all of them confine the heat generated inside their chambers. Industrial furnaces provide high temperatures to harden metals by a process called *heat treating*. These furnaces are also designed to melt materials, such as iron in a foundry. Industrial furnaces provide heat to heat-treat materials, whether by cooking food or hardening metals. They are also designed to melt materials, such as butter to pour over popcorn or iron for foundry use.

Combustion Furnace

The most common heat source in industry is the combustion furnace. It usually combines fossil fuel and oxygen at a high temperature to produce heat. Smaller furnaces are ideal for heat treating machined gears to make their metal harder. For a higher temperature, the blast furnace is used. The high temperature is achieved by forcing large amounts of air into the burning chamber. The blast furnace is used to manufacture products such as glass, steel, and cement.

Systems that use steam from boilers to develop pressure are also used to supply heat. Fossil fuels are often burned to convert the water into steam. Boiler systems provide very safe and accurate temperature control.

Electric Furnaces

Furnaces can also be heated by electricity. There are three types of electrical heating systems commonly used in industry: arc, resistance, and induction.

Arc Furnaces The arc furnace is used in the process of smelting steel in a foundry, as illustrated in Figure 5-4. The voltage is applied by connecting one power supply terminal to an electrode and the other terminal to a crucible made of a conductive material such as graphite. When the voltage is applied, the electrode is in contact with the metal to be melted. Current begins to flow and an arc is formed at ignition. The electrode is placed a small distance from the metal. To keep the arc burning, the heat from the arc melts the metal to a liquid state.

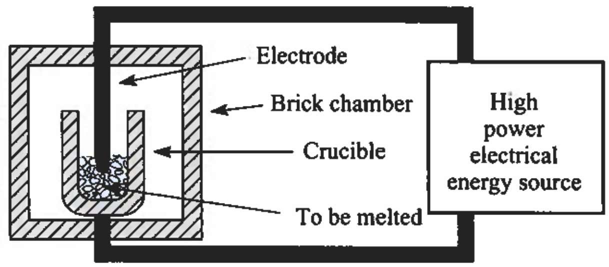


FIGURE 5-4 An arc furnace

Resistance Furnaces Resistance furnaces use heating elements similar to a kitchen oven. The element has large resistance, which produces heat when current flows through. The elements are placed inside an insulated chamber where all surfaces of the object or material being heated are uniformly exposed to heat. This type of furnace is used in batch processing for heat treating purposes. It is also used in burn-in tests where integrated circuits are exposed to high temperatures for several hours to test their reliability.

Induction Furnaces Induction furnaces are also used to melt metals. Again, insulated chambers are used to hold the work to be heated. Coils of wire are wrapped around the chamber and AC current is applied. A magnetic field constantly expands and contracts around the coils. As the field sweeps across the iron, an eddy current is induced, which causes molecules to move around. As the molecules shift positions, an intense heat results in a very short period of time.

Cooling Systems

The most common type of refrigeration system is the household refrigerator. Refrigeration systems are used in the food processing industry to keep perishable products at low temperatures. They are also used in other manufacturing fields, such as chemical plants, to cool liquids to required levels before they are used in a blending operation.

The principles of refrigeration can best be explained by describing an old icebox used in the home 75 years ago. This unit was a wooden box insulated with cork or sawdust. Chunks of ice were placed in an upper compartment and the perishables underneath. The cooling process works on the principle that heat energy from warmer objects transfers to cooler objects nearby. In the icebox, heat from the food moves to the ice. The transfer of heat continues until everything inside reaches the same temperature.

The modern refrigerator operates on the principle that evaporation absorbs heat energy, and condensation gives off heat energy. By controlling these two reactions mechanically, refrigerators are able to perform the same functions as the iceboxes they replaced. Freon is evaporated and condensed in the refrigerator system. This refrigerant is used because it evaporates quickly when exposed to room temperature.

The refrigeration system is illustrated in Figure 5-5(a). Its components include a compressor, a condenser, a capillary tube, an evaporator, and two fans. The compressor is the device that pumps the refrigerant throughout the system. The freon in liquid form enters the capillary tube, shown in Figure 5-5(b), through a port with a small diameter. As the freon leaves the small capillary tube, it enters a larger-sized tube called the evaporator. The sudden increase in tube size creates an abrupt drop in pressure which causes the liquid freon to evaporate into a gas and cool down. As the cold gas flows through the evaporation coils, it absorbs heat from the contents in the refrigerator compartment. The heat energy transfer is assisted by an evaporator fan. As the compressor runs, it creates a suction and draws the warmer gas into its inlet port. Inside the compressor, the gas is compressed into a liquid. The conversion from a gas to a liquid state also generates heat. As the liquid freon is pumped from the compressor outlet port, it flows through a series of folded tubes called a condenser. The condenser is a radiator that releases heat from the warm freon flowing through the tubes to the outside. The heat transfer is assisted by the fan that blows air over the condenser coils.

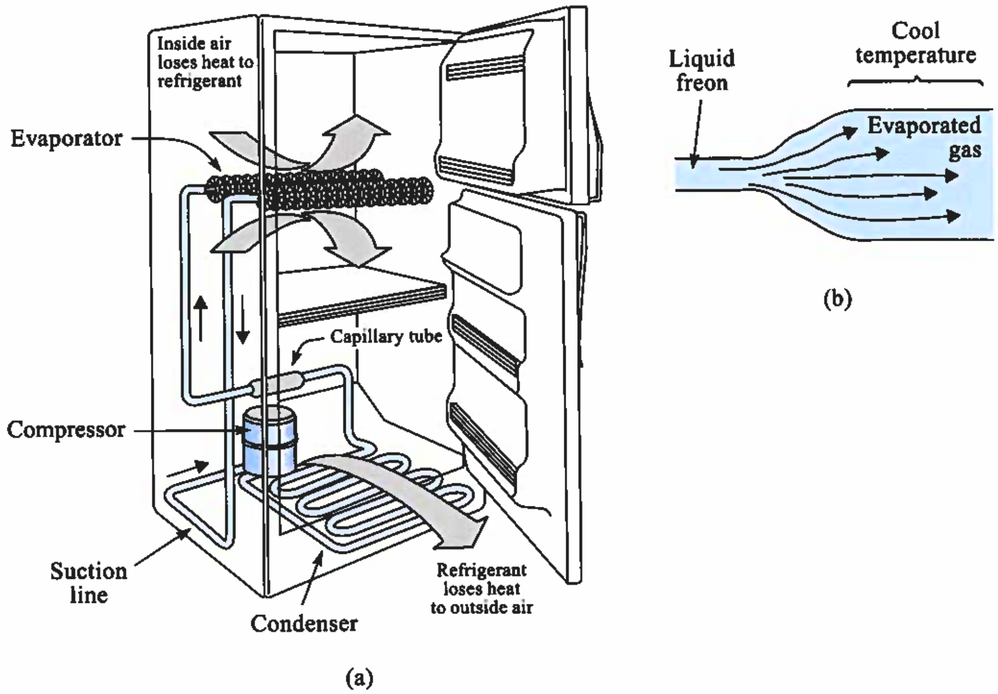


FIGURE 5-5 A refrigeration system

If the refrigerator compressor were to continue running, the food would freeze. To keep the temperature within a desired range, a thermostat is used to turn the compressor on and off. When the temperature rises to a certain level, the thermostat activates a switch to turn the compressor on. The thermostat turns the compressor off when the temperature reaches the desired lower level.

5-5 Temperature Measurements

There are many manufacturing applications that require precise measurements of temperature. This function is performed by instruments placed at the energy source, the controller, or the system load. These devices provide visual indication, or a mechanical or electrical feedback signal in a closed-loop system for automated control.

The components of nonelectrical instruments are physically altered as they respond to temperature changes. Electronic instruments are designed to produce electronic signals proportional to variations of temperature.

To provide good control of industrial processes, accurate measurements of temperature are essential. There are several reasons to monitor temperatures in process control applications:

1. Precise temperature conditions are required when combining two chemicals to form a compound.
2. Over-temperature conditions that could cause excessive pressure must be avoided in an enclosed system to prevent ruptures or explosions.

3. Temperatures must be kept below freezing to prevent stored food from spoilage.
4. By ensuring that the heating system is consuming energy efficiently, fuel costs can be minimized and environmental conservation concerns can be met.

Temperature Scales

Scientists have developed scales to indicate temperature, such as Fahrenheit, Celsius, Kelvin, and Rankine. Each type of temperature scale has fixed reference points at which water boils or freezes, and numerical values that fall between those points. Most industrial applications use the Fahrenheit and Celsius scales for temperature measurements. The other two scales are most frequently found in research and engineering applications.

Fahrenheit Scale The first temperature scale was developed in the early 1700s by Gabriel Fahrenheit, a Dutch instrument maker. Though modified from its original form, it is widely used, especially in the United States. At sea level, the freezing point of water is 32 degrees, and the boiling point is 212 degrees.

Celsius Scale The next temperature scale developed was designed by Anders Celsius. A similar scale was designed by Christin of Lyons who named it the *Centigrade* scale. Both designs use a numerical value of 100 degrees for the boiling point of water and 0 degree for the freezing point of water at sea level. This scale is referred to as either the Centigrade or Celsius scale.

Each of these temperature scales can be converted to the other by the following equations:

$$C^\circ = 5/9(F^\circ - 32)$$
$$F^\circ = (9/5 \times C^\circ) + 32$$

EXAMPLE 5-1 Convert 77 degrees Fahrenheit into its equivalent temperature value in Celsius.

Solution

$$\begin{aligned} C &= 5/9\ (F^\circ - 32) \\ &= 5/9\ (77 - 32) \\ &= 5/9\ (45) \\ &= 25^\circ \end{aligned}$$

EXAMPLE 5-2 Convert 10 degrees Celsius into its equivalent temperature value in Fahrenheit.

Solution

$$\begin{aligned} F &= (9/5 \times C^\circ) + 32 \\ &= (9/5 \times 10^\circ) + 32 \\ &= (18) + 32 \\ &= 50^\circ \end{aligned}$$

Heat is thermal energy that has the ability to perform work. Thermal energy is rated in work units called calories and BTUs (British Thermal Units). A *calorie* is the heat required to raise the temperature of 1 gram of water 1 degrees Celsius. A BTU is the amount of heat required to raise the temperature of 1 pound of water 1 degrees Fahrenheit.

EXAMPLE 5-3

Calculate how many calories are required to raise the temperature of 5 grams of water 2 degrees Celsius.

Solution

$$\begin{aligned} \text{Calories} &= (H_2O)\text{ Weight} \times \text{Degrees (Celsius)} \\ &= 5\text{ grams} \times 2^\circ C \\ &= 10 \end{aligned}$$

EXAMPLE 5-4

Calculate how many BTUs are required to raise the temperature of 10 pounds of water 5 degrees Fahrenheit.

Solution

$$\begin{aligned} \text{BTU} &= \text{Weight } (H_2O) \times \text{Degrees (Fahrenheit)} \\ &= 10\text{ lbs} \times 5^\circ F \\ &= 50\text{ BTUs} \end{aligned}$$

Differential Temperature

In some applications the difference between two temperature measurements is used. Comparing one temperature to another is called *differential temperature.* An application of differential temperature measurements is the system in Figure 5-6 which monitors the efficiency of a heat exchanger used to heat water flowing through a pipe. Sensor T_1 measures the temperature of the water before it enters the exchanger, and sensor T_2 measures the hotter water that exits the exchanger. Signals from both sensors are sent to a differential temperature transmitter that measures the difference between T_1 and T_2 (ΔT). A flowmeter is placed in the piping system to measure the flow rate (Q) of the water.

Signals from the flowmeter (Q) and the differential transmitter (ΔT) are sent to a controller. The controller is programmed to multiply the gain in temperature ($T_2 - T_1$) by flow rate to indicate the relative efficiency of the system. The formula to determine relative efficiency, as a percentage is,

$$\text{Relative Efficiency} = \frac{Q\Delta T}{C} \times 100$$

An example of the heat exchange system in Figure 5-6 operating at 100 percent would be as follows:

> When the flow rate of the water is 20 cubic feet per minute, it rises from 180 to 200 degrees Fahrenheit as it passes through the heat exchanger. Suppose the flow rate doubles to 40 cubic feet per minute. Since the speed of the water doubles, it is inside the exchanger for half the time and therefore rises 10 instead of 20 degrees.

No heat exchanger system can operate at 100 percent efficiency. There is an acceptable limit as to how much the efficiency can deviate, usually established during its design phase. If this limit is exceeded, the system requires attention as to what is causing it to stray.

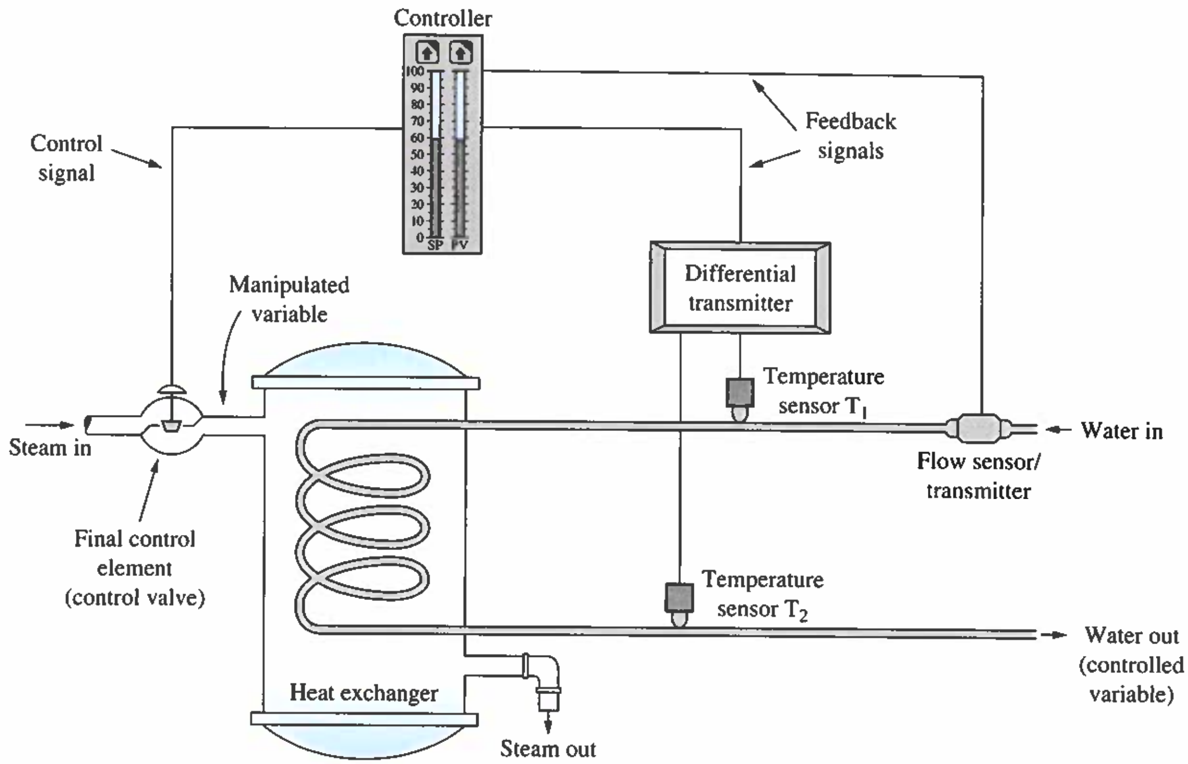


FIGURE 5-6 Differential temperature measurement

EXAMPLE 5-5 If the actual temperature of the water rises from 180 to 192 degrees Fahrenheit as 30 cubic feet per minute passes through the exchanger in the example given above, what is the relative efficiency?

Solution

Step 1:

$$C = (Q\Delta T)\text{ ideal} = (20\ \text{ft}^3/\text{min})(20°\text{F}) = (40\ \text{ft}^3/\text{min})(10°\text{F}) = 400°\text{F}\cdot\text{ft}^3/\text{min}$$

Step 2:

$$(Q\text{ actual})\ (\Delta T\text{ actual}) = (30\ \text{ft}^3/\text{min})\ (12°\text{F}) = 360°\text{F}\cdot\text{ft}^3/\text{min}$$

Step 3:

$$\text{Relative Efficiency} = \frac{(Q\text{ actual})\ (\Delta T\text{ actual})}{C} \times 100\%$$

$$= \frac{360}{400} \times 100\% = 90\%$$

5-6 Temperature Indicating Devices

A number of industrial situations require an indication that a predetermined temperature has or has not been reached. For such situations, several different types of heat-sensitive materials have been developed solely for indication and monitoring purposes. These temperature-sensing materials are made of crystalline solids.

The materials operate on the principle that when heating occurs, a temperature will be reached at which the solids change color or melt to a liquid. The change provides a visual indication that the necessary temperature has been reached. Temperature indicators are available in the form of crayons, paints, pellets, and labels. They are applied directly to or placed near the object being monitored.

These heat-sensitive indicators are accurate to within 1 percent and respond within a few tenths of a second. Because they are inexpensive, they are preferred in situations where they will burn, such as a heat zone of an industrial oven, ceramic kiln, or for products that travel on conveyors through a furnace.

Crayons

The crayon is available in stick form. They are manufactured in 100 different temperature ratings, ranging from 100 to 2500 degrees Fahrenheit. The workpiece is marked with the crayon. When the predetermined temperature is reached, the crayon liquefies, notifying the observer that the workpiece has reached that temperature.

Paints

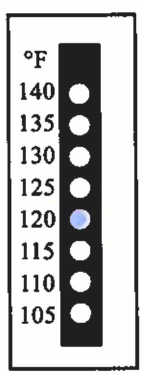
A paint indicator is a lacquer that dries to a dull finish. When the predetermined temperature has been reached, its finish turns glossy and transparent. Paints are often used on very smooth surfaces to which crayons cannot stick.

Pellets

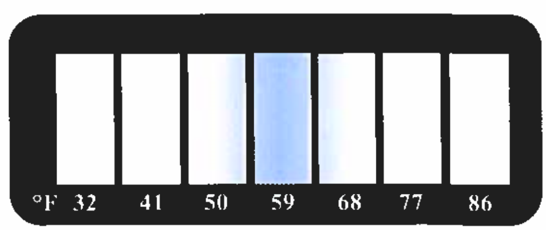
The pellet works on the same principle as crayons and paints. Pellets are used in applications where extended heating periods are involved or when oxidation of a workpiece might obscure a crayon or paint marking. Because pellets are bulkier than crayons or paint, they are used when visual indication must be observed at a distance.

Labels

The label shown in Figure 5-7(a) has one or more heat sensitive indicators sealed under transparent heat-resistant windows. Each indicator changes color at a specific temperature. Labels are available in nonreversible styles to show peak temperature and reversible styles to indicate changing temperatures.



(a)



(b)

FIGURE 5-7 Temperature indicators made of crystalline solids

Liquid Crystal Indicator

The liquid crystal indicator shown in Figure 5-7(b) uses crystal material sandwiched between an adhesive backing and transparent film. The crystals change to different colors indicating different temperatures. Temperature is read by observing which patch has changed to a specific color.

Liquid Filled Thermometers

Glass Thermometer

The thermometer shown in Figure 5-8 is a closed tube with a reservoir at the bottom and is partially filled with a liquid. It operates on the principle that materials expand when exposed to heat. For example, when the temperature increases, the liquid expands and rises in the glass tube. The temperature reading is taken by comparing the top level of liquid to the corresponding number on an adjacent temperature scale. Glass thermometers are very accurate and reliable. However, for industrial applications, they are too fragile and are not adaptable to recording or automatic control situations.

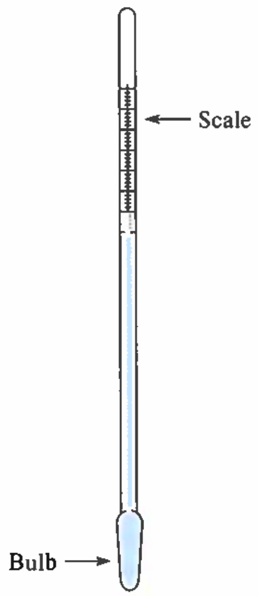


FIGURE 5-8 Liquid glass thermometer

Filled-Bulb Thermometer

By modifying the thermometer principle, filled-bulb thermometers have been developed that are more durable than glass thermometers. They are also capable of providing feedback action for control purposes and recording temperature variations over a period of time. The filled-bulb thermometer is shown in Figure 5-9. The bulb is the primary sensor that detects changes in thermal energy. It also serves as the reservoir for the liquid or gas. For greater durability, the bulb is made of metal. The capillary is a tube that connects the bulb to the pressure–volume element. The element is a spiral tube that bends due to pressure changes in the filled-bulb thermometer system. The linkage is physically connected to the pressure–volume element. As the coil expands or contracts, it causes the linkage to move a needle over a temperature scale. The linkage may be attached to a pen which draws a line on a circulating chart with a temperature scale. The linkage can also be connected to an electrical component such as a potentiometer to provide feedback signals for a closed-loop system.

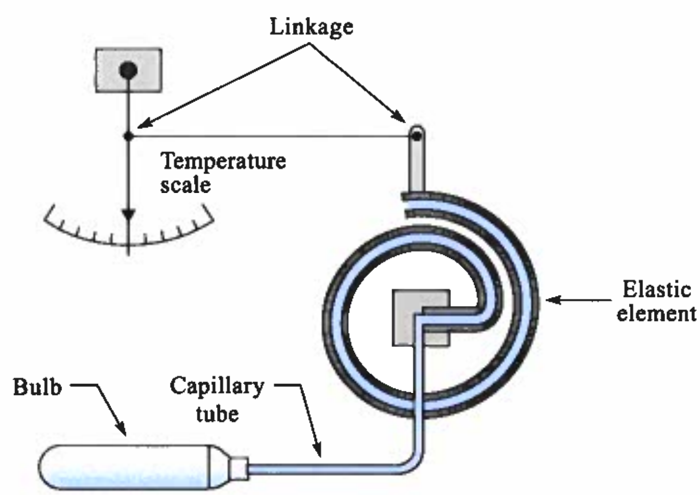


FIGURE 5-9 Filled-bulb thermometer

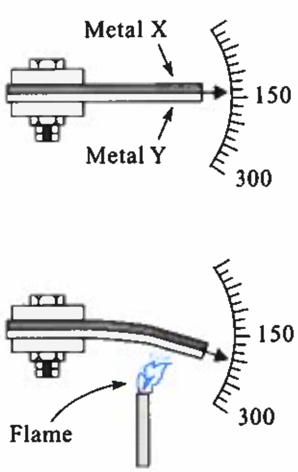


FIGURE 5-10 Bimetallic thermometer

Bimetallic Thermometer

The bimetallic thermometer, as shown in Figure 5-10, is made of two dissimilar metal strips that are physically bonded together. Each metal has a different expansion ratio. As temperature changes, the strip will bend in the direction of the metal with the lower expansion rate. The deflection of the strip settles at a position that represents the temperature value. The strip can be attached to an indicator scale, recording chart, or linkage used to provide a feedback signal for a closed-loop system.

5-7 Electronic Sensors

There are two general types of electrical sensors used to measure temperatures: thermoresistive and thermoelectric. Thermoresistive sensors—thermistors and resistance temperature detectors—change resistance as the ambient temperature varies. Thermoelectric sensors—thermocouples—produce a voltage proportional to the surrounding temperature. Table 5-1 (page 111) compares these temperature sensors.

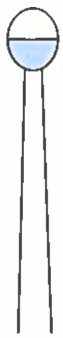


FIGURE 5-11 A thermistor body in the bead form

Thermistor

One type of temperature sensor is the **thermistor.** Its name is a derivation of the term *thermal resistor.* The thermistor exhibits a large change in electrical resistance when subjected to a relatively small change in temperature. Temperature variations can be caused either by a change in the ambient temperature external to the thermistor or, internally, by a change in the current through the thermistor.

Thermistors are constructed by using a paste-like metal oxide mixture to form certain shapes, such as a bead (shown in Figure 5-11), disks, or rods. A set of two conducting wires is inserted into the paste. The mixture is hardened when exposed to heat by a process called *sintering.* The type of oxides, the proportions used, and the physical size of the thermistor determine the desired temperature and resistance ranges for the device.

Oxidized metals have characteristics similar to those of semiconductor materials. At lower temperatures, the valence electrons in the outer shell are strongly bound to each atom and function as good insulators. As the temperature rises, the thermal activity of the atom increases. Valence electrons gain sufficient energy to break away from the atoms. The electrons become free to take part in current that flows through the material. As temperature increases, more electrons become available and the resistance of the material decreases. This characteristic of the thermistor is called a **negative temperature coefficient.** The letters *NTC* are placed inside the thermistor symbol to indicate this characteristic.

How Thermistors Are Used

There are many circuits in which thermistors are used. A few of the more common applications are discussed below.

Temperature Measurement The primary function of the thermistor is to exhibit a change in resistance as a function of temperature. In measurement instruments, this resistance is often converted into a voltage reading by using a voltage divider as part of a voltage divider network. The diagram in Figure 5-12 shows that the output is taken across the fixed resistor.

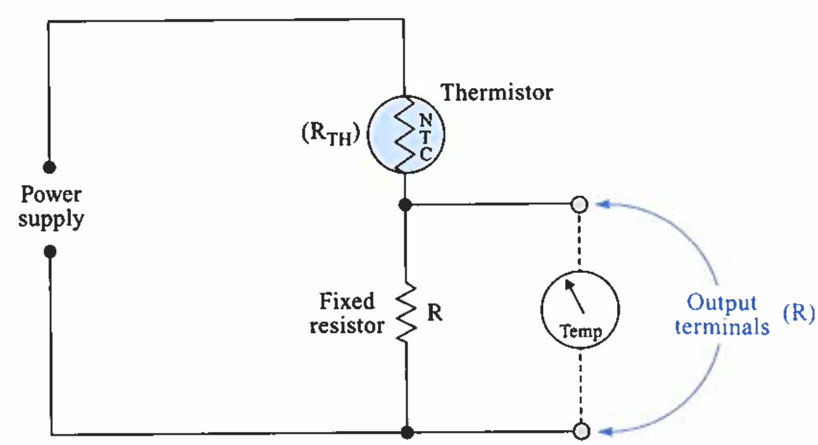


FIGURE 5-12 Temperature measuring voltage divider

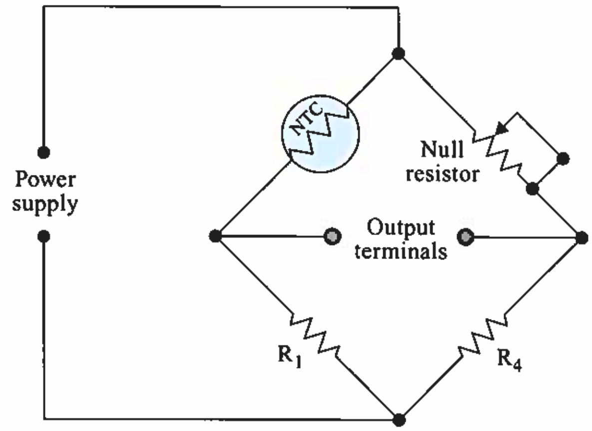


FIGURE 5-13 Temperature measuring bridge network

As temperature increases, the thermistor resistance decreases. Therefore the voltage across the resistor increases. If a meter with a scale that reads temperature is placed across the output terminals, its reading will increase as temperature increases. The output voltage as a function of temperature can be expressed by the following formula:

$$V_o = V_s \times \frac{R}{R + R_{TH}}$$

The resistance of variable R is the parallel equivalent resistance of the load connected to the output terminals and the fixed resistor.

When measuring ambient temperature, the circuit should be designed to keep the current through the thermistor low. If the current is too high, the thermistor will become much warmer than the surrounding temperature due to self-heating.

Another temperature measuring circuit is shown in Figure 5-13. R_1 and R_4 are precision resistors. Their values are selected to match the particular thermistor used. The variable null resistor is adjusted to balance the bridge so that the output is zero volts. Based on bridge theory, a voltage at the bridge output will develop as the thermistor resistance changes.

Temperature Compensation The resistance of metals, such as copper, changes when subjected to temperature variations. These metals have a positive temperature coefficient. Such changes in resistance can affect the accuracy of sensitive measuring instruments, such as meters. To offset the temperature-resistance changes, the negative coefficient properties of a thermistor can be used.

Figure 5-14 shows a thermistor used to compensate for the resistance change of the coil. The resistance of the thermistor changes significantly more than that of the coil over the same temperature range. By placing a shunt resistor of the proper value across the thermistor, the equivalent resistance of the parallel network provides a negative coefficient nearly equal to the positive coefficient of the copper. The network adds less than 15 percent to the total impedance of the circuit.

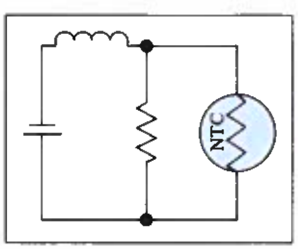
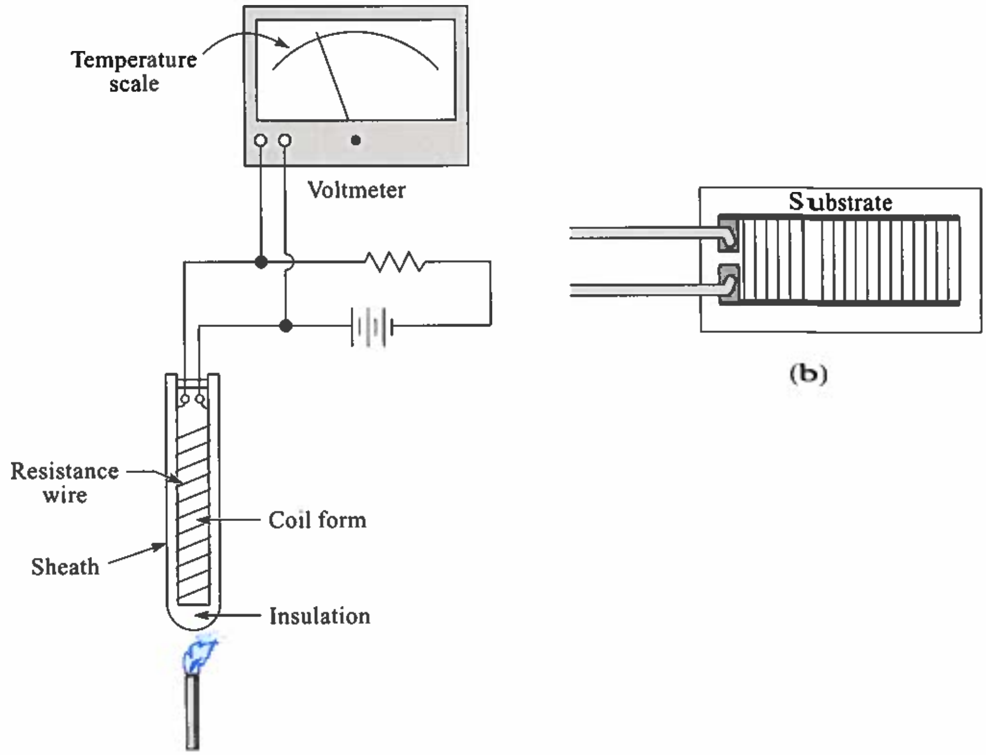


FIGURE 5-14 A thermistor used to compensate for temperature variations

Surge Suppression Cathode ray tubes in televisions and oscilloscopes use heater coils called *filaments*. The filaments emit the electrons for the beam that scans the display screen. When power is initially applied to the cold heater, its resistance is low. To prevent the filament from being damaged by a high surge of current, a thermistor is placed in series. The high starting resistance of the thermistor limits the current to a safe value. As current begins to flow, the thermistor self-heats and its resistance is reduced. At the same time, the temperature and resistance of the filament increase to normal operating values.



(a) (b)

FIGURE 5-15 Types of RTDs

Resistance Temperature Detectors

The resistance of electrical conductivity metals varies directly with temperature. Therefore, metals have a **positive temperature coefficient (PTC).** This means that as their temperature increases, their resistance increases.

Some types of metals are used in a temperature sensing device called a **resistance temperature detector (RTD).** Two metals commonly used in RTDs are nickel and platinum. Nickel is the most sensitive metal because it provides the greatest change of resistance for a given unit of temperature change. Platinum is used in applications that require a resistance change over wider temperature ranges.

RTDs are constructed by placing a coil of fine wire inside a housing, shown in Figure 5-15(a), to protect it from outside contamination. By connecting an RTD in series with a resistor, a constant voltage source, and a voltmeter, changes in temperature at the RTD can be determined by measuring a change in the voltage. The voltmeter uses a temperature scale instead of a voltage scale. RTDs are also constructed by placing a thin film on a ceramic substrate, as shown in Figure 5-15(b). A laser beam is used to burn away the film until its resistance is at a prescribed value. The complete assembly is then sealed in a protective enclosure.

RTD Applications

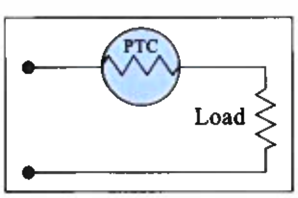


FIGURE 5-16 An RTD used as an overcurrent protection device

Overcurrent Protection The positive temperature coefficient characteristics of an RTD make it an ideal overcurrent protection device. Figure 5-16 shows an RTD connected in series with a load. During normal operating conditions, the RTD resistance is low. Therefore its effect on current flow is minimal. When a short circuit or an overcurrent condition occurs, the RTD resistance goes high and limits the current to a low level.

Motor Starting A single-phase AC motor has a start winding and a run winding that are connected in parallel branches. After the motor is running, the start winding should not be used. At full speed, a centrifugal switch opens the branch with the start coil.

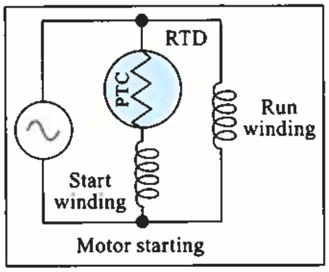


FIGURE 5-17 An RTD used to eliminate the start winding after the motor reaches full speed

Figure 5-17 shows how an RTD replaces the centrifugal switch. At ambient temperature, the initial resistance of the RTD is about 100 ohms. It allows sufficient current to flow through the start winding when the motor starts. By the time the motor is at full speed, the RTD is heated and its resistance is high. This reduces the current flow through the start winding to near zero.

RTDs are generally standardized to provide easy interchangeability and predictable performance. These standards pertain to the following ratings.

- *RTD resistance at freezing,* called *ice point (0 degree).* Common resistance values are 100 Ω, 50 Ω, and 200 Ω, although others are also used.
- *RTD Alpha (α) value.* This value indicates the average slope of the RTD resistance curve from 0 to 100 degrees Celsius. The slope pertains to the amount the resistance of the RTD changes for every 1 degrees Celsius change in temperature to which it is exposed. The α factor is represented by the following formula:

$$\alpha = \frac{R_{100} - R_0}{100(R_0)}$$

Where,

R_{100} = resistance at 100 degrees Celsius
R_0 = resistance at 0 degree Celsius

EXAMPLE 5-6

What is the alpha value for an RTD that has 100 ohms of resistance at freezing, and 138.5 ohms at 100 degrees Celsius?

Solution

$$\alpha = \frac{R_{100} - R_0}{100(R_0)} = \frac{138.5 - 100}{100 \times 100} = 0.00385$$

The alpha of 0.00385 is actually a commonly accepted α value of RTDs used in process instrumentation.

Thermocouple

Figure 5-18(a) shows dissimilar metal wires joined at both ends. At each junction where the wires are in contact, they are exposed to heat from the surrounding ambient temperature. This causes a small number of electrons to drift from metal B and accumulate in metal A. The slight accumulation of electrons causes a small EMF to develop between the metals. Because the junctions are subjected to the same temperature, the same amount of voltage develops across them.

Suppose that heat is applied to the junction on the left. A larger voltage potential will develop across it than across the one on the right. An equivalent circuit in Figure 5-18(b) is used to illustrate the result. Each battery represents the two junctions. The difference in voltage between the junctions forms a net voltage of .05 volts. This causes electron current to flow in the closed circuit formed by the wires. This phenomenon is called the Seebeck effect, named after its inventor, the German physicist Thomas Seebeck.

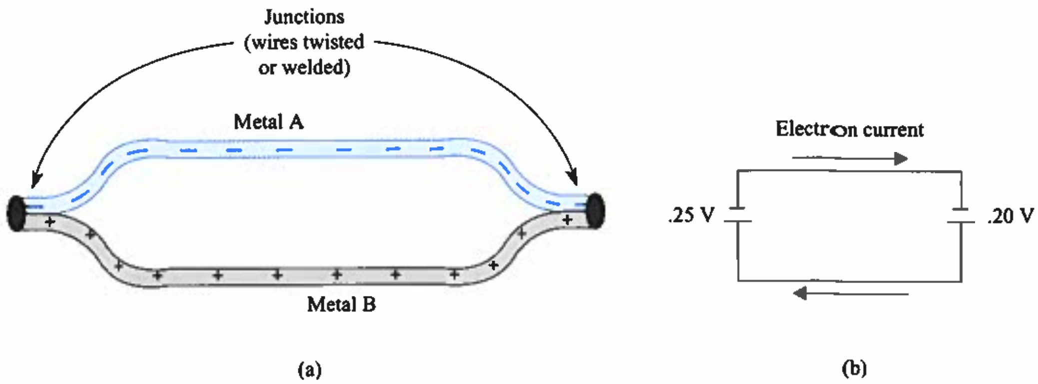


FIGURE 5-18 Thermocouple

The device shown in Figure 5-18 is called a **thermocouple,** which is a transducer that converts heat into voltage. The amount of voltage developed by a thermocouple junction is affected by the amount of heat applied to it. The higher the temperature, the greater the voltage produced. The voltage-temperature characteristics of a thermocouple are nonlinear over its rated temperature range. Equal changes of temperature at the low end of its rated working temperature range produce different output voltages than do equal changes of temperature at its high end. An example of voltage changes at two temperature ranges for a J thermocouple, which is one type commonly used, is as follows:

	Temperature	Output (mV_{DC})	
Lower Temperature Range	−200°C	−7.890	mV = −0.002/°C
	−199°C	−7.868	
Higher Temperature Range	+1190°C	68.980	mV = +0.057/°C
	+1191°C	68.037	

Instrumentation utilizing thermocouples must linearize this nonlinear output voltage in order to properly display the correct temperature. In modern digital instrumentation, this is achieved by a software look-up table stored in memory.

When utilizing a very narrow temperature range within a thermocouple's working temperature specification, the voltage-temperature characteristics can approach a degree of linearity. The metals used determine the polarity and voltage range of the junction. The voltage-temperature characteristics are different for each type of thermocouple, and are shown by the graph in Figure 5-23. Each one of these thermocouple types uses a distinct pair of metals.

Figure 5-19 shows the loop opened at the top wire. The junction exposed to the temperature to be measured is called the *hot junction*. The other junction in the loop is called the

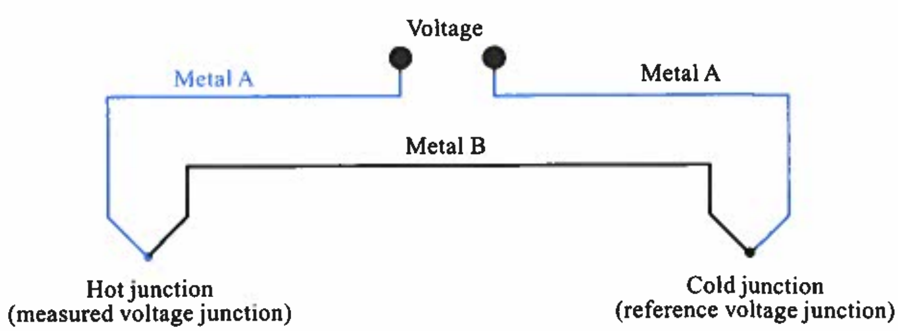


FIGURE 5-19 A thermocouple with hot and cold junctions

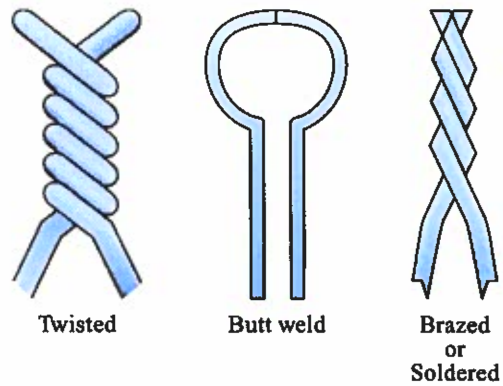


FIGURE 5-20 Types of thermocouple junctions

cold junction. The output voltage that appears across the opening will be proportional to the temperature difference between the junctions. If the temperature of one of the junctions is known, the voltage across the opening can be used to calculate the temperature of the other junction. The cold junction is considered the reference junction in a thermocouple because the temperature applied to it is a known value. A temperature display instrument is usually connected across the open leads. The value it displays is determined by the voltage developed across the terminals. The reference junction is typically exposed to a temperature of 0 degree Celsius (32 degrees Fahrenheit), because it provides a high degree of accuracy. Also, all thermocouple reference tables are designed with their cold junction at 0 degree Celsius.

Several different methods, used to join the thermocouple wires at the junction, include twisting, soldering, brazing, and welding, as shown in Figure 5-20.

An automatic thermocouple network that does not have a 0 degree Celsius cold junction is illustrated in Figure 5-21. It lists the voltages throughout the circuit. Both of the reference

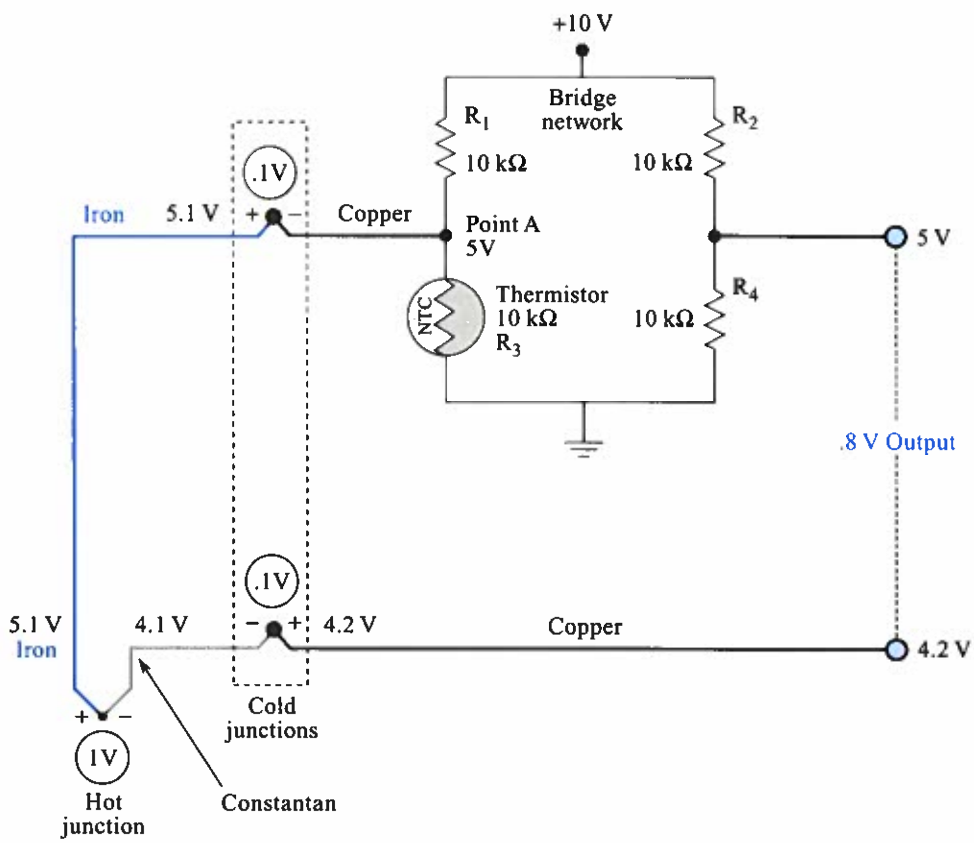


FIGURE 5-21 A thermocouple with a cold junction compensating network

junctions and a resistor bridge network are integrated on a substrate. Therefore they are subjected to the same ambient temperature. One leg of the bridge, R_3, is a thermistor with a negative coefficient. Resistors R_1, R_2, and R_4 are not temperature-sensitive. As the ambient temperature changes, R_3 varies proportionately and unbalances the bridge. The voltage at point A changes the same amount as the two cold junctions, but at the opposite polarity; therefore, both voltages cancel. The only voltage change at the output should be the result of the temperature variance detected at the hot junction.

EXAMPLE 5-7

Refer to Figure 5-21. Make five assumptions:

1. The voltage produced by the measured hot junction is 1 volt as the temperature remains constant.
2. Every 100 degrees Fahrenheit change of ambient themperature causes the thermistor to vary 750 ohms. At +100 degrees Fahrenheit the thermistor resistance is 10 kΩ.
3. Every 100 degrees Fahrenheit change of ambient temperature causes each cold junction to change 0.1 volt.
4. The output of the thermocouple network is 0.8 volts.
5. At +100 degrees Fahrenheit the thermistor resistance is 10 kΩ and each cold junction produces 0.1 volt.

Suppose that the circuit in Figure 5-21 is exposed to an ambient temperature of 100 degrees Fahrenheit. If the ambient temperature increases to 200 degrees Fahrenheit, determine whether the output voltage remains at 0.8 volts.

Solution

Figure 5-22 shows the voltage drop changes, which cause the output voltage drop to remain at 0.8 volts.

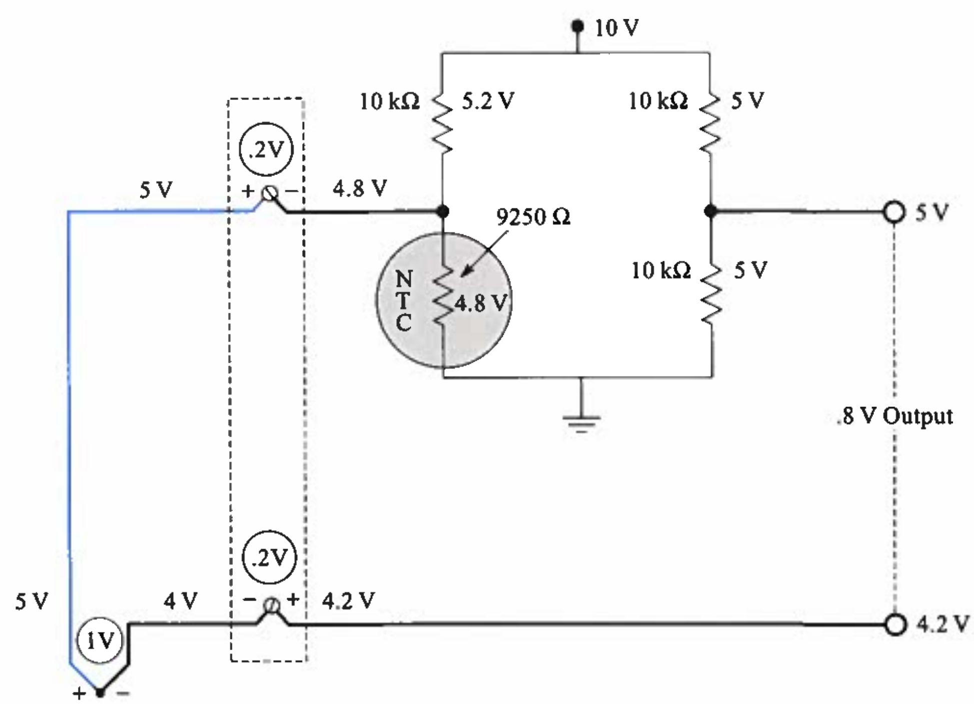


FIGURE 5-22 Example 5-7 solution

Devices that perform automatic compensation for thermocouples are commercially available. They are called *cold junction compensators*. In recent years, computers have also been used to compensate thermocouples.

Some thermocouple metal combinations are in common use throughout industry. They have become standardized by the American National Standards Institute (ANSI), and are identified by letter designations. The more common types include:

1. Iron-Constantan (Type J)
   The iron produces the positive voltage and the constantan produces the negative voltage. The materials are rugged, but the iron wire is susceptible to oxidation, especially at high temperatures. This type is recommended for applications in which reducing atmospheres exist. A reducing atmosphere refers to a reduced level of oxygen in the air. If the air has a high level of oxygen combined with a high temperature, certain metals, especially iron, will become oxidized. Therefore, a thermocouple with iron as one of its metals should only be exposed to a reducing atmosphere, otherwise it will deteriorate at an accelerated rate.
2. Copper-Constantan (Type T)
   The copper produces the positive voltage and the constantan produces the negative voltage. This type is used in low temperature applications. It is capable of resisting moisture and is effective when exposed to reducing atmospheres and oxidizing conditions.
3. Chromel-Alumel (Type K)
   The chromel produces the positive voltage and the alumel produces the negative voltage. This type is recommended for high temperature applications and can be used in high-oxidizing conditions, but not reducing atmospheres.
4. Chromel-Constantan (Type E)
   The chromel produces the positive voltage and the constantan produces the negative voltage. This type has the highest sensitivity because it produces the highest output and can be used over a wide range of temperatures. It should not be used in applications with reducing atmospheres.
5. Platinum-Rhodium, Platinum (Types R, S, and B. The difference depends on the ratios of the two metals.)
   The combined metals produce the positive voltage and the pure platinum produces the negative voltage. These types are recommended for very high temperature measurements in which an oxidizing atmosphere exists and high accuracy is required.

The graph in Figure 5-23 shows the voltages produced at various temperatures by each type of thermocouple.

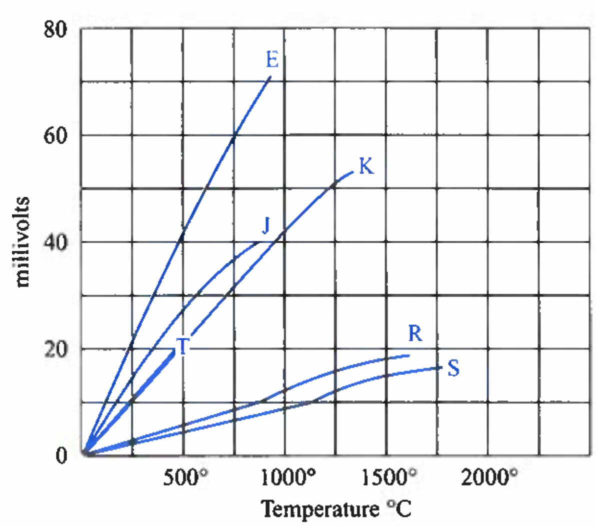


FIGURE 5-23 millivolts produced by thermocouple types at various temperatures

Each type of thermocouple has different characteristics and its accuracy is affected by various conditions. The selection of a thermocouple is based on the following considerations:

1. Temperature range
2. Susceptibility to oxidation
3. Reducing atmosphere
4. Sensitivity
5. Accuracy
6. Cost

Thermocouples are used in industry to measure temperatures of ovens and furnaces, molten plastic vats, and nuclear reactor cores. Thermocouples respond quickly to temperature changes, are rugged, and have a wide temperature range.

Table 5-1 provides a comparison of the three types of temperature sensors.

TABLE 5-1 Temperature Sensor Comparisons

Type/Range	*Advantages*	*Disadvantages*
Thermistor Resistive negative Temperature coefficient −40°F to 300°F	High sensitivity Fast response Low cost Vibration resistant	Narrow temperature span Nonlinear output
RTD Resistive positive Temperature coefficient −150°F to 1400°F	Linear output Large temperature span Large resistance range Interchangeability	Low sensitivity High cost Vibration
Thermocouple Produces voltage or current proportional to temperature −300°F to 4200°F	Linear output within a given temperature range	Least sensitive Requires reference

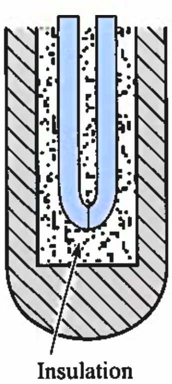


FIGURE 5-24 Protective housing for a thermocouple

FIGURE 5-25 A thermowell

Probe Assemblies

In most applications, temperature-sensing elements should be protected from the environment surrounding the point of measurement. For example, if the sensor is immersed in a liquid, the leads or body may become corroded. Conductive liquids may short the two leads connected to the sensor body, resulting in false readings. The measurement of air temperature can be misread if the humidity is high or if the probe is exposed to wind, which causes a cooling effect.

These false readings can be avoided by enclosing the sensor body within a housing. Protective housings such as the one shown in Figure 5-24 are made of glass, ceramic, epoxy, stainless steel, and other metals.

One type of protective device is the **thermowell.** An RTD or thermocouple is placed inside the device, which is a tube like that shown in Figure 5-25. The tube is usually threaded or welded into a vessel or pipeline. The disadvantage of using the thermowell is that the response time is slower because the thermoconduction through the tube must occur before reaching the sensor body. A spring inside the tube is often used to keep the sensor body firmly in contact with the thermowell tip to improve the conduction and response time.

Radiation Thermometry

Most temperature instruments are invasive devices that make physical contact with the solids, liquids, or gases being measured. They make direct temperature readings as thermal energy is transferred by conduction to the sensing element.

It is also possible to take temperature readings without making physical contact by using a noninvasive device. A method called **radiation thermometry** infers temperature by measuring the thermal energy radiated from the surface of the measured body. The instrument used to make these readings is usually referred to as a radiation pyrometer. The term *pyrometer* is derived from this instrument's ability to measure high temperatures. Instruments of this type are ideally suited for applications where conventional sensors cannot be employed, such as:

1. When objects are moving, such as rolling mills in steel production, paper manufacturing, glass making, and conveyor belts.
2. Where temperatures are extremely hot, such as in furnace atmospheres.
3. Where noncontact measurements are required because of contamination, such as in food and pharmaceutical production.
4. Where corrosive and hazardous conditions exist, such as around high voltage conductors.
5. Where measurements are taken from a distance.

The principle of operation of radiation thermometry is based on the basic law of physics, which states that every object at a temperature above absolute zero radiates electromagnetic energy. The frequency range of the electromagnetic waves includes visible light and lower-frequency infrared light. As the temperature of the object changes, the frequency also changes. For example, if the temperature rises, the frequency increases and the wavelength becomes shorter. This principle is illustrated by observing metal being heated. As it gets hotter, the color changes from red, to yellow, to white. The color change is a result of the frequency increasing.

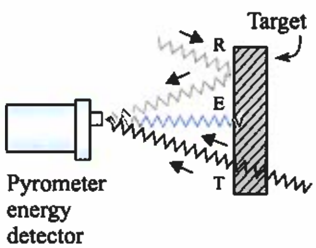


FIGURE 5-26 The target object radiating emitted (E), reflected (R), and transmitted (T) energy to the measurement detector

By focusing the electromagnetic energy waves emitted by the measured object (target) on a detector element, measurements are taken. The signal from the element is electronically processed and the frequency is converted into a proportional temperature readout for display. Radiation thermometry theory is based on the assumption that the total energy emitted by a body is the result of its temperature. An object with this capability is referred to as a *blackbody*. Most objects, however, do not radiate energy from temperature alone. Instead, they also reflect and transmit (as fiber optics do) radiant energy, as shown in Figure 5-26. Therefore, the total radiated energy is the sum of emitted energy (E), reflected energy (R), and transmitted energy (T).

$$E + R + T = \text{Radiated Energy}$$

For a perfect blackbody, $E = 1$, $R = 0$, and $T = 0$. For a non-blackbody object, the value for E is still 1.0, but the values for R and T are greater than 0. To account for the reflective and transmitted energy of an object, a term referred to as *emissivity* must be considered when making measurements. Emissivity is defined as the ratio of total energy radiated by an object to the emitted energy of a blackbody made of the same material at the same temperature. The emissivity of a blackbody is 1.0. The emissivity of non-blackbodies falls between 0.0 and 1.0. For example, the emissivity of non-blackbody carbon at 76 degrees Fahrenheit is approximately 0.8. This value means that the carbon is radiating more energy than a carbon blackbody at the same temperature. Therefore, a pyrometer detector measuring the temperature of this target will record a reading higher than the actual temperature because it detects three types of energy instead of one. Many radiation pyrometers have an emissivity adjustment knob that allows the operator to compensate for the emissivity ratio factor. By setting the knob to 0.8, for example, the instrument electronically calculates this value and the frequency it detects to indicate the correct temperature of carbon. The operator uses a specific emissivity reference table to determine the adjustment setting of the instrument required for various materials. This table is developed in a research lab where measurements of emitted energy from holes drilled into various materials, and measurements of total radiated energy from non-blackbodies made of the same materials are taken at various different temperatures required for various materials. The holes become blackbodies because they are not capable of emitting reflective or transmitted energy. Some targets have very low emissivity. If the values are below 0.2, accurate measurements are not always possible. Examples of these objects are polished metallic surfaces that are reflective, and thin film plastic that transmits a high amount of energy.

Based on the different techniques used to measure radiant energy, there are three categories of instruments: broadband, optical detector, and ratio pyrometers.

Broadband Pyrometers

A broadband pyrometer, shown in Figure 5-27(a), uses a lens system or sight tube that directs the radiation onto a blackened reference surface inside the instrument. The filter is used to pass electromagnetic waves within a desired frequency range. The energy detector employs a device known as a *thermopile* to measure the temperature of the reference area. A thermopile, shown in Figure 5-27(b), consists of several thermocouples connected in series to provide greater sensitivity to small changes in temperature. The composite output of this detector is a DC voltage that is proportional to the amount of energy at its surface.

Optical Pyrometers

The optical pyrometer is shown in Figure 5-28(a). A viewfinder is positioned to allow observance of the target and the filament of a lightbulb simultaneously Figure 5-28(b). The object being measured is compared to the brightness of the filament. A current adjustment is made by the operator until they are both the same intensity, at which time the filament visually

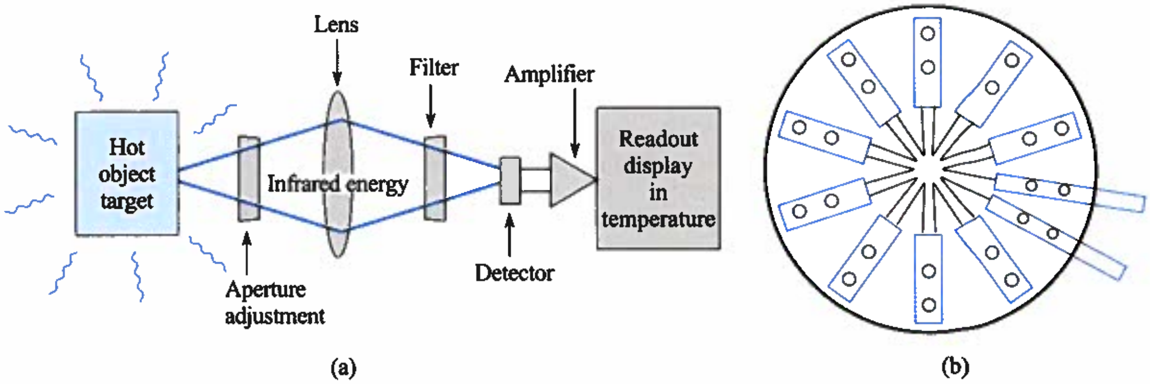


FIGURE 5-27 A simplified pyrometer temperature-measuring instrument and a thermopile

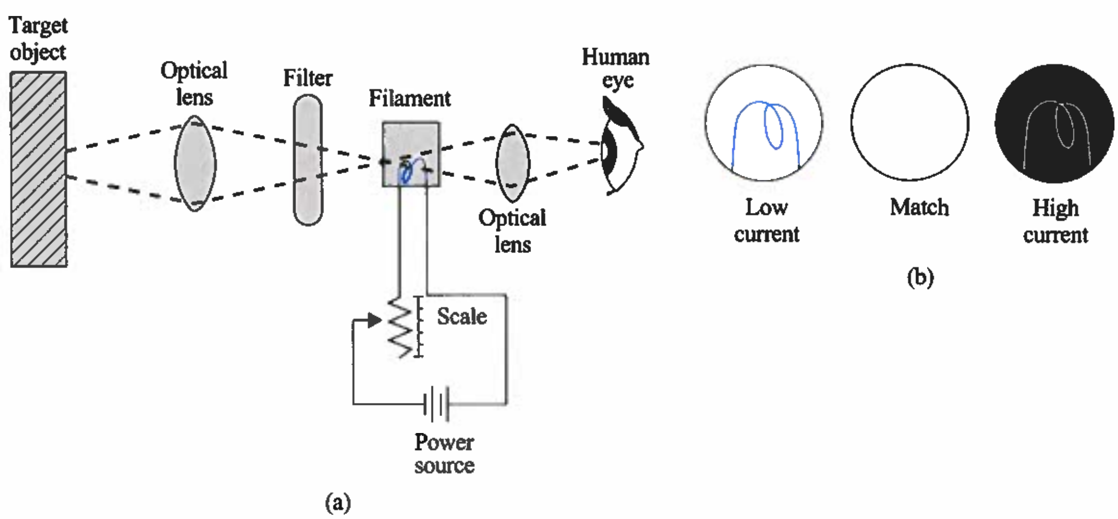


FIGURE 5-28 Optical pyrometer

disappears into the background. When the brightness of both objects is equal, their temperatures are also the same. A scale on the current adjustment knob is calibrated to indicate the temperature of both the target and the reference filament.

Ratio Pyrometers

At all temperatures the target object radiates energy at different frequencies. Most pyrometers measure the dominant waves with the most energy.

The ratio pyrometer differs from other pyrometers by taking measurements of two different frequencies emitted by an object. First, the radiant energy of a blue wavelength is passed through a blue filter and its power strength is measured. Then the radiant energy of a red wavelength is passed through a red filter and measured. These measured values, along with the actual lengths of blue and red magnetic waves, are used in the following formula to determine a ratio quantity:

Red Wavelength = 1.0
Blue Wavelength = 0.8
RP = Power Reading of Red Wavelength
BP = Power Reading of Blue Wavelength

$$\text{Ratio} = \frac{RP - BP}{1.0 - 0.8}$$

The target temperature is inferred from the ratio value electronically calculated by the instrument. Figure 5-29 graphically illustrates the power readings taken at the blue and red wavelengths for two different temperatures.

The advantage of the ratio technique is that it is less susceptible than other measurement methods to dust, steam, and other factors that distort readings.

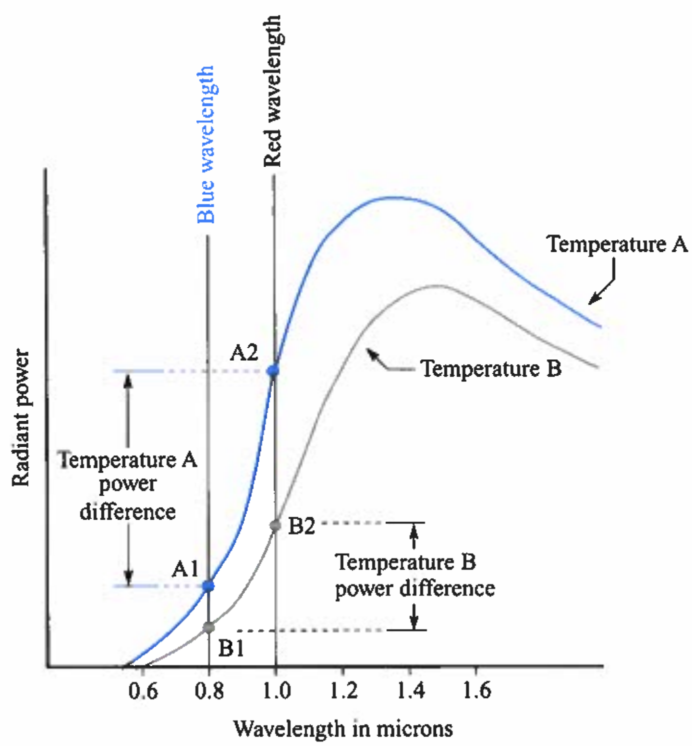


FIGURE 5-29 The power detection of two different wavelengths by a ratio pyrometer

Field of View

When using a pyrometer, the target being measured should completely fill the view of the instrument. Figure 5-30(a) shows a proper technique for measuring the target. The reading in Figure 5-30(b) will not be accurate because the pyrometer will also detect the temperature of the wall surface in the background.

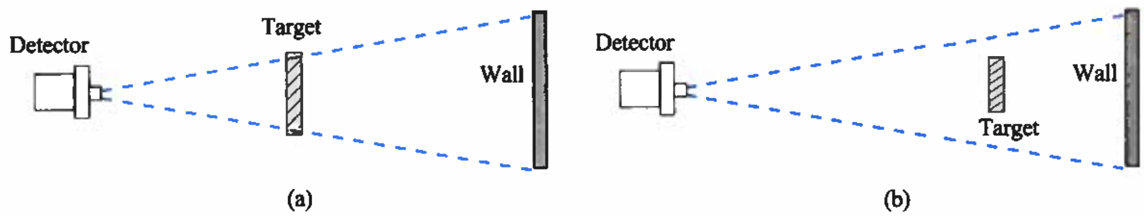


FIGURE 5-30 Field of view

Problems

1. Molecular movement creates heat known as ______ .
2. Thermal energy moves from ______ objects to ______ .
   a. warmer b. cooler
3. The process by which thermal energy transfers through a solid is called ______ .
   a. conductance c. radiation
   b. convection
4. The type of thermal energy transfer that takes place through a vacuum is called ______ .
   a. conductance c. radiation
   b. convection
5. Name a functional application for each of the following heating sources:
   Blast Furnace, Resistance Furnace, Fossil Fuel Furnace, Induction Furnace, Arc Furnace
6. As freon turns from a liquid to a gas, it becomes ______ .
   a. cooler b. warmer
7. As the cold freon flows through the evaporation coils of a refrigerator, it cools the food by ______ .
   a. emitting cold air
   b. absorbing heat from the contents
8. The freezing point on a Celsius scale is ______ degrees.
9. How many calories are used to raise the temperature of 5 grams of water 10 degrees Celsius?
10. Convert a Celsius reading of 16 degrees into an equivalent Fahrenheit value.
11. Convert a Fahrenheit reading of 74 degrees into an equivalent Celsius value.
12. How many BTUs of heat are used when the 3 pounds of water are raised 6 degrees?
13. For what type of functional application is a temperature-sensing indicator made of crystalline solids used?
14. When heated, why does the liquid in a thermometer rise in the tube?
15. As a bimetallic thermometer element straightens, the ambient temperature is ______ (increased, decreased).
16. A thermocouple is a ______ device.
   a. thermoelectric b. thermoresistive
17. The ______ (hot, cold) junction of a thermocouple is the reference point.
18. Give a functional application of a thermocouple.
19. The resistance of an RTD is ______ (directly, inversely) proportional to temperature.
20. RTDs are considered ______ (linear, nonlinear) devices.
21. What is the alpha value for an RTD that has 50 ohms of resistance at freezing, and 69.25 ohms at 100 degrees Celsius?
22. How many calories are required to raise the temperature of 15 grams of water 3 degrees Celsius?
23. Give a functional application of an RTD.
24. A tube that encloses a temperature-sensing device to protect it from being damaged by environmental elements to which it is exposed is called a ______ .
25. The thermistor has a ______ (negative, positive) temperature coefficient.
26. An RTD has a/an ______ (PTC, NTC).
27. Give a functional application of a thermistor.
28. List the three types of energy radiated from a non-blackbody.
29. How can emitted energy be radiated exclusively from a non-blackbody?
30. The emissivity value of a non-blackbody is ______ .
   a. greater than 0 but less than 1
   b. 1
   c. greater than 1
31. What does a thermopile consist of?
32. What type of pyrometer views a lightbulb and target simultaneously in a viewfinder?
33. Which type of pyrometer is the least susceptible to dust and smoke?

CHAPTER

6

Flow Control

OBJECTIVES

At the conclusion of this chapter, you should be able to:

- Define flow.
- Describe the importance of measuring and controlling flow in industrial processes.
- List some types of materials measured for flow and how they are transferred.
- Explain the difference between volumetric flow rate and mass flow rate.
- List common measurement units of flow rate.
- Describe the method used for measuring the volumetric flow rate and mass flow rate of solid materials.
- List four factors that affect the flow rate of liquids.
- Calculate the Reynolds number for a liquid.
- Describe the operation of the following mechanical measurement instruments used to determine flow rate:

Differential Pressure	Rotary-Vane	Turbine Flowmeter
Rotameter	Lobed Impeller	

- Describe the operation of the following electronic sensors used to measure flow:

Coriolis Meter	Electromagnetic Flow Detector	Vortex Flowmeter
Rotor Flow Detector	Thermal Flowmeter	Ultrasonic Flowmeter
Time-of-Flight Flowmeter		

- State a rule that describes the placement of flow sensors in a pipe system.
- Select the most appropriate flow measuring device for a particular application.

INTRODUCTION

Many types of industrial applications involve the flow of materials during the manufacturing process. **Flow** is the transfer of material from one location to another. The materials can be raw materials, products, or wastes in the form of solids, liquids, gases, or solids that float on liquids, called slurry. The flow, or movement of materials, is transferred through such components as pipes, hoses, channels, or conveyor belts. Flow can be continuous or sporadic, depending on the type of process being performed.

This chapter will first discuss the basic principles of flow, and then describe the operation of mechanical and electronic measuring instruments.

6-1 Systems Concepts

Automated systems that control flow first determine flow rates or volume by various measurement techniques, and then use the data to regulate the movement. These systems employ a source, a path, a control function, an actuator, and a measuring instrument to operate.

An automated flow control system is illustrated in Figure 6-1. It shows a batch process machine that makes soft drinks. A computer-based controller turns the valves on and off to direct the flow. Flow sensors that measure flow rate and volume are located on each pipe. They send feedback data to the controller.

At the beginning of a batch, valve V_1 opens and water drains into the batch tank. When the flow sensor S_1 registers that a certain volume of water has passed through the pipe where it is located, the controller closes V_1. V_2 then opens until the required amount of water enters the carbonation tank. As V_2 closes, V_3 opens to allow CO_2 into the carbonation tank. When sensor S_3 measures that a certain volume of gas has entered the tank, the controller closes V_3 and V_4 opens to fill the seltzer tank. Selected valves then open in a certain sequence to allow the necessary coloring and flavoring ingredients to drain into the batch tank. The volume of each coloring and flavoring fluid is monitored by sensor 4. When the

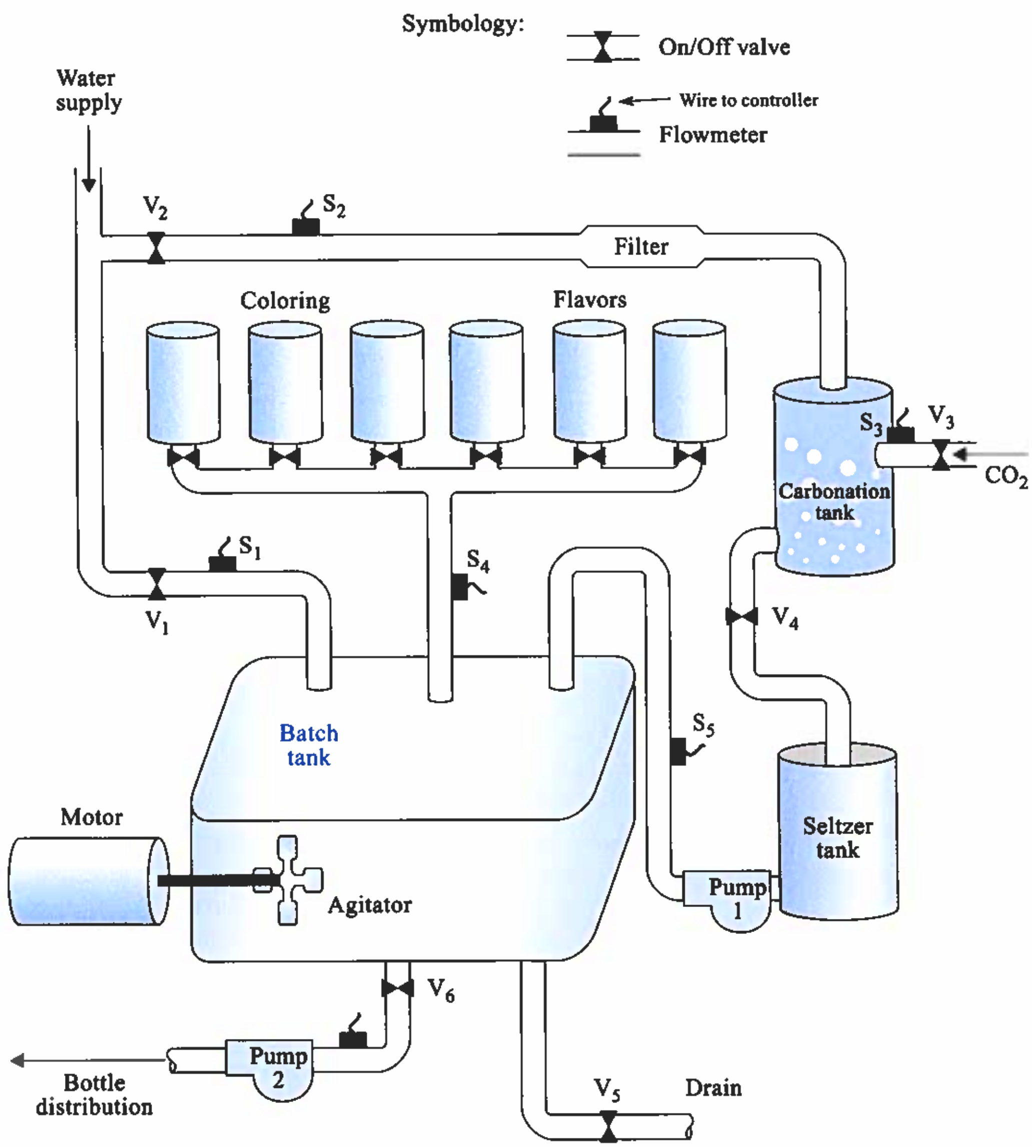


FIGURE 6-1 Flow control system used to batch process soft drinks

required amount passes S_4, the valve allowing an ingredient to flow closes, and the next valve in the sequence is opened. After the sequence is completed and the final valve closes, pump 1 turns on to transfer the seltzer ingredients at a desired flow rate into the batch tank. Sensor S_5 monitors the rate of flow as the carbonized fluid passes through its pipe. The controller will vary the speed of the pump so that the flow rate is at the required value. When the desired portions of the formula are present in the tank, pump 1 stops and the motor starts to run an agitator that mixes the contents for the required period of time. When the motor stops, pump 2 transfers the finished product to the bottle-filling stage.

After the batch run is completed, V_1 opens and fills the tank with a supply of fresh water to rinse the tank. Then the motor is activated to aid the rinsing process by agitating the water. When the agitation cycle is complete, V_5 opens to allow the batch tank to empty. After V_5 is closed, the tank is clean and ready for the next production run.

Reasons for Control

To provide good control in the process industries, accurate measurement of flow is essential. Three reasons to monitor the flow of materials are:

1. To ensure that the correct proportions of raw materials are combined during the manufacturing process.
2. To ensure that ingredients are supplied at the proper rate during the mixing and blending of the materials.
3. To prevent a high flow rate that might cause pressure or temperatures to become dangerous, overspills to occur, or machines to overspeed.

Flow measurements are also used to determine how much of a product is passed from the supplier to the customer. This application is known as **custody transfer.** Measuring flow accurately is essential in keeping records for accounting purposes.

The flow of materials is a response to an applied force. The force may be produced by a motor that drives a pump or a conveyor belt. Force may be supplied by pressure in a hydraulic system or an air compressor. Force is also produced by static head pressure.

6-2 Flow Units of Measurement

Three common classifications that are used to determine flow measurements are **volumetric flow rate, flow velocity,** and **mass flow rate.**

Volumetric Flow Rate

Volumetric flow rate instruments are used to determine the volume of material that flows during a specific period of time. The volume can be read as cubic feet, gallons, or liters. The time can be read per unit of time, such as seconds, minutes, or hours.

In many situations, volumetric flow rate is not measured directly. Instead, an *inferred* measurement is taken. **Inferred** means that some other variable is measured, and then translated into the reading that is required. For example, volumetric flow rate of a liquid can be determined by measuring the velocity at which it flows through a pipe. By using the velocity measurement and the area of the pipe in the following formula, the volumetric flow rate can be calculated:

$$Q = VA$$

where,

Q = the volumetric flow rate in units of volume per units of time
V = the velocity of the fluid
A = the cross-sectional area of the pipe

Most volumetric flow rate measurements are taken using an inferred method.

Flow Velocity

Flow velocity is the distance a material travels in a carrier per unit of time. Typical units of measurements are kg/h or lb/h. It is expressed by the formula,

$$V = \frac{Q}{A}$$

Mass Flow Rate

Mass flow rate instruments are used to determine the weight of materials that flow during a specified time period. The weight can be read in pounds, tons, grams, or kilograms. The time can be read per unit of time, such as seconds, minutes, or hours. It is expressed by the formula,

$$M = pQ$$

Where,

M = Mass
p = Mass density or weight density

EXAMPLE 6-1

Water is forced by a pump through a pipe with an inside diameter of 2 inches at a flow velocity of 5 feet per second. Find the volumetric flow rate and the mass flow rate. *The weight density of water is 62.4 lb/ft³.*

Solution

Step 1: Determine the pipe's inside area, where the diameter in feet equals,

$$D = \frac{2 \text{ in.}}{12 \text{ in./ft}} = 0.167 \text{ ft}$$

$$A = \frac{\pi d^2}{4}$$

$$= \frac{3.14\,(0.167)^2}{4} = .0218 \text{ ft}^2$$

Step 2: Calculate the volumetric flow rate.

$$Q = VA$$

$$= (5 \text{ ft/s})\,(.0218 \text{ ft}^2)\,(60 \text{ s/1 min})$$

$$= 6.54 \text{ ft}^3\text{/min}$$

Step 3: Determine the mass flow rate.

$$M = pQ$$

$$= (62.4 \text{ lb} \cdot \text{ft}^3)\,(6.54 \text{ ft}^3\text{/min})$$

$$= 408 \text{ lb} \cdot \text{min}$$

6-3 Solid Flow Measurement

The solid materials that are measured for mass flow rate are typically in the form of small particles, such as powder, pellets, or crushed material. A conveyor belt is usually used to move these materials from one location to another.

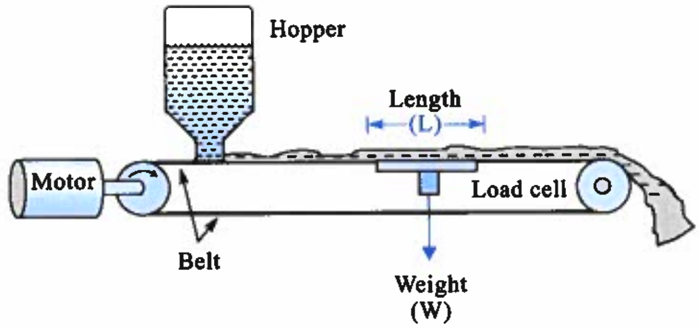


FIGURE 6-2 A conveyor system used to measure the flow of solid materials

Figure 6-2 shows one method of measuring the flow of powder as it is being transported by a conveyor system. The powder is released by the hopper and transferred to another location, such as a mixing vat, a storage tank, or the hold of a ship. A measurement is taken by a load cell device that determines the weight of a fixed length of the belt. Using inferred data, such as the weight measurement and speed of the belt, allows a calculation of the mass flow rate, as shown by the following formula:

$$F = \frac{WS}{L}$$

where,

F = Mass flow rate in lb/min
W = Weight of a material on a section of length
S = Conveyor speed in ft/min
L = Length of the weighing platform

EXAMPLE 6-2

A taconite ore conveyor system moves at 50 feet per minute, and the weighing platform is 10 feet long. Determine the mass flow rate if the load cell measures 300 pounds of taconite.

Solution

$$F = \frac{WS}{L} = \frac{(300\text{ lbs})(50\text{ ft/min})}{10\text{ ft}}$$
$$= 1500\text{ lb/min}$$

The load cell that measures the weight is a strain gauge. Another instrument used to measure the ore weight is a linear voltage differential transformer (LVDT). The LVDT produces a variable voltage. Its amplitude is proportional to the amount at which its core moves within the coils of a transformer. Figure 6-3 shows a conveyor belt with a section that is allowed to droop due to the weight of the material it carries. The more the belt droops, the heavier the weight. The LVDT makes a weight measurement by reading the droop in the belt.

6-4 Fluid Flow Measurement

Liquids, gases, and vapors are classified as fluids. The accurate measurement and control of fluid flow is essential in industrial processing plants that use water, steam, gases, petroleum, acids, base solutions, and other types of fluid materials.

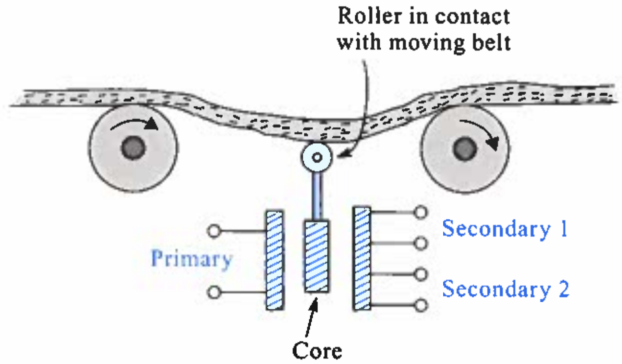


FIGURE 6-3 An LVDT used to measure the weight of materials flowing on the conveyor belt

Pipe Flow Principles

There are several influences that determine how fluids flow through a system. These influences often have a significant impact on how well a particular flowmeter will perform in a given application. The following terms list and describe each influence. They must be understood when studying the principles of liquid flow control:

Velocity. The velocity of a fluid is the speed at which it moves through the pipe. The faster the fluid is flowing, the more inertia it has. Some flowmeters work well with very high or very low velocity fluids, while others do not. In the United States, the unit of measurement is feet per second. In the United States, the most common unit of measurement is feet per second. Meters per second, used more commonly in other countries, are also being adopted as a unit of measurement.

Density. The density of a fluid is its weight per unit of volume. Both temperature and pressure affect the density of fluids and can alter the accuracy of measurements, especially for gases and vapors. High temperatures or lower pressure cause the fluid to expand so that the molecules move farther apart, which causes the weight of a given volume to be less than it would be at a lower temperature or higher pressure.

Viscosity. The viscosity of a fluid represents the ease with which it flows. A numerical unit of measure used to represent viscosity is called the *poise* or centipoise. A higher number indicates increased viscosity and more reluctance to flow.

The temperatures to which the fluids are exposed affect viscosity. With liquid, a lower temperature will cause the viscosity to increase, creating more reluctance, which slows the flow rate. With gases, a lower temperature decreases viscosity, and creates less reluctance to flow.

Pipe Size. The size of the pipe carrying a fluid affects the flow. The larger the diameter, the more easily the fluid will pass through.

Reynolds Number

In 1883, Sir Osborne Reynolds, an English scientist, submitted a paper to the Royal Society that described the effects of the preceding four factors on fluid flow. He also presented a numerical scheme that assigned values to express the fluidity of a moving liquid based on the influence of these four factors. The numerical value, known as **Reynolds number** or **R number,** is determined by the following formula:

$$R = \frac{VDp}{u}$$

where,

V = Velocity
R = Reynolds number
D = Pipe inside diameter
p = Fluid density
u = Liquid viscosity

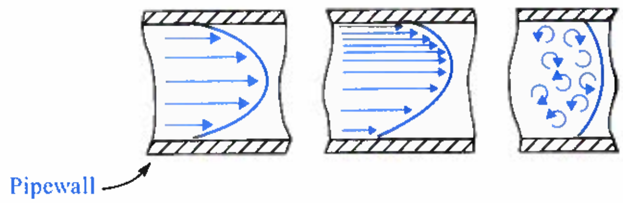


FIGURE 6-4 Flow currents of fluid

The R number represents the ratio of the liquid's inertial forces to its drag (viscous) forces. The velocity, pipe diameter, and fluid density are inertial forces, and viscosity is the drag force. The R number is used to identify the type of flow currents that are likely to occur. These currents are illustrated in Figure 6-4: *laminar* flow (Figure 6-4(a)), *transition* flow (Figure 6-4(b)), and *turbulent* flow (Figure 6-4(c)). The information supplied by the R number is useful when determining the proper flowmeter for a specific application. For example, some flowmeters are designed to read laminar flow, and would give erroneous readings if they were measuring turbulent flow. By knowing a fluid's R number, a suitable flowmeter with a rating of the same value can be selected.

At very low velocities, R is low and laminar flow takes place. With this type of flow, liquid moves in layers. However, the fluids do not flow in uniform velocities across a given cross section of the pipe. The layers in contact with the pipe wall move at velocities close to zero because of friction. As drag forces decrease farther away from the pipe, the layers progressively travel at faster speeds as they near the center. The result is the parabolic shape of the velocity profile shown in Figure 6-4(a), which shows the laminar flow at an R value of 2000 or less. As the Reynolds number approaches 3000, the laminar flow becomes nonsymmetrical, as shown in Figure 6-4(b). At very high velocities or low viscosities, the R value is high. When the R number reaches the range of 7000 to 8000, the uniform layers break up and develop into turbulent eddies that travel in all directions in the fluid stream, as shown in Figure 6-4(c). This mixing action tends to produce a flow rate velocity that is constant across the full stream profile. The R number range of 3000 to about 7000 is the transition range between laminar and turbulent flow.

EXAMPLE 6-3

Determine the Reynolds number for the following values given for each factor used in the equation. Indicate if the flow is laminar, nonsymetrical or turbulent.

Solution

$$R = \frac{VDp}{u}$$

V = 2.3345 meters per second
D = 0.00508 meters (inside diameter)
p = 250 kg · m^3
u = 0.002 pa × s
R = 1482, therefore laminar

Fluid Flowmeter Classification

One method of classifying flowmeters is to divide them into the following four categories:

1. Differential Pressure
2. Positive Displacement
3. Velocity
4. Direct Reading Mass

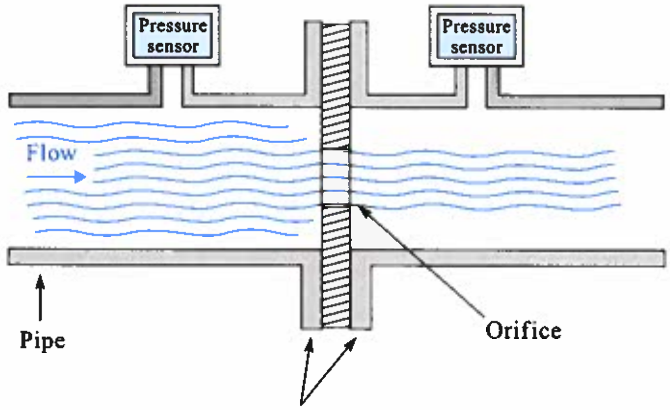


FIGURE 6-5 Differential pressure flowmeter

Differential Pressure Flowmeter

The **differential pressure flowmeter** is the most common type of instrument used to measure the flow of fluids through a pipe. These instruments account for well over 50 percent of all flow measuring devices used in the process industry.

Differential Pressure Meter Figure 6-5 illustrates the operation of this device. A restriction on the flow, called an orifice, is installed in the pipe between two flanges. An orifice is a metal plate with a hole of a specified size bored through it. The purpose of the orifice is to reduce the area that the fluid can flow through. According to the laws of conservation of energy, the mass (fluid) entering a pipe must equal the mass leaving the pipe during the same time period. Therefore, the velocity of the fluid that leaves the orifice is faster than the fluid that approaches it. According to Bernoulli's principle, as the velocity of a fluid increases, pressure decreases. The result is that there is more pressure on the incoming side of the orifice than on the outgoing side. As the fluid flow rate increases, back pressure on the oncoming side increases as the orifice is restricting the flow. The pressure of the fluid on the outgoing side of the orifice also increases, but not as much as on the incoming side. That is why the differential pressure across the orifice plate increases. If the exact relationship between differential pressure and velocity is known, velocity can be calculated from an inferred differential pressure measurement and used to determine volumetric flow rate.

The flow rate of a liquid through an orifice plate increases in proportion to the square root of the pressure difference on each side. For example, if the flow rate doubles, the differential pressure is increased by four. This relationship is shown mathematically by the formula,

$$Q = K\sqrt{\Delta P}$$

where,

Q = Flow rate
K = A constant determined by the orifice size and type of liquid
P = Differential pressure across the orifice plates

EXAMPLE 6-4 Suppose the differential pressure increases by 25. How much has the flow rate increased if K = 1?

Solution

$$\text{Formula: } Q = K\sqrt{\Delta P}$$

$$\text{Original Flow Rate Value: } Q = 1\sqrt{1} = 1$$

$$\text{NEW Formula Value: } Q = 1\sqrt{25} = 5$$

Therefore, the flow rate has increased by 5.

The signals from the sensors of each side of the orifice plate are sent to a transmitter. The output signal it produces varies in proportion to the square of the flow rate. Therefore, if the flow rate doubles, the signal increases by a factor of 4.

The signal can be made to vary in direct proportion to flow rate by connecting a device called a *square root extractor.* The device will produce a signal that will double if the flow rate doubles. The orifice that converts fluid flow into differential pressure is also referred to as a primary element. There are several types of primary elements used, as shown in Figure 6-6, but the orifice style shown in Figure 6-6(a) is the most popular. It is used to measure clean liquids and gases and produces its most accurate reading when measuring turbulent flow. A flowmeter also contains a secondary element. Its function is to convert the pressure difference into a measurement that is used to indicate fluid flow. Various types of detectors, such as piezoelectric sensors, are placed on either side of the plate to detect the pressure difference. The outputs of the detectors are compared, and their differences are converted electronically into the actual flow value.

The disadvantage of the primary element's design in Figure 6-6(a) is that the plate has sharp corners on which solid materials can catch. Therefore, it is not used to measure slurries, dirty fluids, or corrosive liquids. To measure these types of fluids, alternative restriction devices have been developed.

The *flow nozzle* type, shown in Figure 6-6(b), has a constriction with an elliptical contour shape. Since there are no sharp edges at the inlet side, there is less friction to the flow. Therefore, because of its slope, it is used to measure steam and high capacity applications that deal with dirty or corrosive liquids.

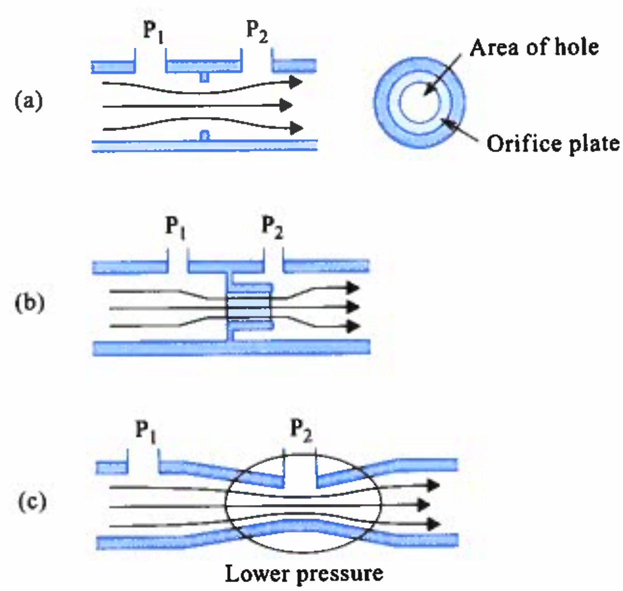


FIGURE 6-6 Three different types of flow restrictors used to convert pressure difference into flow measurements

The *Venturi tube* style in Figure 6-6(c) consists of a converging inlet section in which the cross section decreases in size. The high pressure reading is taken at the incoming portion of the pipe just before it converges. As the diameter becomes smaller, the velocity of the fluid increases, resulting in a decrease of pressure. The low pressure reading is taken at the location of the orifice with the smallest diameter. Since the Venturi tube has no sudden change in contour, solid particles tend to slide through its throat. Therefore, this style is recommended when measuring slurries and dirty fluids. The disadvantage of this style is that the resulting measurements are not as accurate as those based on plates with sharp-edged orifices.

The advantages of using differential pressure (DP) meters are that they are popular, well understood, inexpensive; they have no moving parts; and they are well suited for most gases and liquids. One limitation is that there is a nonlinear relationship between differential pressure and flow. Therefore, to linearize the signal, a transmitter or controller is used to extract the square root of the differential pressure measurement. Another limitation is that these meters present an obstruction to flow, which results in some unrecoverable pressure loss.

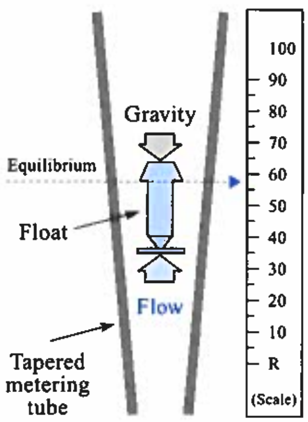
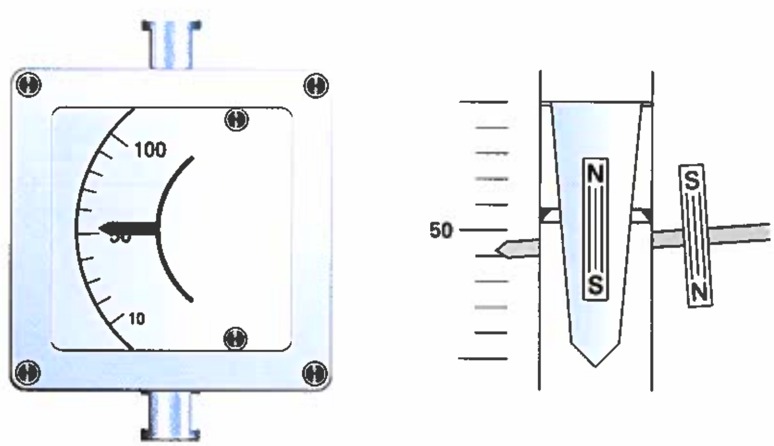


FIGURE 6-7 The rotameter used to measure the flow of liquids and gases

Rotameter The **rotameter** is a variation of the differential pressure flowmeter. It is also known as a variable area flowmeter. The rotameter is shown in Figure 6-7. It consists of a tapered metering tube that is vertically mounted and a float that is free to move up and down within the tube. The fluid to be measured enters the bottom of the tube and exits at the top. Its operation is based on the variable area principle, where the flow raises the float to allow passage of the fluid.

When there is no fluid flowing through the meter, the float will settle at a location in the tube that has the same diameter as the float. As fluid begins to flow, it pushes the float upward, allowing passage between the tube and float. The greater the flow, the higher the float is raised, and the area through which the fluid can pass is increased. The movement of the float is directly proportional to the flow rate. A marker on the float is used to identify a number on a measurement scale that indicates the flow rate.

Figure 6-8(a) shows a rotameter with an analog gauge that displays flow rate. A magnet is embedded into the float, as shown in Figure 6-8(b). As the flow rate increases and causes the float to rise, this increase causes the adjacent magnet connected to the pointer to rise and indicate a higher corresponding reading, By connecting the end of the pointer, opposite to the graph, to an electromechanical device, it will enable an electronic transmitter to produce a 4–20 mA signal. This signal can then be used to provide a feedback signal for closed-loop control.



(a) (b)

FIGURE 6-8 (a) Rotameter gauge; (b) measurement principle

When liquid flow is measured, the float is raised by a combination of the buoyancy of the liquid and the velocity force of the fluid. With gases, the float responds only to the velocity force of the gas. The float reaches a stable position when the upward force exerted by the fluid equals the downward gravitational force exerted by the weight of the float. Differential pressure meters are suitable for use with most types of liquids and gases. They are simple in construction, have no moving parts, and are inexpensive. However, they are inefficient because the restrictions cause pressure losses in the system, and their pressure vs. flow rate is nonlinear across the entire scale.

Positive Displacement Methods

Positive displacement (PD) devices are rotary instruments that mechanically make direct measurements to determine flow. They operate by separating the fluid into segments of known values, and passing them downstream through the pipe. Multiplying the count times the known volume of each segment provides a volumetric measure of flow.

Rotary-Vane Flowmeter The most common type of PD meter is the **rotary-vane flowmeter,** illustrated in Figure 6-9. This meter operates by fluid entering each chamber section through the inlet port. As fluid fills the chamber, it forces the rotor to turn clockwise, as shown in Figure 6-9(a). The chamber is separated by spring-loaded vanes located in channels of the rotor body, as shown in Figure 6-9(b). As the rotor turns, the vanes slide in and out so that they make constant contact with the cylinder wall. The fluid is discharged when each chamber section reaches the outlet port, as shown in Figure 6-9(c). Since the volume of each revolution is known, the volumetric flow rate can be determined by multiplying the displacement times the revolutions per minute (RPM).

Lobed Impeller Flowmeter The **lobed impeller flowmeter,** illustrated in Figure 6-10, is a PD meter constructed with two carefully machined lobes that have very close clearances with each other and with the meter housing. The lobes are geared so that they rotate 90 degrees out of phase with each other. Since they are always in rolling contact with the housing

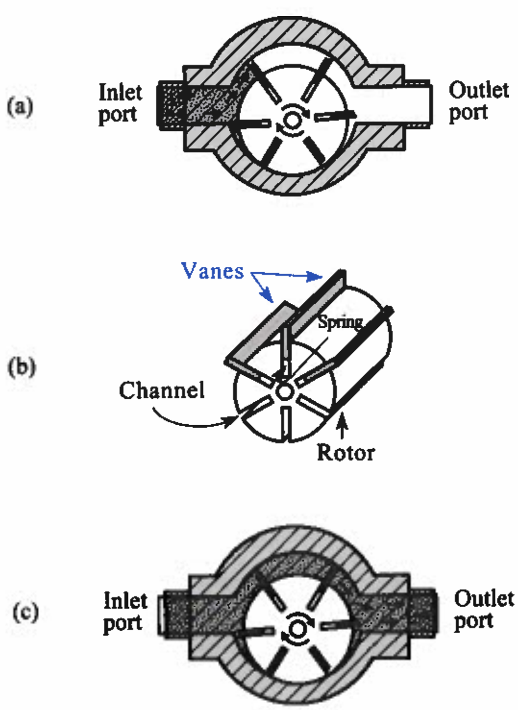


FIGURE 6-9 Rotary-vane flowmeter

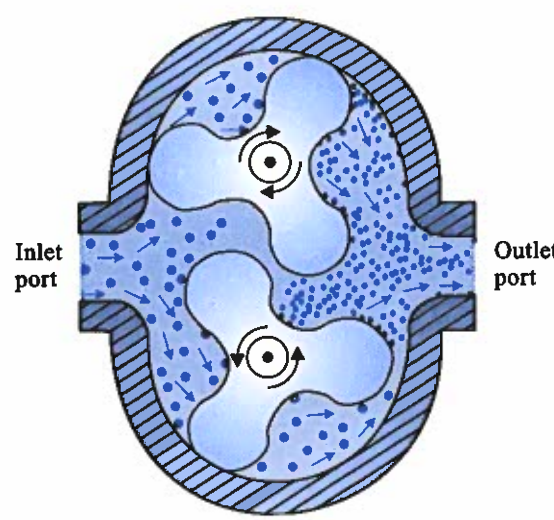


FIGURE 6-10 Lobed impeller flowmeter

and with each other, they form a seal. The force that turns the lobes is the flowing fluid. Since the volume of fluid required to turn the lobes one revolution is known, a volumetric measurement can be determined. By multiplying the displacement per revolution times the RPM, volumetric flow rate can be measured.

Limitations of PD Meters The measurements taken from PD meters are accurate. However, because they are self-powered, they extract some energy from the system. Also, since they consist of mechanical parts, they are prone to wear.

Velocity Meters

Velocity flowmeters measure the velocity of fluid flow directly. A volumetric flow measurement is determined by the formula $Q = VA$, where Q is volumetric flow rate, V is velocity, and A is area.

Turbine Flowmeter The most common type of velocity meter is the **turbine flowmeter**, illustrated in Figure 6-11. Fluid flow causes a rotation of the turbine that is proportional to the flow rate. The output of the turbine flowmeter is a pickup coil. Stationary flux lines extend from a permanent magnet placed inside the coil to the area in which the turbine blades turn. Each time one of the ferrous blades passes through the magnetic field, the flux lines become distorted due to a change in reluctance. As the lines are being altered, they cut across the pickup coil which generates a pulse voltage by induction. The frequency of the pulses is proportional to the rotational speed of the turbine.

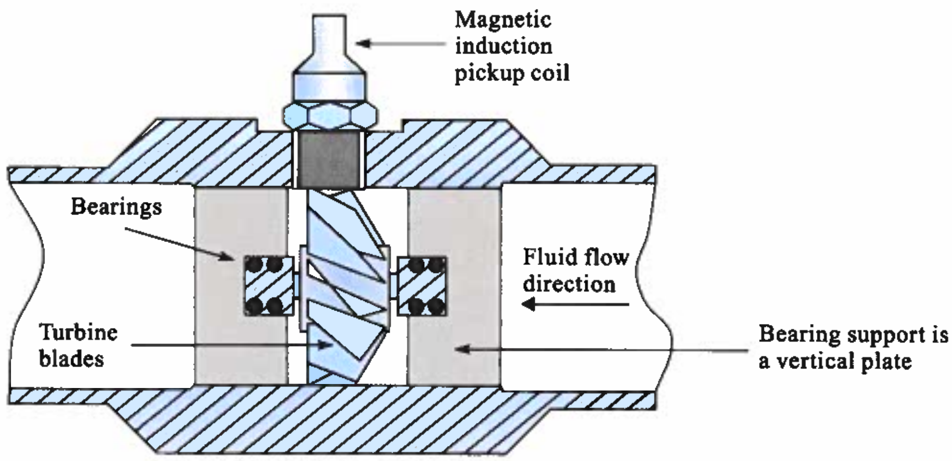


FIGURE 6-11 Turbine flowmeter that measures velocity

The output of the turbine flowmeter indicates volumetric flow rate. These flowmeters can also be used to record *totalization* measurements, that is, the total volume of flow. Each pulse generated by the meter is equivalent to a measured volume of liquid. By feeding each pulse into a counter, the total volume that flows can be recorded and displayed. Totalization measurements are used in applications such as batch processes.

Turbine flowmeters provide high accuracy and repeatability, and their output is linear. However, they are limited to measuring low viscosity fluids only.

Direct Reading Mass

Directly reading the mass, called **mass flow measurement,** provides the actual weight of the fluid during a given period of time. The readings are made directly, instead of using inferred data from other variables. Since the measurement data is independent of solids, temperature, pressure, viscosity, and other factors that affect fluids, the readings tend to be very accurate. The conveyor system illustrated in Figure 6-2 is an example of a mass flowmeter.

6-5 Electronic Sensors

Several electronic flowmeters have been developed: the Coriolis meter, the rotor flow detector, the electromagnetic flow detector, the thermal flowmeter, the vortex flowmeter, the ultrasonic flowmeter, and the time-of-flight meter.

Coriolis Meters

One type of device that measures mass flow of liquids is the **Coriolis meter**. It features a U-shaped tube for fluids to flow through, as shown in Figure 6-12(a). Fluctuating currents are sent through coils mounted near the tube. The magnetic forces they generate cause the tube to vibrate, similar to a tuning fork, as shown in Figure 6-12(b). As fluids flow through the tube, kinetic energy is produced by its speed and mass. The energy from the liquid tends to resist the vibrating motion of the tube, causing it to twist sideways, as shown in Figure 6-12(c). The degree of deflection is directly and linearly proportional to the mass of liquid passing through the U-tube. Magnetic position sensors are mounted on both ends of the tube to measure the amount of twist. The outputs from each sensor are conditioned into standard signals before they are sent to display units or to control equipment.

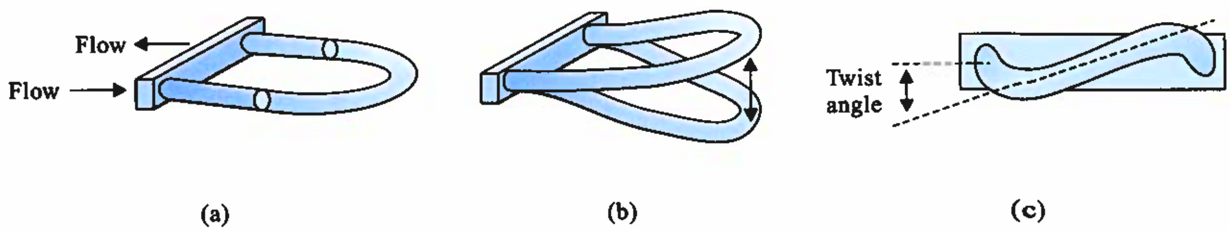


FIGURE 6-12 Coriolis mass flowmeter

Coriolis meters are capable of measuring the mass flow of all types of fluids. However, their accuracy can be diminished if exposed to mechanical noise vibration.

Rotor Flow Detectors

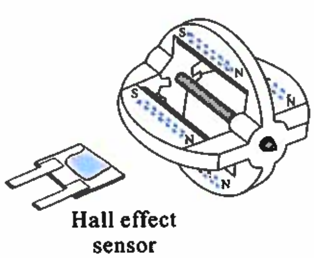


FIGURE 6-13 Rotor flow detectors

Rotor flow detectors are inserted inside pipes by using tee or saddle fittings. They utilize a simple paddle wheel design to provide flow indication. Figure 6-13 illustrates the rotor flow detector. A permanent magnet is embedded in each of the four rotor blades. Fluid flow causes a rotor rotation that is proportional to the flow rate. Each pass by a magnetized blade excites a Hall-effect device in the sensor body, producing a voltage pulse. The number of electrical pulses counted for a given period of time is directly proportional to flow volume.

This sensor can measure the flow rate of a wide variety of liquids including acids, solvents, and most corrosive fluids. They have a flow response of 0.3 fps to 10 fps in pipe sizes with diameters from 0.5 in. to 36 in. Rotor flowmeters must be placed on the edge of the flow. If the entire rotor is placed in the flow, the paddle wheel may not turn at all. Turbine flowmeters can be totally immersed within the flow.

Electromagnetic Flow Detectors

The **electromagnetic flow detector** is a transducer that converts the volumetric flow rate of a conductive substance into voltage. Figure 6-14 shows the electromagnetic flow detector. Major components are a flow tube, two electromagnetic coils mounted across from each other outside the flow tube, and two electrodes inside the pipe wall.

The electromagnetic flow detector's principle of operation is based on Faraday's Law of electromagnetic induction, which states that a voltage will be induced into a conductor when it moves through a magnetic field. The liquid serves as the moving conductor. The magnetic

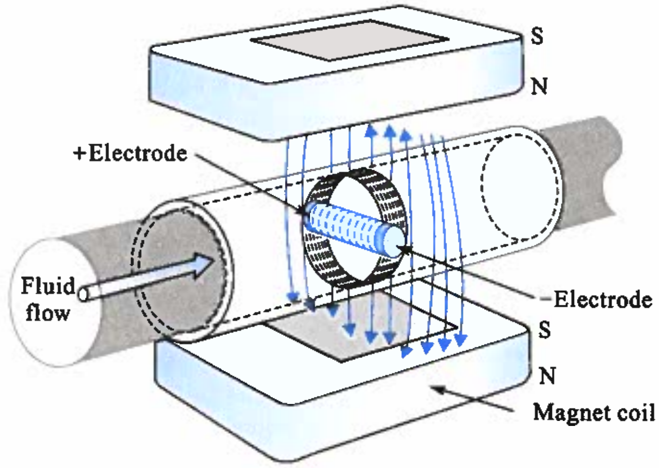


FIGURE 6-14 Simplification of the electromagnetic flowmeter principle

field is created by the energized coils, which produce flux lines perpendicular to the fluid flow. The induced voltage is measured by the two electrodes. This voltage is the summation of the voltage developed by each molecule in the flowing substance. As the fluid speed increases, the number of molecules a voltage is induced into also increases. Therefore, the amount of voltage produced is proportional to the flow rate.

Electromagnetic flow detectors are generally used to measure difficult and corrosive liquids and slurries such as acids, sewage, detergents, and liquid foods.

Thermal Flowmeters

Flow detectors that use a paddle wheel or an orifice are susceptible to clogging. Also, their ability to detect flow at low velocities is limited due to the inertia of the wheel or the inability of the orifice sensors to detect small differential pressures.

Thermal flowmeters that use a thermistor have only a sensor tip that is inserted into the flow stream. They do not become clogged and can detect very low flow rates.

Figure 6-15 shows a thermal flow detector. It works on the principle of thermal conductivity. Thermistor sensing head 1 is mounted inside a pipe. As fluid passes, it carries away heat from the thermistor. The higher the rate, the cooler the thermistor becomes, increasing its resistance. The result is that the bridge becomes more unbalanced and the output voltage goes higher. A meter with a flow rate scale is connected across the output terminals and indicates the increase.

If the temperature of the fluid happens to change, so will the thermistor resistance. To prevent the flowmeter from giving a false reading, a second thermistor sensing head is used. Since both thermistors are in the pipe, the fluid temperature affects their resistances equally. Their placement in the bridge causes the resulting voltage changes to cancel each other. Therefore, the only voltage at the output is the one caused by the flow rate. Thermistor 2 is shielded, so its resistance is not affected by the flow.

Vortex Flowmeters

A liquid-measuring device called a **vortex flowmeter** is illustrated in Figure 6-16. A blunt unstreamlined object such as a bar or strut is placed in the flow path of the fluid. As the liquid is forced around the obstacle, viscosity-related effects cause a series of vortices to develop downstream. The swirls are shed from one side of the obstacle and then the other in a predictable pattern. Within a wide range of Reynolds numbers, the number of vortices that appear downstream in a given period is directly proportional to the volumetric flow rate. A pressure detector placed downstream from the blunt object detects the vortices. The sensing

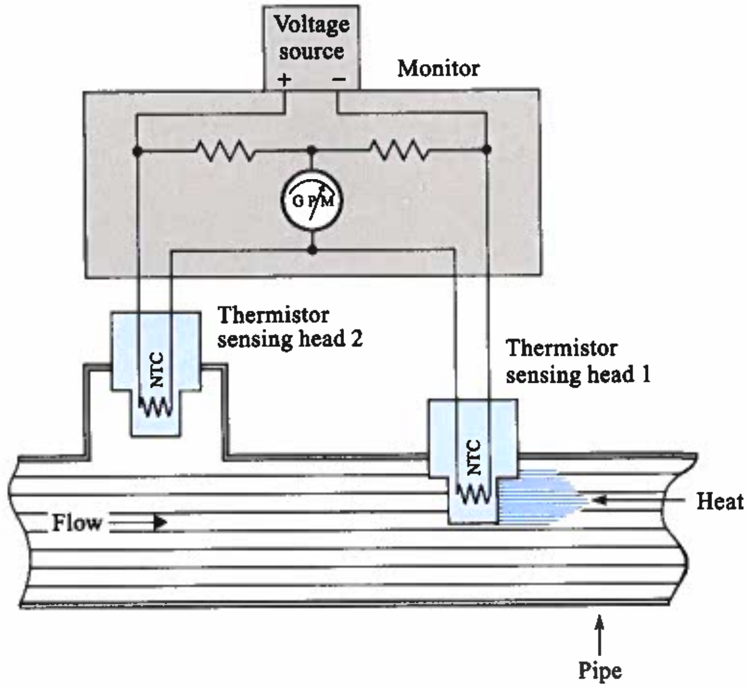


FIGURE 6-15 Thermal flowmeter

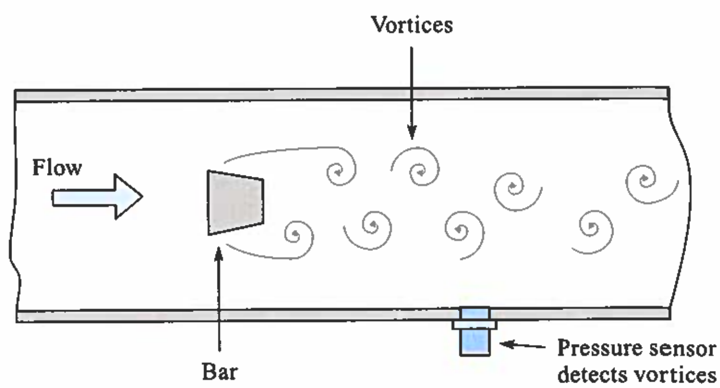


FIGURE 6-16 The vortex flowmeter

element converts the pressure fluctuations into electrical pulse signals. Within the sensor, the electronics convert the frequency into velocity, and velocity into a volumetric flow rate according to Q = VA.

The vortex meter requires little or no maintenance because it is rugged, simple, and has no moving parts. However, since it introduces an obstruction in the pipe, it is limited to measuring only clean liquids to avoid clogging the pipe.

Ultrasonic Flowmeters

A liquid-measuring device called an **ultrasonic flowmeter** is shown in Figure 6-17. It operates on a principle of sound propagation in a liquid called the Doppler effect. As current pulses are sent by an oscillator through a piezoelectric transducer, it vibrates and produces sound waves that are transmitted upstream into the flowing liquid. Each ultrasonic wave is reflected from particles or gas bubbles in the fluid back to a receiving element. The receiver is a piezoelectric device that detects pressure fluctuations created by the pulsating sound waves. This transducer converts the sound into electronic pulses that are processed by the measuring instrument circuitry.

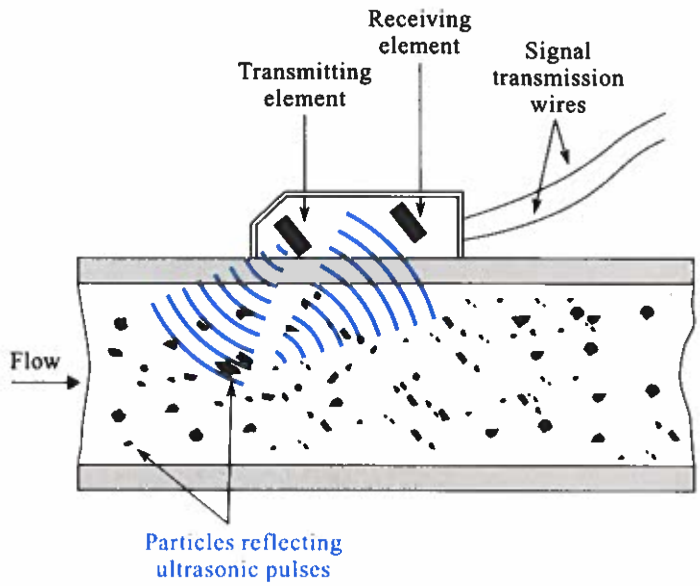


FIGURE 6-17 The Doppler ultrasonic flowmeter

Because the fluid is moving toward the receiver, the frequency of the reflected pulse received is higher than that of the transmitted pulse. The difference in frequency is proportional to the fluid velocity. As the velocity increases, the received frequency increases to create larger differences relative to the fixed frequency of the transmitter. Therefore, by measuring the frequency difference between the electrical pulses of the oscillator and the pulses at the receiver, flow rate can be recorded by the meter.

Ultrasonic flowmeters are not suited for clean fluids because they require particles from which the sonic pulses are reflected. For this reason, and because the sensor is placed outside the pipe, they are ideal for dirty liquids and slurries.

Time-of-Flight Flowmeter

The ultrasonic flowmeter using the Doppler approach requires reflective objects in the fluid. Therefore, it is ineffective when measuring clean fluids. When very clean fluids are used, the time-of-flight ultrasonic method is generally recommended.

The time-of-flight approach operates on the principle that the speed of an ultrasonic sound wave will increase when transmitted in the direction of flow, and decrease when transmitted against the direction of flow movement. An analogy is that an airplane can fly faster when traveling in the direction of the prevailing wind current than it can when flying against the wind.

The **time-of-flight flowmeter** is shown in Figure 6-18. It contains two transducers, one on each side of the pipeline. An ultrasonic signal is sent from the upstream transducer on a diagonal path toward the downstream transducer. As it travels through the flowstream, the natural velocity of the ultrasonic signal is increased by the speed at which the fluid flows. The time at which the signal travels from the upstream detector to the downstream detector is recorded. As soon as the downstream transducer receives the signal, it records the time and sends a signal back to the upstream transducer. By moving against the direction of flow, this signal travels at its natural speed minus the velocity of the fluid. When the upstream transducer receives the signal, the time is recorded. The difference in time it takes for the signals to move in both directions is a direct measure of fluid velocity. This information is electronically converted to volumetric flow rate.

One requirement for this type of meter is that the liquid being measured must be relatively clean. Any particles in the fluid may absorb or scatter the signal and make the reading inaccurate.

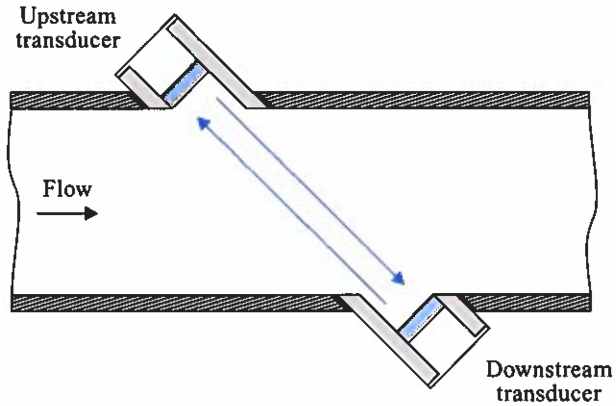


FIGURE 6-18 Time-of-flight flowmeter

The advantages of ultrasonic flowmeters are that they are noninvasive and that the absence of obstructions does not create a pressure loss. Their limitations are that they are relatively expensive and are not as accurate as some types of flowmeters.

6-6 Flowmeter Placement

As fluid encounters obstacles, such as valves or other geometric obstructions in the piping, the flow profile may become distorted and swirl, as shown in Figure 6-19. One of the effects of swirl is that fluid flows in a direction that is not parallel to the pipe, but in a direction across the diameter to the pipe. Fluids flowing in such random paths can take more time to move past the point of measurement and cause the reading to become inaccurate.

To minimize these conditions, the measuring device should be placed 5 to 20 pipeline diameters downstream from an obstruction. One method used to eliminate destructive swirls is to use a flow straightener, as shown in Figure 6-20.

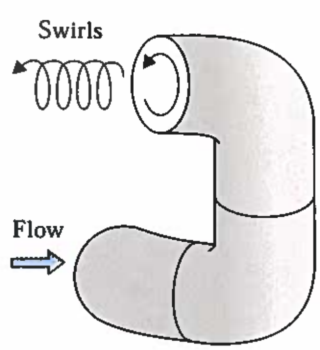


FIGURE 6-19 The swirling current produced by pipeline elbows

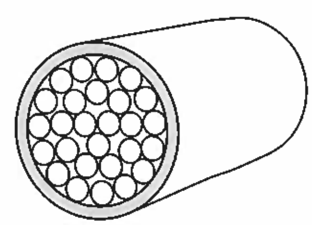


FIGURE 6-20 Flow straightener

6-7 Selecting a Flowmeter

When selecting the most appropriate flow measuring device for a particular application, the following issues should be considered:

- Is the fluid a gas or a liquid?
- Is the fluid corrosive?
- Is the fluid electrically conductive or not?

- Does the fluid contain a slurry or large solids?
- What is the fluid viscosity?
- Will the fluid density or viscosity change?
- Is there a need for a noninvasive approach?
- What is the need for accuracy and repeatability?
- What is the cost?

Problems

1. List two units of measurement for volumetric flow rate.
2. List two units of measurement for mass flow rate.
3. A conveyor belt moves at 100 feet per minute and the weighing platform length is 5 feet. What is the mass flow rate if the cell measures 100 pounds?
4. The speed at which fluid moves through a pipe is called __________.
5. If water is forced through a pipe with an inside diameter of 4 inches and a flow velocity of 30 feet per second, what is the volumetric flow rate? What is the mass flow rate?
6. List two factors that influence the density of a fluid.
7. If liquid viscosity increases, the Reynolds number will __________ (increase, decrease) and its ability to flow will __________ (increase, decrease).
8. Explain the importance of using Reynolds numbers for fluid flow.
9. What is the Reynolds number under the following conditions?
   Volume = 3.528 meters/second
   Inside Pipe Diameter = 0.0041 meters
   Fluid Density = 300 kg/m^3
   Viscosity = 0.0025
10. The Reynolds number that represents the transition range between laminar and turbulent flow is __________ to __________.
11. If the differential pressure across the orifice plate flowmeter increases by 16, how much has the flow rate increased if K = 1.22?
12. A ____-styled orifice in a differential pressure flowmeter can be used to measure the flow of slurry material.
    a. orifice b. flow nozzle c. Venturi tube
13. A rotary-vane flowmeter__________ (is, is not) classified as a positive displacement device.
14. Rotameters can measure ____.
    a. gases
    b. liquids
    c. both gases and liquids
15. The Coriolis meter __________ (is, is not) capable of measuring slurry material.
16. A velocity meter __________ (is, is not) capable of measuring mass flow.
17. To avoid distorted liquid flow, the sensor should not be placed within __________ pipeline diameters of an obstacle.
18. An electromagnetic flow detector is ____ sensor.
    a. an invasive b. a noninvasive
19. What kind of sensing element is used to detect the number of swirls in a vortex meter?
20. Thermal flowmeters use ____ to sense the temperature of the fluid flowing in the pipe.
    a. a thermocouple
    b. an RTD
    c. a thermistor
21. The time-of-flight flowmeter operates on the principle that the speed of ultrasonic sound waves ____.
    a. increases when transmitted in the direction of flow
    b. decreases when transmitted in the direction against the flow
    c. both a and b
22. The pulses transmitted upstream in an ultrasonic flowmeter are ____ waves.
    a. electromagnetic
    b. sound
    c. light
    d. infrared
23. A device used to eliminate destructive swirls downstream from a bend in a pipe is the __________ __________.
24. As a general rule, a flow measurement device should be placed ____ to ____ pipeline diameters downstream from an obstruction.

CHAPTER 7

Level Control Systems

OBJECTIVES

At the conclusion of this chapter, you should be able to:

- Define level.
- Describe the importance of measuring and controlling level in industrial processes.
- Define *interface* and list three types of interfaces that may be measured for level indication.
- List four level measurement units.
- Define direct level measurement and list types and applications of this method.
- Define indirect level measurement and list types and applications of this method.
- Explain the difference between continuous and point level measurements.
- Describe the operation of the following level indicator devices:

  Rod gauge
  Sight Glass

- Describe the operation of the following mechanical measurement instruments used to determine level:

  Float
  Displacement
  Bubbler
  Paddle Wheel Detector
  Hydrostatic Pressure Detector
  Differential Pressure Detector
  Weight Detector

- Describe the operation of the following electronic sensors used to measure level:

  Conductive Probes
  Capacitive Probes
  Ultrasonic Sensors

- Select an appropriate level measuring device for a particular application based on various considerations.

INTRODUCTION

In industrial process control, **level** refers to the height to which a material fills a container. The material can be either a liquid or a solid, such as granules or powder. The container can be a tank, a bin, a hopper, a silo, or a vessel.

Two types of techniques are used to control the level of materials in a container: On-Off and proportional. The On-Off method activates a device used to fill a container when the level is too low. When the desired level is reached, the filling operation stops. The proportional method maintains a desired level by filling the container at the same rate as the material it holds is removed.

Accurate measurements of level are essential to provide good control in the process industries. There are several reasons to monitor the level of materials in containers:

1. To ensure that enough material is available to complete a particular batch production process.
2. To prevent an industrial accident by overfilling an open container. Spilling caustic, hot, or flammable materials could be catastrophic.
3. To prevent the overfilling of a closed container or an enclosed system. This situation could cause an overpressure condition that may result in a rupture or explosion.
4. To determine an inventory of the materials in stock.
5. To prevent a heating element from overheating and being destroyed, by ensuring that a container holding heated liquid does not become empty.

7-1 A Level Control System

An automated system is illustrated in Figure 7-1. It shows a liquid solvent distribution system located in a factory. Its purpose is to release the solvent into the system after the product in a batch process vessel has been emptied. As the solvent flows through connecting pipes, tubes, and vessels, it cleans the system in preparation for the next batch.

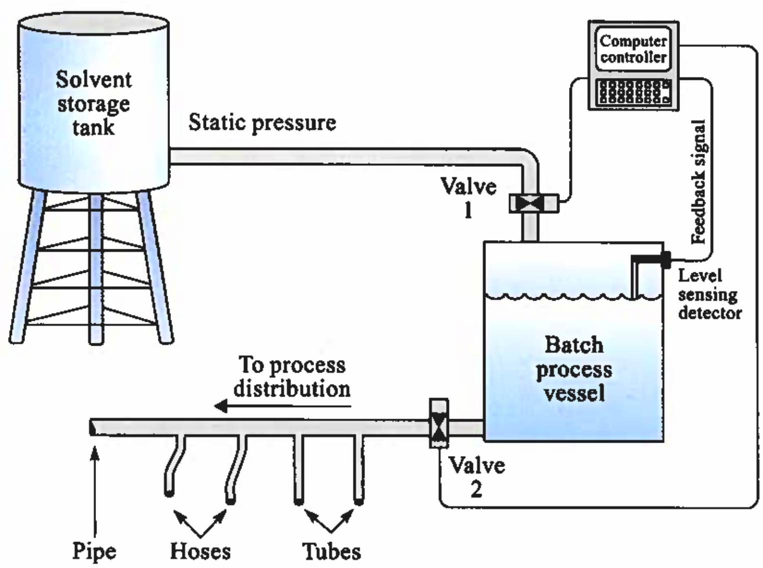


FIGURE 7-1 A level determination system

Before some type of automatic control can be implemented, it is necessary to determine the level with a mechanical or electronic sensing detector. The control function is initiated by a signal from the sensing device, which indicates the actual level of the batch process vessel. The solvent is transferred from a storage reservoir that functions as the source, through pipes that serve as the path, to the process vessel that is the load. Until the solvent level reaches the sensor, the controller keeps valve 1 open to allow the fluid to pass through. When the level reaches the sensor, valve 1 is shut off. The controller is programmed to keep the solvent in the vessel for a period of time while the chemical reaction by the liquid performs the necessary cleaning action. After the required time has elapsed, the controller opens valve 2 to enable the solvent to drain into and clean the distribution system. Work is performed when the solvent is in the vessel, and again when it is released into the distribution system.

Power Sources

Sources that provide the force required to transfer materials include pumps, static pressure tanks, and augers.

Pumps

A pump is primarily used to move liquids a required distance, or to an elevated level. The pump is powered by an electric motor, a combustion engine, or a hydraulic system.

Static Pressure Tanks

Static pressure tanks are employed to transfer liquids and solids a required distance, or to a lower level. The tank stores the material. Valves located near the output ports of the tank open and close the pathway, which controls the flow of material as needed. The pressure from the tank provides the force that moves the material. Gravity adds to the force if the flow is vertical.

Augers

The auger is used to move powders or granules in an upward vertical direction. The auger is driven by an electric motor, a combustion engine, or a hydraulic system.

Transfer Systems

There are various types of distribution systems that serve as the pathway for materials to be transferred from one location to another.

Pipes

A pipe is the primary vehicle used for transporting solids and liquids, which need to be moved upward, downward, and horizontally.

Conveyor Systems

The conveyor belt is often used to transfer solid materials. The belt is powered by a motor. The movement is horizontal, or on an upward or downward slope.

7-2 Methods of Measurement

Level is measured by locating the boundary between two media, called the **interface.** The media can be liquid and gas, liquid and liquid, liquid and solid, or solid and gas. An example of a liquid and gas medium is water making contact with air in an open vessel. A liquid and liquid medium is two liquids that do not mix, such as oil floating on top of water. An example of a solid and gas medium is powder in contact with air in an open vessel.

Level can be measured *directly* or *indirectly*. The direct method includes measuring with a float or a dipstick. Direct measurement devices are also referred to as *invasive* devices because the sensor is in direct contact with the material. The indirect method, also known as *inferred measurement*, means that a variable other than level is measured and used to *infer*, or indicate, a level measurement through some conversion method. For example, the level of a vessel can be determined by weight, pressure, volume, buoyancy, or electrical properties. Indirect measurement devices are also referred to as *noninvasive* devices, because no part of the sensor comes in contact with the material. Noninvasive devices are preferred when the material is corrosive, hazardous, sterile, or at a high temperature or pressure.

Regardless of the method, level is measured either at a point value or continuously across a range.

Point Level Measurements

Point level measurements detect if the interface is at a predetermined point. Generally, this type of detection is used to signal either a low-level limit when a vessel needs to be refilled, or a high-level alarm to warn of an overfill condition. The output of point level measurement devices typically produces On-Off, or 1 and 0 state digital signals.

Continuous Level Measurements

Continuous level measurement locates the interface point within a range of all possible levels at all times. The output of continuous level measurement devices typically produces an analog signal between 4 and 20 mA, which is both proportional and linear to the level. The electrical signal can be converted into information that represents various quantitative values used to indicate levels. They include:

Height: In units of feet or meters

Percentages: Percent full, or percent of measured span

Volume: In gallons, cubic feet, or liters

Weight: In pounds, tons, or kilograms

Continuous measurements are frequently used to maintain the level of a material at a given setpoint.

A factor that must be considered when taking level measurements is the shape of the container. If the vertical walls of a tank are parallel, its volume can easily be determined. If the sides are irregular and not parallel, volume is more difficult to calculate.

7-3 Level Measurement Methods

Level measurements are made by a number of instruments that use different methods to make the readings. The instruments are classified either as visual observation systems, or as float and displacement systems, including buoyancy displacement, purge, hydrostatic head, differential pressure, weight, rotational suppression, electrical concepts, and ultrasonic radiation.

The selection of a specific method of measuring level is often based on the following considerations:

Material	Accessibility
Cost	Turbulence
Accuracy	Pressure
Level range	

Visual Methods

Visual method simply means that a direct measurement is taken by observing the location of the material's top surface in the container.

Rod Gauge

A **rod gauge** is a dipstick that is inserted into the material being measured. It is the same type of device used to indicate oil level in a car. It has weighted line markings that indicate depth or volume. This device is very accurate and is often used during the calibration of other level measurement devices. It is not used to measure hazardous materials, to produce remote indication, or in vessels that are pressurized.

Sight Glass

The **sight glass** is a transparent tube connected to the side of a vessel. As the tank level changes, so does the level in the sight glass. This device provides a direct, local, and continuous measurement. Sight glasses are used for high pressure applications and for hot or corrosive fluids. They are not useful when foam or viscous liquids are used, because visual quality is obscured.

Float and Displacement Methods

Rod gauges and sight glasses give visual indication of level. However, they do not produce a feedback signal in automated control applications. The remainder of the measurement devices described in this chapter can provide feedback information through mechanical linkages or electrical signals.

Buoyancy Method

Float-Type Level Indicator The float-type level indicator is a spherical or cylindrical element that rides on the surface of the liquid as a means of detecting the level. A **float** is a direct, invasive method that provides either point or continuous measurement. By using different types of linkage connections between the float and the indicating device, such as the gauges in Figure 7-2, a continuous measurement reading can be taken. Figure 7-2(a) shows a high level; Figure 7-2(b) shows a lower one.

A float providing the point method of measurement is often connected to an electrical switch. The switch activates a light or buzzer for high and low limit indication. One type of float switch is shown in Figure 7-3. It consists of a magnetic toroid as part of a buoyant device with a guide tube, or stem, through its center. One or more Reed switches are placed inside the guide at desired levels. As the liquid level changes, the float moves. When it comes close to the Reed switch, the magnetic field closes the switch's contacts. The switch closure indicates a point level measurement.

Float devices can also be used for automatic control. By connecting the float element to the stem of a flow control valve with a linkage, it will allow water to replenish a vessel if the level becomes too low. An example is the float mechanism used in a household toilet tank. To provide more accurate control, a linkage can connect the float to the potentiometer of an electronic computing device. Small-diameter floats are used to measure higher density fluids. Larger floats are used for liquid-liquid interface detection or for reading lower density materials.

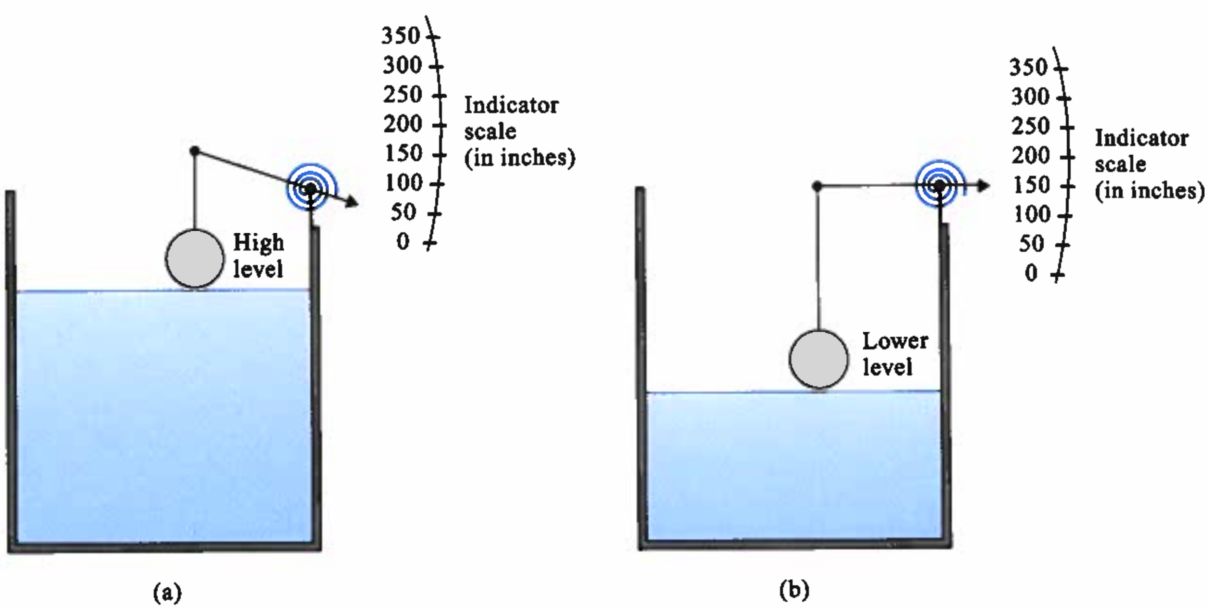


FIGURE 7-2 A float-type level instrument taking continuous measurements

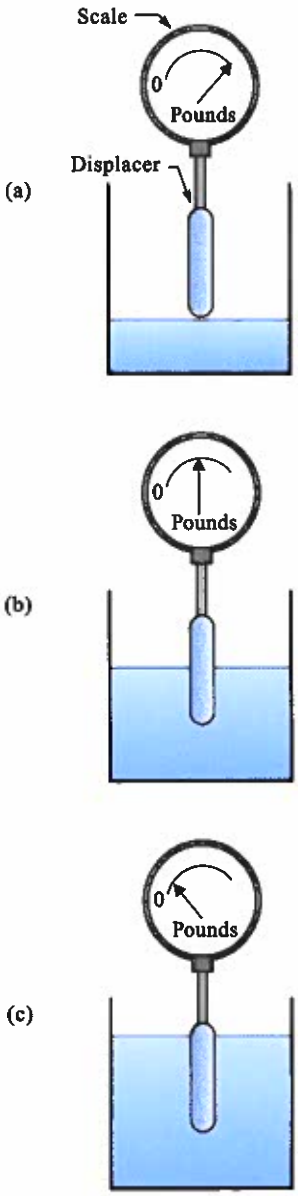


FIGURE 7-4 A displacement level sensor

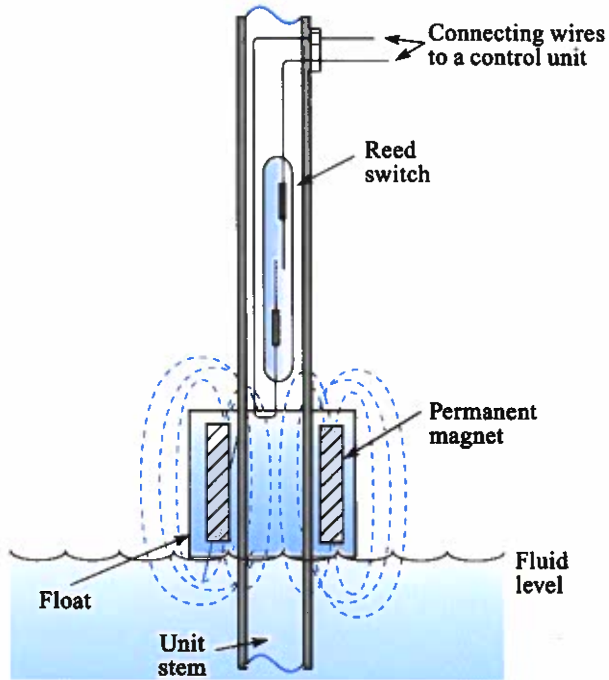


FIGURE 7-3 A magnetic float moves with the liquid level to actuate the magnetic Reed switch within the unit system

Displacement Method

Displacement Sensor The **displacement** level sensor is somewhat different from a float sensor in that its probe is weighted so it actually sinks in the measured fluid. However, the probe has bouyancy, meaning it tends to float as the liquid rises up over it. Displacement level sensors operate on the Archimedes's principle: A body immersed in a fluid, either partially or fully, is buoyed up by a force equal to the weight of the fluid displaced. The mathematical equation for this principle is,

$$B = pV$$

Where,

B = buoyancy force

p = the weight density of the fluid

V = volume of the displaced fluid

EXAMPLE 7-1

Determine the buoyancy force on an object that displaces 5 ft^3 of water at 20 degrees Celsius. *(At this temperature, the weight density of water is 62.4 lb/ft^3.)*

Solution

$$\begin{aligned} B &= pV \\ &= 62.3 \times 5\ ft^3 \\ &= 311.5\ lbs \end{aligned}$$

Figure 7-4 illustrates the operation of the displacement level sensor. The probe is suspended from a spring scale. In Figure 7-4(a), the level is below the displacer and the scale shows the full weight of the displacer. When the level rises as shown in Figures 7-4(b) and (c),

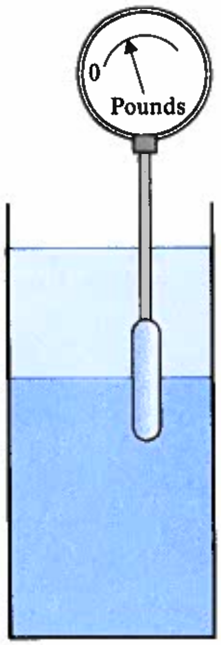


FIGURE 7-5 A displacement sensor that measures liquid-liquid interface

there is an apparent loss of weight of the displacer. The weight change causes the displacer to move, thereby yielding a linear and proportional signal. Notice that the change in displacer movement is small in comparison to the change in liquid level. This device is limited to applications in open tanks and is capable of transmitting electronic signals for remote readings.

Displacement sensors are especially appropriate for measuring liquid-liquid interfaces, that is, two liquids that do not mix together, such as oil and water, different chemicals in the same container, and slurries. Two typical applications are monitoring water condensation in fuel storage tanks and separating chemical emulsions in process systems. Figure 7-5 shows the displacement method used to measure a liquid-liquid interface in a tank.

Displacement systems are very accurate, relatively simple, easily understood, and can be used at high temperatures and in pressurized vessels. Their disadvantages are that they are expensive, and require the density of the liquid to be constant to make accurate readings.

Purge Method

Bubbler Another pressure-based system is commonly referred to as a bubbler. The **bubbler,** or purge, is one of the oldest methods of level determination. This type of system can measure such materials as water, oil, corrosive liquids, molten metal, pulp, and fine powders. A bubbler system at both low and high levels is shown in Figure 7-6. It consists of a dip-tube vertically immersed in the fluid of a tank with an open end placed close to the bottom. A tee connection joins the supply line, the bubbler pipe, and a pressure gauge.

The pressure at the bottom of the tank is hydrostatic head pressure. The more fluid in the tank, the higher the static head pressure. To make a level measurement, the air supply regulator must be adjusted so that its pressure is at least 10 psi higher than the highest hydrostatic pressure to be measured. The result is a flow of air that passes through the dip-tube producing bubbles in the liquid. As the liquid rises, there is more static head pressure above the outlet of the tube. Therefore, backpressure at the bottom of the bubbler tube increases. The increase in

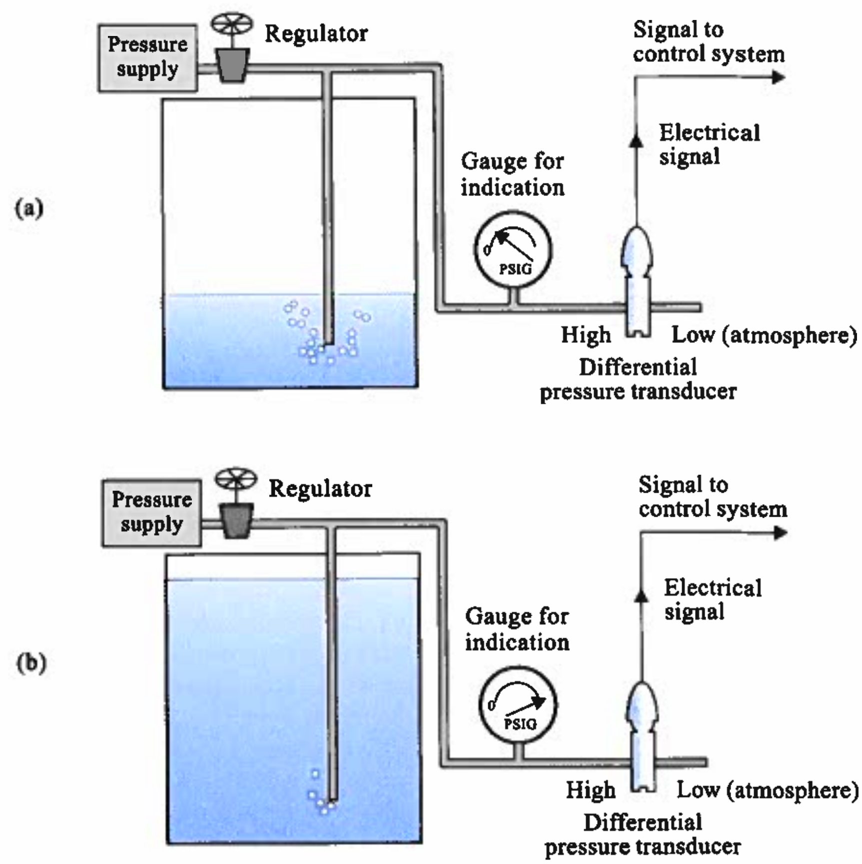


FIGURE 7-6 Bubble level detector

backpressure allows less air flow through the bubbler tube and an increase in pressure at the gauge, causing a larger deflection. The increase in pressure is proportional to an increase in liquid level. Purge instruments are popular level detectors in the paper industry because they are self-cleaning and do not allow the pulp, measured in a vat, to clog the orifice.

Rotational Suppression Method

Paddle Wheel Detector The **paddle wheel detector** uses motion to measure the level of either granular or powdered solid material. This invasive detector is a point-measuring device that spins freely when the level is below the paddle. As the level rises, the presence of the material is detected when it makes contact with the paddles and prevents the wheel from turning.

Hydrostatic Pressure Method

Hydrostatic Head Level Detector The **hydrostatic head level detector** is a pressure detector that determines level in an open container using the indirect, or inferred, measurement technique. It operates on the principle that any column of material exerts a force at the bottom of the column due to its own weight. This force is called hydrostatic pressure, or head pressure. Hydrostatic pressure is determined by the following formula:

$$\text{Pressure} = \text{Height} \times \text{Density}$$

As the height of the material changes, there is a proportional change in pressure. By placing a pressure gauge at the bottom of the vessel, the level of material can be determined using the following formula:

$$\text{Height} = \frac{\text{Pressure}}{\text{Density}}$$

EXAMPLE 7-2

Water at 60 degrees Farhenheit is stored in an unpressurized tank. A pressure gauge that displays readings in pounds per square inch indicates a value of 100 psi. To determine the level of the water, divide 0.43, which is the weight of a 1 × 1 inch column of water 1 foot high (at 60 degrees Farhenheit), into the pressure value.

Solution

$$\text{Level (Height)} = \frac{100\text{ psi (Pressure)}}{0.43\text{ psi per ft (Density)}}$$
$$= 232.56\text{ ft}$$

This type of pressure detector is capable of measuring the level of solids and liquids.

Differential Pressure Method

Differential Pressure Level Measurement Hydrostatic pressure measurements determine the liquid level in an open container where the top is exposed to the atmosphere. When a liquid level inside a pressurized tank is determined using this method, the gauge will measure not only the fluid, but the pressure above the liquid as well.

The vessel pressure in the vapor space above the liquid can be compensated for by using a **differential pressure transducer.** This measurement device uses two pressure detectors. One is placed at the bottom of the vessel to make the high pressure measurement. The other sensor is placed in the vapor space to make the vessel pressure measurement. The differential pressure transducer subtracts the vessel pressure signal from the high pressure signal to produce a reading that represents the hydrostatic head proportional to the liquid level. The following formula indicates what factors influence its reading:

$$\text{High Pressure Measurement} = \text{Hydrostatic Head} + \text{Vessel Pressure}$$

Weight Method

Level Measurements by Weight The level of a material in an unpressurized container can be determined by obtaining an inferred measurement value of weight. This method is both noninvasive and very accurate. To measure the weight, devices such as mechanical springs are placed under the container and onto a supporting surface. As the springs compress, a linkage device connected to a pointer deflects to a calibrated position that indicates the weight.

Level in a container with parallel walls is found by following these five steps:

1. Weigh the container.
2. Weigh the container with the contents.
3. Determine the weight of the contents using the following formula:

   Contents Weight (lbs) = Measured Weight – Container Weight

4. Determine the volume using the following formula:

$$\text{Volume (cubic feet)} = \frac{\text{Contents Weight (lbs)}}{\text{Density (lbs/cubic ft)}}$$

5. Determine level using the following formula:

$$\text{Level (feet)} = \frac{\text{Volume (cubic feet)}}{\text{Surface Area (square feet)}}$$

EXAMPLE 7-3 Determine the level of water inside a cylindrical container with an open top by measuring its weight.

Solution

Step 1: The container is 15 feet high and its inside diameter is 5 feet. It weights 1365 pounds.

Step 2: The weight of the container with its contents is 13,611 pounds.

Step 3: Determine the weight of the contents,

Measurement Weight − Container Weight = Contents Weight

13,611 − 1365 = 12,246 lbs

Step 4: Determine the volume of the water in cubic feet.

$$\text{Volume} = \frac{12{,}246\ \text{lbs}}{62.4} = 196.25\ \text{ft}^3$$

Step 5: Determine the level of the water.

$$\text{Level} = \frac{\text{Volume ft}^3}{\pi^2} = \frac{\text{Volume}}{3.14 \times 2.5^2} = \frac{196.25\ \text{ft}^3}{19.625} = 10\ \text{ft}$$

Weight is also detected by electronic sensors. The signals from these devices can easily be connected electronically to proportional weight, volume, and level readings for display. Weight level measurements can be used for solids and liquids.

7-4 Electronic Sensors

Electronic level sensors are devices that use a change in level to change an electrical property. There are three main types of electronic level sensors: conductive probes, capacitive probes, and ultrasonic sensors.

Conductive Probes

Conductive probe sensors are used in single- or multiple-point measurement systems to detect the presence of a conductive liquid. Figure 7-7 shows two conductive probe sensors, one with two probes and the other with five. Figure 7-7(a) shows the terminal housing, which contains the controller, and two projecting electrodes. A low AC voltage is applied to the electrodes as they are immersed in the liquid. The conductive liquid completes the electrical circuit of the control, which activates a semiconductor switch. When the level drops below the shortest electrode, the circuit opens, and the current flow stops. Figure 7-7(b) shows that by adding more probes, signals can be sent to a controller that automatically supplies liquid to the container. These signals will activate an alarm if the level becomes too high or too low.

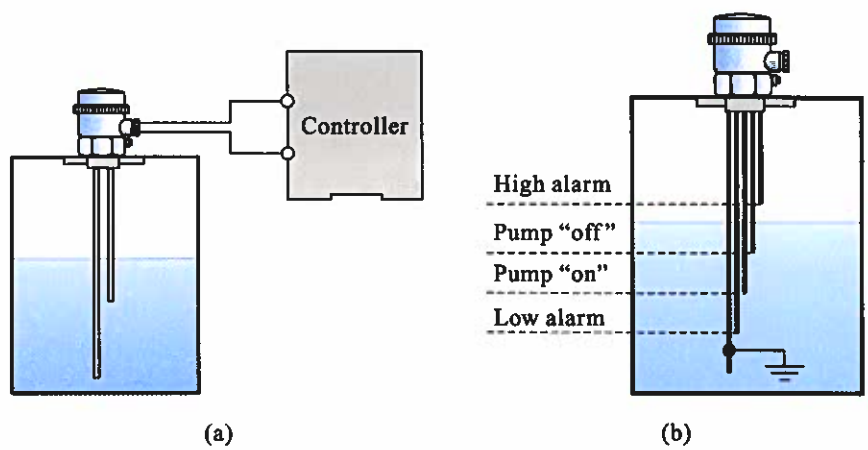


FIGURE 7-7 Conductive level probes

The advantage of conductive probes is their low cost and simple design. The disadvantage is that they are limited to point measurements and can only be used with conductive liquids.

Capacitive Probes

Capacitive probe sensors are shown in Figure 7-8. They are used for continuous level measurement. The principle of operation is based on the theory of capacitance. According to this theory, the value of a capacitor can change by varying the size of one or more plates, or by changing the dielectric. The probe and the metal wall of the tank form the two plates of a capacitor, and the contents in the tank is the dielectric. When a nonmetallic tank is used, a second electrode—referred to as a *counterelectrode*—is used.

When the tank is empty, the dielectric is the air. As the tank fills, the nonconductive liquid and the air become the dielectric. As the level varies, the dielectric constant changes and causes the capacitance to change.

If the medium is conductive, the probes must be coated with an insulating material, usually Teflon, that becomes the dielectric. The wall is not coated, which causes the liquid to become the other plate of the capacitor. As the level varies, the effect is that the size of a capacitor plate becomes larger or smaller and causes the capacitance to change.

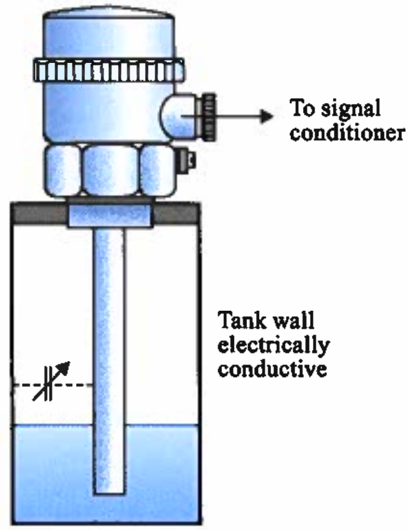


FIGURE 7-8 Capacitive probe

If the walls of the vessel are not parallel, the side of the container cannot be used as one of the plates. In this situation, a second probe must be used.

Capacitive level probes are simple to use and are relatively inexpensive. A limitation is that their accuracy is dependent on the condition of the liquid. The presence of solids in the liquid, or exposure to a large temperature change, will cause the dielectric to vary.

Ultrasonic Sensors

The **ultrasonic sensor,** another type of continuous level detector, is shown in Figure 7-9(a). Ultrasonic sound waves (above the frequency heard by humans) are developed by an oscillator. They are emitted by a transmitter toward the top surface of the medium and are reflected back to the ultrasonic signal receiver. The time it takes the waves to travel from the transmitter to the target surface and back to the receiver is measured. The time lapse between transmission and detection is proportional to distance. This data is calculated electronically and converted into a liquid-level measurement. The auto-focus mechanism of a camera works on the same principle.

The ultrasonic sending unit consists of a piezoelectric crystal sandwiched between two metal plates. An AC voltage with a frequency of 20 K to 100 kHz is applied to the plates.

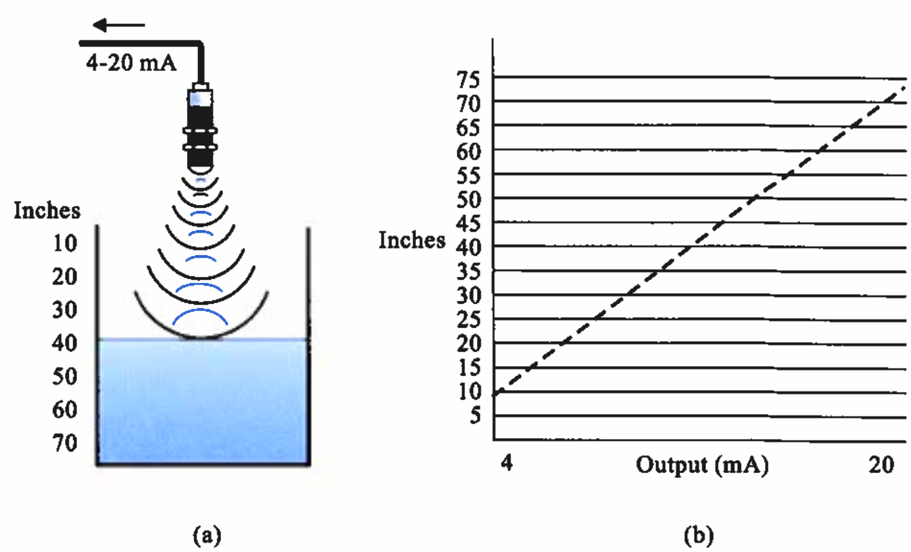


FIGURE 7-9 Ultrasonic sensors

Because of its atomic structure, the side of the crystal connected to one polarity expands, and the other side contracts when the opposite polarity is applied. The high-frequency expansion and contraction of the crystal causes the surrounding air to emit ultrasonic waves.

By replacing the AC source with a voltage amplifier, a second assembly, made of the same components as the transmitter, can operate as an ultrasonic receiving unit. The incoming ultrasonic waves cause the diaphragm to vibrate. The result is that the piezoelectric crystal expands and contracts, which creates a high-frequency AC voltage between the plates.

The magnitude of the receiver's output is proportional to the distance between the sensor and the target. The sensor can detect the object within a given range.

Most analog sensors have the capability of varying the range by performing a calibration procedure. The desired minimal distance at which the target is placed from the sensor is called the *zero* calibration setting. At this distance, the following types of sensors will produce its minimum output value:

Voltage Sensor: 0 V

Current Sensor: 4 mA

The desired maximum distance at which the target is placed from the sensor is called the *span* calibration setting. At this distance, the following types of sensors will produce its maximum output value:

Voltage Sensor: 10 V

Current Sensor: 20 mA

The specific distance of the zero and span settings can be programmed into a microcontroller incorporated into the sensor head.

After the zero and span settings are made, the sensor produces a linear output that is proportional to the distance the target is located from the sensor. For example, an analog voltage sensor will produce 5 volts when the target is halfway between the minimum and maximum sensing distance established during the calibration procedure. Figure 17-10 shows the relationship of the zero and span settings of an analog ultrasonic sensor both pictorially and graphically.

The graph in Figure 7-9(b) shows that the output current produced by the ultrasonic sensor is proportional to the distance it measures. The controller to which the sensor is connected can be programmed to convert 20 mA to indicate that the tank is empty and 4 mA when it is at full capacity with 75 inches of material. Ultrasonic sensors should not be used in applications where a mist is present in the vapor space above the liquid. The reason is that sound travels through a mist at a different speed than it does through dry air. Inaccurate readings are also made if a layer of foam on the surface is detected.

The advantages of ultrasonic sensors are that they are noninvasive, they have a long sensing range, and they have a long lifespan because there are no moving parts.

EXAMPLE 7-4

For an analog ultrasonic sensor that produces an output of 0 – 10 volts, at what distance is the target located when it produces 2 volts if the *zero* calibration setting is for 20 inches and the *span* setting is for 70 inches?

Solution

Step 1: Determine the unit volts per inch. This value represents how much the sensor's output voltage changes for each inch the target moves.

$$
\begin{aligned}
U_V \text{ (Unit Volts)} &= \frac{\text{Sensor Voltage Range}}{\text{Target Range}} \\
&= \frac{10\text{ V} - 0\text{ V}}{70\text{ in.} - 20\text{ in.}} \\
&= \frac{10}{50} \\
&= 0.2\text{ V}
\end{aligned}
$$

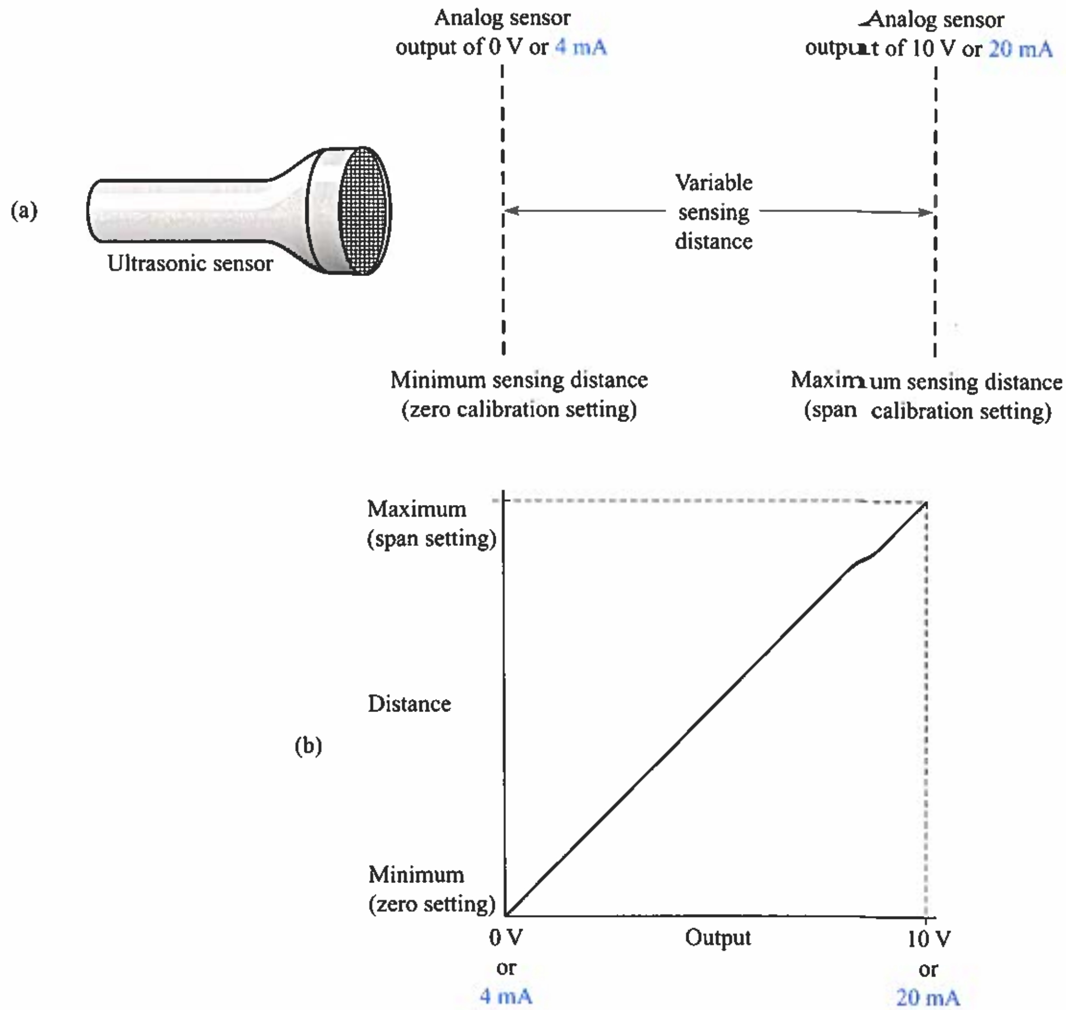


FIGURE 7-10 Zero and span settings of an analog ultrasonic sensor: (a) pictorial drawing; (b) graph

Step 2: Divide the sensor's voltage by the unit volts value to determine how far the target is located from the minimum sensing range distance *(which is used as a reference).*

$$\frac{\text{Sensor Voltage}}{\text{Unit Volts }(U_V)} = \frac{2\text{ V}}{0.2\text{ V}} = 10\text{ in.}$$

Step 3: Add the distance calculated in Step 2 to the minimal sensing distance of 20 inches to determine how far the target is located from the sensor.

$$\begin{aligned}\text{Target Location} &= 10\text{ in.} + 20\text{ inches}\\ &= 30\text{ in.}\end{aligned}$$

7-5 Selecting a Level Sensor

When selecting the most appropriate level measuring device for a particular application, the following considerations should be made:

What are the physical properties of the medium?

- Is it a solid or a liquid?
- Will foam, vapors, or a mist be present?

- Does the material contain chunks or voids?
- Is the material prone to density changes?

What are the chemical and thermal properties?

- Corrosive
- Flammable
- Caustic
- Sterile

These factors are considered along with reliability, cost, and safety.

Problems

1. List two common units of measurement to describe height.
2. List two types of inferred values used to indicate level measurement.
3. List two reasons why it is essential to monitor the level of material in a container.
4. Explain the meaning of the term interface.
5. A dipstick is ________ (a direct, an indirect) measurement device.
6. Point measurements are used to determine ____.
   a. high-level limits c. both high- and low-level limits
   b. low-level limits
7. Using the weight of an object is ____ method of measuring level.
   a. an invasive b. a noninvasive
8. List an indicator method used for level measurements that does not provide a feedback signal.
9. A float is ____ method of determining level.
   a. an invasive b. a noninvasive
10. As fluid level rises, the weight of a displacement float indicator appears to ____.
    a. increase b. decrease
11. As the fluid level decreases, the back pressure developed in a purge level measurement device ________ (increases, decreases).
12. List a common mechanical instrument used to measure the level of solid materials.
13. Where is the pressure detector placed in a vessel to measure the level of a liquid?
14. A differential pressure to determine level is used in ________ (an open, a closed) vessel.
15. Weight measurements can be used to determine the level of ____ in a tank.
    a. solids c. both solids and liquids
    b. liquids
16. Capacitance measurements are made to determine the level by ____ method(s).
    a. point c. both point and continuous
    b. continuous
17. The ultrasonic instrument uses ____ method(s) to determine the level of foods and pharmaceuticals in a container.
    a. invasive c. both invasive and noninvasive
    b. noninvasive
18. Hydrostatic head pressure is measured from the ____ of a full tank.
    a. bottom c. top
    b. middle
19. In a purge level measurement system, the rate at which the bubbles leave the tube ____ as the level of the contents rises.
    a. increases b. decreases
20. A conductive probe is capable of making ____ type measurements.
    a. point c. both a and b
    b. continuous
21. Water is stored in a vessel at 60 degrees Fahrenheit. A pressure gauge at the bottom of the tank reads 40 psi. What is the height of the water?
22. At what distance is the target located from a 4–20 mA ultrasonic sensor that produces 13 mA if the zero calibration setting is 2 feet and the span setting is for 10 feet?
23. Determine the buoyancy force on an object that displaces 3.2 ft^3 of water at 20 degrees Celsius.

CHAPTER 8

Analytical Instrumentation

OBJECTIVES

At the conclusion of this chapter, you should be able to:

- Identify acidic and alkaline solutions and describe how to make them neutral.
- Explain how to treat solutions that are too conductive.
- Describe how proper combustion is achieved, and how to eliminate a volatile condition with a combustible gas.
- Explain how to increase or decrease the moisture content in air.
- Define the following terms:

  Aqueous Solution
  Absolute Humidity
  Combustion
  Conductivity
  Dew Point
  Dissociation
  Effluent
  Humidity
  Hydrocarbon Fuel
  Hygroscopic
  Influent
  Reagent
  Relative Humidity
  Process Stream

- Describe the operation of the following types of analytical measurement instruments:

  pH Electrodes
  Psychrometric Detector
  Conductivity Electrode Probe
  Hygrometric Detector
  Conductivity Inductive Probe
  Electronic Capacitance Detector
  Infrared Gas Analyzer
  Chilled Mirror Detectors
  Optical Chilled Mirror Hygrometer
  Aluminum Oxide Sensor
  Sampling Measurement System
  Adiabatic Expansion Sensor

- List practical applications of the following types of analytical control systems:

  pH
  Conductivity
  Combustion
  Humidity

INTRODUCTION

Some types of industries involve chemicals to manufacture their products. When the chemical composition of a product is a variable that must be controlled, a procedure called *analytical measurement and control* is performed. The process for which the chemical is used involves the flow of either a gas or a liquid, and is called a *process stream*. The instrument used to determine the condition of the chemical is called an *analyzer*. Process analyzers can be categorized as those that analyze gases and those that analyze liquids. In this chapter information about the following types of analytical processes will be provided: pH, conductivity, combustion, and humidity.

8-1 pH Measurement and Control

The concentration of acids and alkaline (bases) in a chemical solution must be controlled in many industrial applications. The analytical process that performs this function is referred to as **pH control.**

The term *pH* represents a unit of measure that describes the degree at which a solution is acidic or alkaline. Most solution becomes acidic or alkaline when a compound is mixed with water (anything mixed with water is referred to as an *aqueous solution*). A stable compound by itself is electrically neutral. When some compounds are combined with water, they *dissociate,* which means they break up into two or more charged particles. The charged particles formed are called *ions,* and are created by molecules which either gain or lose electrons. The degree to which a solution becomes acidic or alkaline is determined by the number of positive and negative ions that form, and the percentage of charged particles compared to the neutral undissociated molecules with which they are combined. This relationship is called *dissociation (ionization) constant,* and is represented by the following formula:

$$K = \frac{(M+)(A-)}{(MA)}$$

where,

K = Dissociation Constant
M+ = Concentration of Positive Ions
A− = Concentration of Negative Ions
MA = Concentration of Undissociated Ions

The number of negative ions compared to positive ions determines whether the solution is acidic or alkaline. If the majority of ions are positive, it is an acidic solution. Conversely, a solution with predominately negative ions is alkaline. Pure water has an equal amount of positive and negative ions, and therefore is considered neutral.

The water dissociates into equal concentrations of two types of ions, hydrogen (H+) and hydroxyl (OH−). However, the number of water molecules dissociated is very small in comparison to those undissociated. Its dissociation constant is only 1. When a compound such as hydrochloric acid is combined with water, it breaks up almost completely into many positive charged ions and few negative charged ions. Therefore, its dissociation constant is practically infinity, which indicates it is a strong acid. When acetic acid is combined with water, fewer than one molecule ionizes for every 100 molecules that do not dissociate. Therefore, it has a low dissociation constant, which indicates it is a weak acid. When sodium hydroxide is combined with water, most of its molecules dissociate into negatively charged hydroxyl ions. Therefore, it becomes a strong base. A small concentration of hydroxyl ions form when ammonium hydroxide combines with water, forming a weak base solution.

The measured scale for pH is from 0 to 14. A pH value is directly related to the degree of acidity, or the amount at which hydrogen ions (H+) form in a solution. One liter of pure water for example, has a 10^{-7} (0.0000001) gram equivalents of H+ ions. The power of 10 for this quantitative value is 7. Therefore, 7 is used as the pH number for water.

Table 8-1 shows the pH concentration, known as activity, through the pH range of 0 to 14. Any number less than 7 indicates that a solution is acidic. Acid solutions increase in strength as its pH value becomes closer to 0. Any number greater than 7 indicates an alkaline solution. Alkaline solutions increase in strength as the pH values rise above 7 (up to 14).

The table also shows the number of H+ and OH− ions for each pH value. Recall that there are equal numbers of positive and negative ions in water. The table lists 10^{-7} hydrogen ions and 10^{-7} hydroxyl ions. The product of water concentration of H+ ions and OH− ions is 10^{-14}. Regardless of what other compounds are dissolved in water, the product of the concentration of H+ ions and OH− ions is always 10^{-14}. Note that there is an inverse relationship between the number of hydrogen and hydroxyl ions. If the concentration of one type of ion is known, the concentration of the other ion can be determined.

Table 8-1 also shows that a change of one pH unit represents a tenfold change in the hydrogen ion concentration. Therefore, pH is a logarithmic function. This information helps explain how the term *pH* is derived. "p" refers to the mathematical symbol of the negative logarithm, and "H" is the symbol for hydrogen. Figure 8-1 graphically shows pH values of some common acidic and alkaline products manufactured in the process industry.

TABLE 8-1 pH Activity

	pH	Hydrogen ion (H^+)		Hydroxyl ion (OH^-)
Acid	0	(10^0=)	1	0.00000000000001
	1	(10^{-1}=)	0.1	0.0000000000001
	2	(10^{-2}=)	0.01	0.000000000001
	3	(10^{-3}=)	0.001	0.00000000001
	4	(10^{-4}=)	0.0001	0.0000000001
	5	(10^{-5}=)	0.00001	0.000000001
	6	(10^{-6}=)	0.000001	0.00000001
Neutral	7	(10^{-7}=)	0.0000001	0.0000001
Base	8	(10^{-8}=)	0.00000001	0.000001
	9	(10^{-9}=)	0.000000001	0.00001
	10	(10^{-10}=)	0.0000000001	0.0001
	11	(10^{-11}=)	0.00000000001	0.001
	12	(10^{-12}=)	0.000000000001	0.01
	13	(10^{-13}=)	0.0000000000001	0.1
	14	(10^{-14}=)	0.00000000000001	1

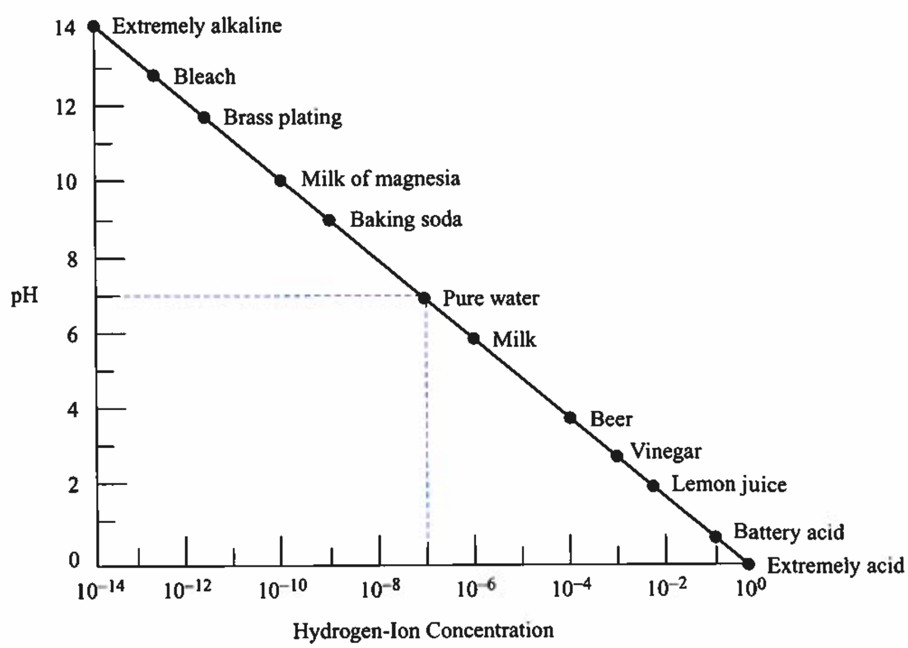


FIGURE 8-1 Relationship of pH and hydrogen-ion concentration

The values listed are based on the solution at a temperature of 25°C (77°F), which is referred to as *standard temperature*. As the temperature of the solution varies, the dissociation constant also changes. This situation causes the ratio of H+ to OH– ions to be altered, which changes the pH value. Table 8-2 shows the effect on pure water when it is exposed to temperatures ranging from freezing to boiling point. At the standard temperature of 25°C, the neutrality pH value is 7.00. However, the neutrality value goes above 7 when its temperature is lower than 25°C, and goes below 7 when its temperature is higher than 25°C.

TABLE 8-2 Effect of Temperature on the pH Value of Pure Water

Temperature		Dissociation Constant	Neutral pH
°C	°F		
0	32	14.94	7.47
25	77	14.00	7.00
50	122	13.26	6.63
75	167	12.69	6.35
100	212	12.26	6.13

To make accurate measurements, the effect of temperature must be considered. By measuring the degrees of the solution, a correction factor calculation can be used to compensate for any temperature effects. Many electronic pH analyzers have circuitry that is designed to automatically make the correction.

pH Measurements

Devices used to measure pH values detect the concentration of hydrogen ions. Early techniques involved paper indicators. When submerged into the measurement sample, the indicator would produce a color change. The color to which it changed would indicate the value of the pH concentration.

One drawback of this method is that it cannot be used to measure solutions that are colored. Also, it does not provide an electrical measurement signal necessary for automatic control applications. For this reason, electronic sensors were developed to provide a continuous feedback signal used in closed-loop systems. The instrument used to measure pH consists of two separate electrodes and an amplifier. One electrode is the *active,* or sensing device, which produces a voltage proportional to the hydrogen-ion concentration. The other electrode is a *reference* device that provides a potential against which the output of the active measuring electrode is compared. The amplifier boosts the small signal from the electrodes to a level that can either be transmitted or used for display.

Figure 8-2 shows the pH *active electrode.* It consists of a thin-walled tube made of a special glass designed to be sensitive only to hydrogen ions. The bottom of the tube contains a buffer solution, which is a liquid of known pH, usually potassium chloride. The cable from the electrode amplifier connects to the inner wire of the electrode, which is made of silver wire. The wire is coated with a silver-silver chloride that makes the electrical connection between the inner wire and the buffer solution in which it is immersed.

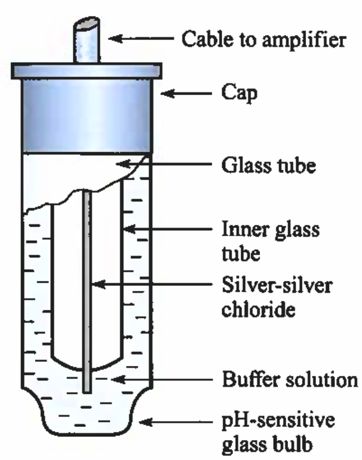


FIGURE 8-2 pH sensing electrode

Figure 8-3 shows the *reference electrode.* It also uses glass to form the outer shell of a tube. The cable between the electrode and amplifier connects to an inner tube wire made of silver that is coated with a paste made of silver chloride. The paste is in contact with potassium chloride (KCl) which is a solution that is an electrical conductor. The purpose of the KCl is to provide electrical contact between the pH process solution being measured and the amplifier. The electrode connection is made through a porous strand of ceramic material. This material acts as a wick and is fitted through the glass at the bottom of the electrode.

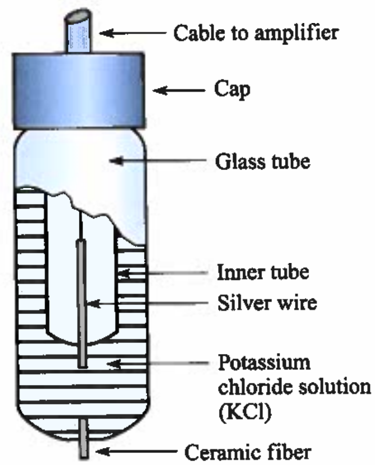


FIGURE 8-3 pH reference electrode

The pH active electrode operates on the principle that a potential (voltage) is formed between two solutions of different hydrogen-ion concentrations. The buffer solution within the electrode has a constant concentration of hydrogen ions at a pH of 7.0. Whenever the hydrogen-ion concentration of the process solution being measured is different from that of the buffer solution, there is a potential difference across the thin glass insulator of the electrode. The magnitude of the voltage is proportional to the pH of the process solution. For every pH unit of the process solution being detected, a potential of 59.2 mV is produced. If the process solution has a pH of 7.0, the potential difference is 0. When the pH is greater than 7.0, a voltage of one polarity is applied to the amplifier from the inner wire of the electrode. When the pH of the solution is less than 7.0, a voltage of the opposite polarity is applied to the amplifier.

The best way to understand the operation of the pH electronic sensor is to compare its operation to a battery measured by a voltmeter. The amplifier operates as the voltmeter. The wire inside the sensing electrode and the amplifier cable to which it is connected function as one lead of the voltmeter. A voltage measurement cannot be made with only one meter lead. The reading can only be taken if a second lead of a voltmeter is used. The reference electrode, which makes the electrical connection between the measured solution and the amplifier, functions as the second lead of the voltmeter. The buffer solution of the active electrode can be compared to one battery terminal, and the pH solution being measured is the other battery terminal.

Some pH amplifiers include a resistive element that is also immersed in the solution being measured. Its resistance changes with the temperature of the solution. Adding this element into the circuit enables the device to compensate for any changes in the pH measurement due to temperature variations. The sensing electrode, reference electrode, and the resistive element are shown in Figure 8-4. These three devices are often contained in the same housing instead of being separate.

Some manufacturers offer several different glass formulations from which probes are made. Each type is tailored to a particular process application. Figure 8-5 shows the classifications they are used for.

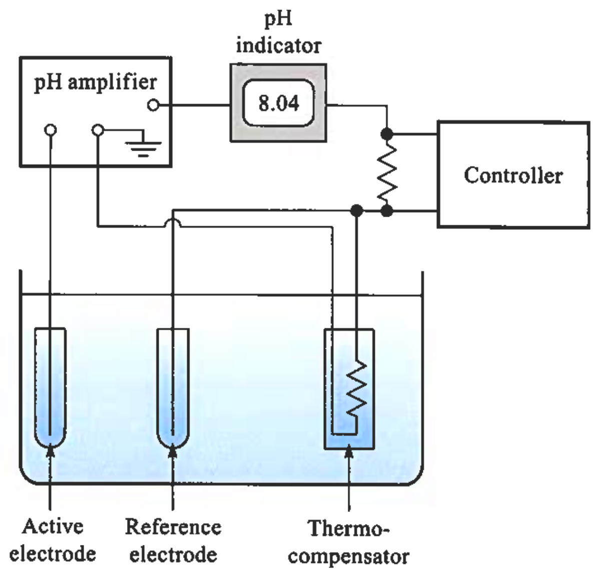


FIGURE 8-4 Electronic pH sensor

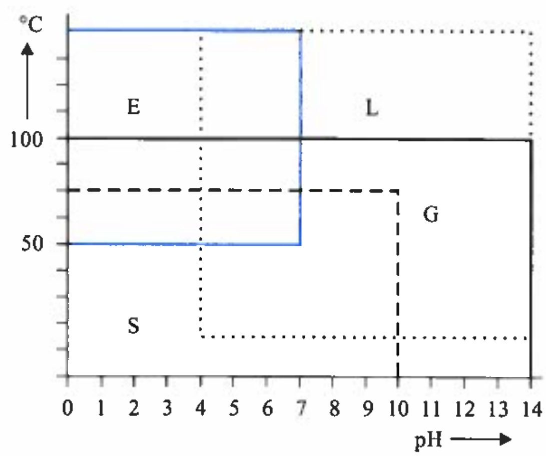


FIGURE 8-5 Glass characteristics

Controlling pH

One of two conditions typically exists when controlling pH. Either a solution is too alkaline and an acid must be added to reach a specified lower pH, or a solution is too acidic and a base must be added to increase the pH. In both situations, the corrective ingredient, called a **reagent,** must be added at a proper amount and rate to bring the pH to the desired level.

One objective of a pH control system is to minimize the amount of reagent added to the solution. However, determining and feeding the exact amount is difficult because of the logarithmic characteristics of pH reaction in a solution. A problem that often arises is overshooting. By properly designing a control system, overshooting can be either eliminated or minimized. pH control may be implemented in batch or continuous systems.

Batch Systems

A batch system usually employs a tank to store the solution for treatment. Figure 8-6 shows a batch tank. The solution that enters the tank through an inlet is called an *influent.* After the tank is filled, the pH value of the solution is measured. A controller compares the feedback signal to the setpoint. If there is a difference, it sends a signal to an actuator, which causes a reagent to be applied. Overshoot is prevented and the control action is usually most accurate when the flow rate of the reagent is slow and a stirring action is provided by a mixer. To ensure accurate measurements, the electrode should be located away from the tank inlet and the feed point of the reagent. This separation is required to allow proper mixing before measurements are made. After the solution is treated, the tank is drained. This solution is called an *effluent,* and flows through an outlet port.

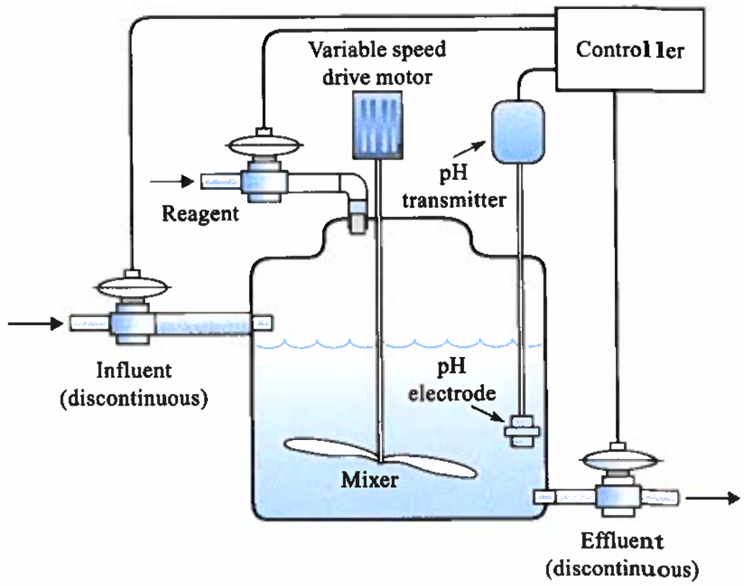


FIGURE 8-6 Batch pH control system

Batch pH control is typically used when the volume of the solution to be treated is relatively small. A common application is the treatment of waste water. Liquids are collected efficiently in tanks. By adding a reagent and using a mixing action, the solution is neutralized to a pH level of 7.0.

Continuous Systems

Many continuous systems use a tank to treat a solution, as shown in Figure 8-7. A reagent is applied and mixed as a continuous flow of influent enters the tank and the treated effluent is discharged.

If the pH of the influent varies by a small amount in batch or continuous systems, an On-Off controller that drives a solenoid valve is used to apply the reagent. If the pH of the influent varies widely, a proportional controller that drives a control valve should be used.

One disadvantage of using a tank in a continuous process system is that there is typically a long delay time. This characteristic can cause the process pH level to rise above and below the setpoint by a large amount. In applications that require a pH value to be within 4 and 10, a *static mixer* is used. Figure 8-8 shows a continuous system that uses this device. By injecting the reagent at the mixer input and placing the pH sensor at the mixer output, the reaction time becomes very short.

pH analyzers are used in practically every industry that uses water within its process. Applications can be found in water and waste treatment operations; power generating plants; petroleum refineries; and in food processing, pulp and paper, metal production, pharmaceutical and chemical industries.

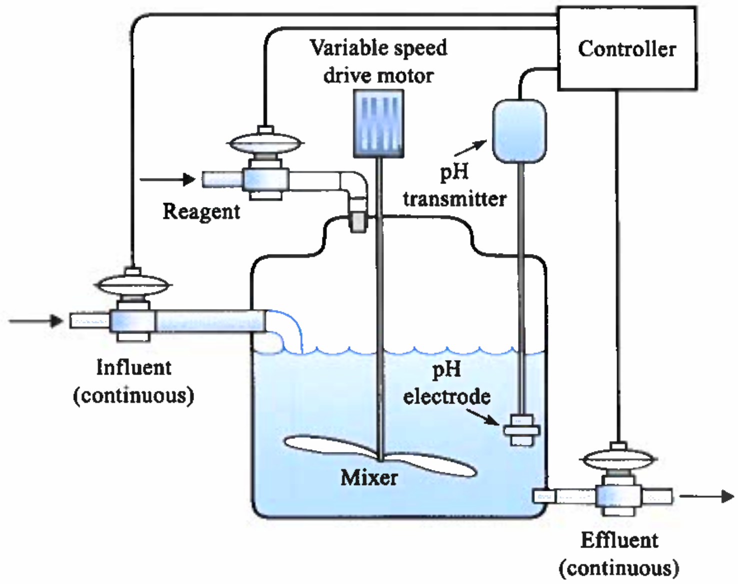


FIGURE 8-7 Continuous pH control system

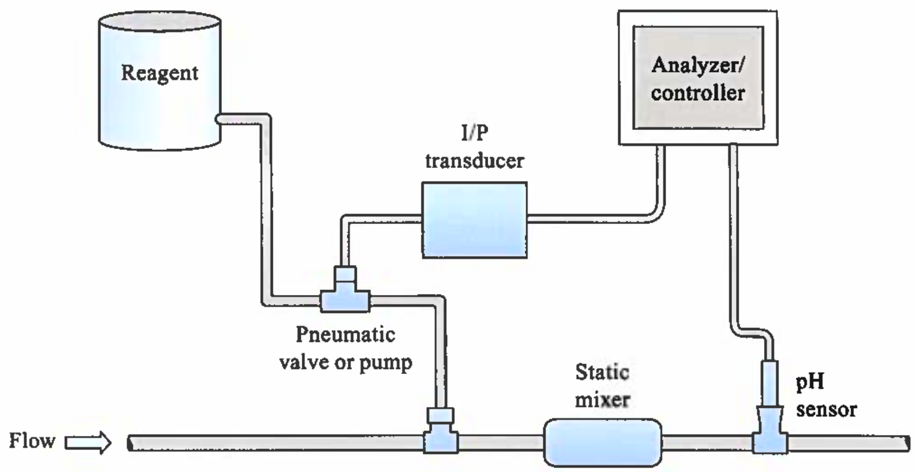


FIGURE 8-8 Continuous on-line control system using a static mixer

8-2 Conductivity

Any process that involves liquid requires flow. The flow may be continuous, or discontinuous, such as in a tank that is periodically filled or drained in a batch application. The liquid that is used in these processes is referred to as a *process stream.* Process streams contain either pure water, water or solutions that are combined with other ingredients. In many manufacturing applications, it is necessary to either determine the purity of the water, or the concentration level of the solutions dissolved in a liquid. This information may be obtained by using a measurement procedure called **conductivity.**

Conductivity refers to the ability of a material to pass electric current. The symbol for conductance is G, and its unit of measurement is siemens. The following formula shows that conductance is the reciprocal of resistance (R):

$$G = \frac{1}{R}$$

All liquids possess conductivity to some degree, ranging from low to very high. High conductivity indicates that electrons can flow easily through a liquid because it contains a large number of ions. These ions are formed by dissolving *electrolytes* such as acid, bases, and salts in water. Low conductivity indicates that less current flows because of the higher resistance caused by the presence of fewer ions in the liquid. An example is distilled or pure water. The only ions which are present are hydrogen and hydroxyl formed from the dissociation of water itself. Unlike pH measurements, which respond specifically to hydrogen ions, conductivity measurements respond to any and all ions in solutions. The degree of electrical conductivity of a liquid is determined by the following factors:

1. The concentration of an ingredient dissolved in water, ranging from zero to very high
2. The type of electrolyte contained in a dissolved ingredient
3. The temperature of the liquid

Several kinds of sensors, or probes, are used to measure the conductivity of a process stream. The two main types are the electrode probe and the inductive probe.

Conductivity Electrode Probe

Conductivity measurements can be obtained by immersing two plates in the process liquid. Shown in Figure 8-9, each of the plates, called electrodes, is placed parallel to each other. A known voltage is applied across the electrode, which causes a current to flow through the solution from one plate to the other. The current, which is linearly related to conductivity, is measured by the analyzer and converted by its circuitry to a conductivity reading for display.

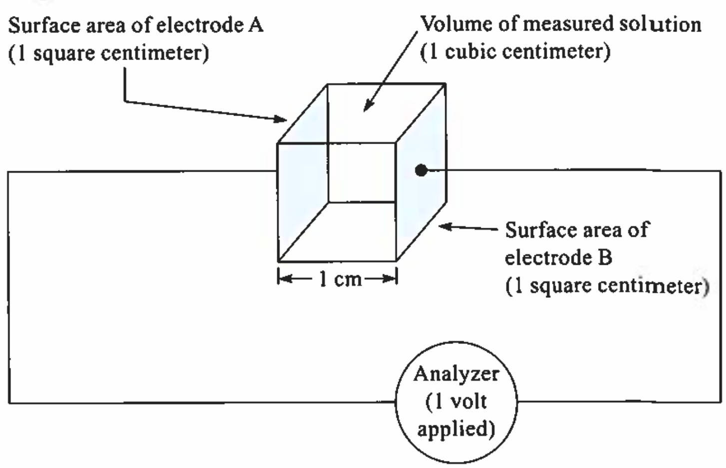


FIGURE 8-9 Conductivity electrode probe

The conductivity analyzer makes measurements at different ranges, similar to the way an ohmmeter reads resistance within several ranges. However, instead of having the same type of range switch used by an ohmmeter, conductive values are measured within ranges by changing the dimensions of the electrodes. By changing the area of the plates and the distance they are apart, the volume between them changes. Therefore, the current and indicated conductivity varies, although the applied voltage has not changed. The formula that shows the relationship of the dimensions to conductance is:

$$G = \frac{AK}{L}$$

where G is conductance (siemens), A is the area of each electrode (cm^2), L is the distance between the plates, and K is the specific conductivity of the material between the plates.

A standard to which conductivity measurements are compared uses the following criteria:

- The area of each plate is 1 cm^2.
- The distance between the plates is 1 cm.
- The solution consists of potassium chloride (KCl) at 25°C.

Under these constants, the volume of the solution is one cubic centimeter and the conductance is one siemen.

A theoretical reference value, which is shown in Figure 8-9, establishes a cell constant of 1. Cell constants range from 0.01 to 100 and vary by multiples of 10. Different cells must be used for different ranges so that the amount of current fed to the analyzer circuitry is within its operating requirements. Either the surface area of the plates or the distance between them is changed to each range. If the solution has low conductivity, sensors with plates that are either large or placed closely together are needed to increase the current between them. Conversely, a solution with high conductivity will use plates that are smaller or placed farther apart. Therefore, the cell constant used is determined by the range of conductivity of the liquid being measured. Solutions with an extremely high conductivity require a sensor with a cell constant greater than 1.0. Solutions with a low conductivity require a sensor with a cell constant less than 1.0.

The unit of measurement for conductivity is typically in siemens per centimeter. A sensor with a cell constant of 0.01 has a range of 1 to 10 microsiemens; a sensor with a cell constant of 0.1 has a range of 1 to 100 microsiemens and a sensor with a cell constant of 1.0 has a range of 1 to 1000 microsiemens.

A DC voltage is seldom applied to the electrodes because, over a prolonged period of time, a complete ion migration to the plates will occur. This condition, called *polarization,* would develop because a gaseous layer would form on the surface of the electrodes and alter the measurement. To prevent this situation, an alternating current is applied to the plates. A Wheatstone bridge with a null balance adjustment is often used as a part of the electrode circuit for calibration purposes.

The temperature of the solution has a significant effect on its conductivity. For example, decreasing the temperature of a liquid increases its viscosity, thus decreasing the mobility of its ions and therefore its conductivity. To compensate for the effects of temperature variations a series-parallel network, a thermistor is added to the Wheatstone bridge.

Conductivity Inductive Probe

The *conductivity inductive probe* uses two toroidal coils. Shown in Figure 8-10, both coils are wrapped around a nonconductive core. Because the probe is inserted into the process liquid, the coils are protected by being encased inside a corrosion-resistant material.

One coil is connected to an oscillator that supplies AC voltage. Its function is to generate a fluctuating-current loop in the solution. A magnetic field formed around the current path cuts across the other (pickup) coil and induces a current into its circuit. The current induced in the pickup coil is directly proportional to the conductivity of the solution. The current from the pickup coil is converted by electronic circuitry into a conductivity reading for display.

Inductive probes are used in applications where the measured solutions are dirty or corrosive. These solutions are highly concentrated with impurities that contain many ions. Therefore, induction probes typically make high conductivity measurements. Conductivity values for some common process solutions are shown in Table 8-3.

Conductivity Applications and Control

Conductivity control is used in a variety of applications.

Closed Water System

To recycle the water used for equipment such as cooling towers and boilers, it is continually recirculated through the system as it flows. After a prolonged period of time, some of this

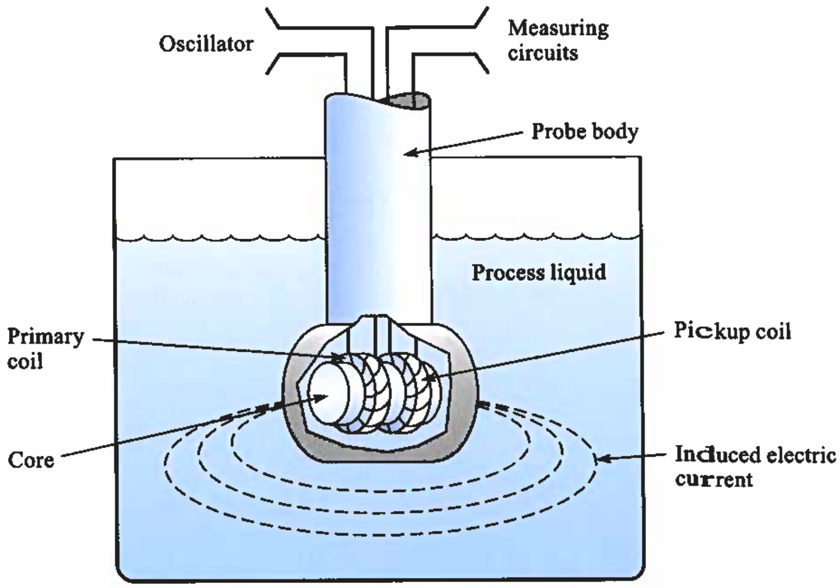


FIGURE 8-10 Conductivity inductive probe

TABLE 8-3 Conductivity Values of Common Solutions

Solutions	*Conductivity*
Water (theoretical)	0.055 µS/cm
Distilled Water	0.5 µS/cm
Power Plant Boiler Water	1.0 µS/cm
Pure Mountain Stream	10.0 µS/cm
City Tap Water	500–700 µS/cm
Ocean Water	54 mS/cm
10% Sodium Hydroxide	355 mS/cm
10% Sulfuric Acid	432 mS/cm
31% Nitric Acid	865 mS/cm

water evaporates, allowing the concentration of solids dissolved in the water to rise. If the concentration level becomes high enough, solids cause scaling to form, which can cause damage to the equipment. Conductivity control causes a system bleed valve to discharge the contaminants from a location where they collect.

Semiconductor Production

Water is used in the formation of semiconductor components. The water must be of very high purity and contain a negligible amount of ions. Conductivity sensors are used to measure the quality of the water. The information from these measurements is used to control the output of a *deionizer.* Water is neutralized as it passes through the device.

Conductivity control is also used in the following industries: textiles, brewing, mining, electroplating, food processing, paper, petroleum, and photographic development.

8-3 Combustion Analyzers and Control

The energy required for many industrial processes is obtained from a chemical reaction called **combustion.** Combustion, commonly known as *burning,* uses a combination of gases and fuel. As a by-product of the reaction, other gases are formed.

There are two types of fuels required for combustion to occur. One type is a hydrocarbon (fossil) fuel. Oxygen must also be present for this type of combustion to occur. The other type of fuel is referred to as a combustible gas. These combustible gases include hydrogen, carbon monoxide, hydrogen sulfide, methane, propane, butane, and ethane. Oxygen must also be present for these gases to burn.

The burning operation in industrial applications must be accomplished under precise control conditions. The objective is to ensure that it is performed efficiently and safely. By measuring the presence of gases or their concentration, it is possible to determine if the burning is being properly achieved. These gases are monitored by several types of analytical sensors. Each type of sensor is specifically designed to measure one kind of gas.

The following information describes the types of gases that are present in many industrial processes and the sensors used to measure them.

Combustible Gases

A combustible gas is used as a fuel to provide heat. These gases are usually confined under controlled conditions within a container, where they are stored, or as they burn. If they escape from their container, they can become very dangerous. For example, if they are exposed to a spark, they can create a fire or an explosion. These gases include hydrogen, carbon monoxide, hydrogen sulfide, methane, propane, butane, and ethane. Analytical sensors for combustible gases are designed to detect their presence to prevent damage or injury.

A common type of combustion gas analyzer is the *thermo-conductivity detector* (TCD). Its operation is based on the behavior of gases when they are exposed to heat. Each type of gas has the ability to conduct thermal energy. The type of gas and its concentration determines the rate at which the heat is conducted. The TCD uses a bridge network, as shown in Figure 8-11. One portion of the bridge is connected to two resistive heating elements (made of a tungsten-rhenium alloy) that are inside an enclosed chamber that contains a known reference gas. The other portion of the bridge has two resistive elements inside a chamber that is exposed to the measured gas. If this gas is the same type of gas as the one inside the

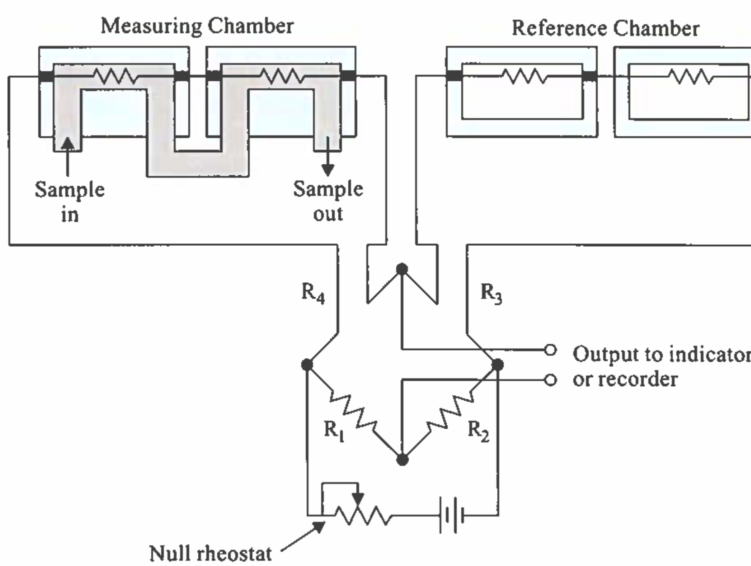


FIGURE 8-11 Thermo-conductivity detector

reference chamber, the bridge network will be balanced and its output will be zero volts. When a different gas flows through the measuring chamber, the rate of heat loss of the gas to which the heating element is exposed changes and its resistance becomes different. As a result, the bridge output changes. The reading is an inferred indication of which type of gas is present. Table 8-4 shows some common thermal conductivity readings of various combustible gases.

TABLE 8-4 Relative Thermal Conductivity (TC) of Gases at 100°C

Gas	TC
Air	1.0
Hydrogen	6.990
Helium	5.840
Carbon dioxide	5.3
Methane	1.450
Ethane	0.970
Nitrogen	0.996
Benzene	0.573

Hydrocarbon Gases

Combustion occurs when oxygen and *hydrocarbon fuels* are ignited. Together, they contain the elements of hydrogen, carbon, and oxygen. When they burn completely, their by-products are water and carbon dioxide. Complete combustion is the result of an efficient burning process. This action requires a proper fuel-to-air ratio. If the fuel does not burn completely, some of it becomes carbon monoxide. The carbon monoxide gas can be very dangerous in two ways. By itself, it is a combustible gas and can be reignited unintentionally. It is also very poisonous and can be harmful to humans if inhaled.

The presence and concentration of carbon dioxide and carbon monoxide can be detected by using an *infrared gas analyzer.* This type of sensor is often placed in the flue or stack of a combustion chamber to monitor the gases that are discharged.

An infrared gas analyzer is shown in Figure 8-12. It consists of six major elements:

1. An infrared light source, which supplies an electromagnetic signal outside the frequency range that can be seen by humans.
2. A sample chamber that holds the gas that is monitored. The chamber has glass windows that allow light to pass through.

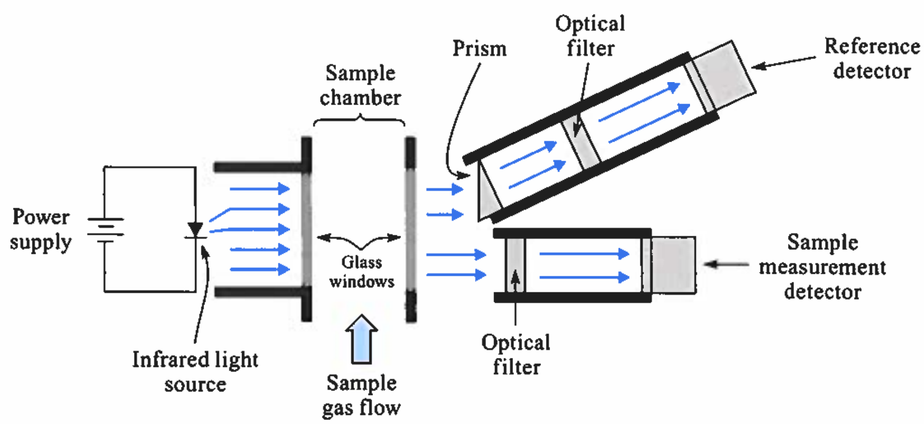


FIGURE 8-12 Split-beam optical gas analyzer

3. A prism, which splits a portion of the light from the sample into a second beam.
4. Two optical filters, each of which allows the light of only one particular wavelength to pass through.
5. Two detectors, each of which senses the amount of light that strikes its surface.
6. Electronic circuitry that converts the signal from the detector into a reading that indicates the consistency of the measured gas.

The analyzer operates as follows:

- Electromagnetic radiation containing many different wavelengths from a light source passes through the sample chamber. Each type of gas absorbs a certain wavelength of the light that passes through. Therefore, most of a certain wavelength is blocked by the gas inside the chamber, and the light of other wavelengths passes through.
- Light transmitted through the chamber is divided into a second beam by a prism.
- Both optical filters permit the radiation from the wavelengths that were not blocked to pass through. The wavelengths absorbed by a gas are referred to as an *absorption band.* Each type of gas has a different absorption band frequency. Figure 8-13 shows the absorption bands of carbon dioxide and carbon monoxide. Infrared light is used because the absorption bands of both gasses fall within its frequency range.
- The upper optical filter permits light, which is at a frequency that will not be affected by the sample gas, to pass through. The frequency of this light is referred to as the *reference wavelength.* It strikes a light detector that produces an output voltage. The detector is designed to produce a steady amplitude that varies little or not at all with a change in the concentration of the gas.
- The light intensity of the measuring wavelength reaching its detector varies greatly with a change in the sample concentration. By comparing the signal strength of both detectors, the analyzer circuitry can compute the concentration of the gas. Figure 8-14 shows these wavelengths in relation to the absorption band of a gas.

Controlling Combustion

There are two ways in which combustion must be controlled in an industrial environment. Combustion must be controlled while it is occurring, or before it starts.

To achieve proper combustion while it is occurring, either measurements of gases used in the burning process are made or measurements of gases given off from the burn are taken. If the readings indicate an improper quantity, corrections can often be made by changing the fuel-to-air ratio.

Unwanted gases exposed to a spark can cause an explosion. These gases are usually present because of a leak. Sensors are used to detect their presence. Corrective action is often achieved by closing a valve, providing ventilation, and searching for the leak.

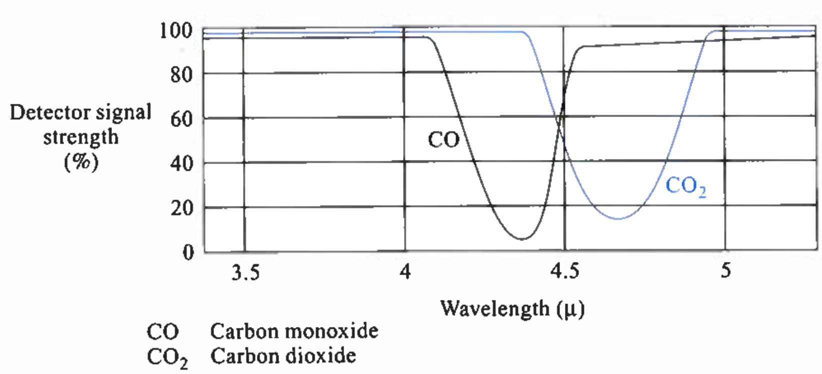


FIGURE 8-13 Absorption bands of carbon monoxide and carbon dioxide

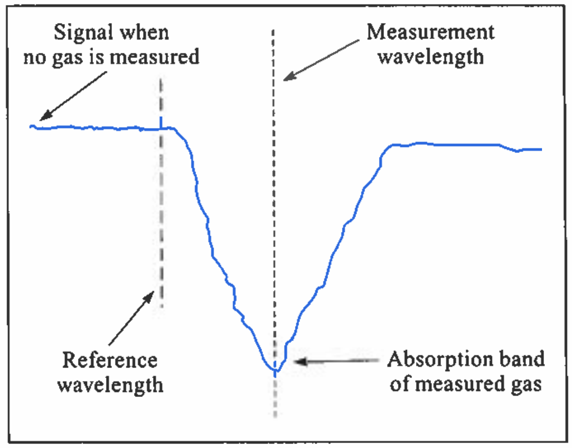


FIGURE 8-14 Absorption band signal in reference to associated wavelengths

8-4 Humidity

Humidity is defined as the amount of moisture in the air. The air may be isolated or part of the atmosphere. In industry, where products are either being made or stored, the air to which they are exposed must contain humidity levels that are within certain parameters. The wrong amount of humidity can be potentially damaging to a process. Too much humidity can promote the growth of mold and mildew; dry air causes moisture to evaporate quickly from the surface of an object, creating a cooling effect that may be undesirable. Dry air also causes static electricity, and with it, the likelihood of an explosion if combustible materials are present.

Humidity affects *hygroscopic* materials. Hygroscopic refers to the property of a material to absorb and retain moisture. These materials include paper, wood, flour, textile fibers, and tobacco. As they take on or give off moisture, they undergo changes in dimensions, weight, quality, and usefulness.

Quantitative Measures of Humidity

The first step in controlling humidity within an industrial environment is to measure the quantity of moisture in the air. There are three different quantitative measures of humidity, *absolute, relative,* and *dew point.*

Absolute

Absolute humidity is defined as the mass of water vapor present in a particular volume of atmosphere. This definition is based on the number of water molecules that are present in a known amount of air or gas. The absolute humidity value, or vapor concentration, is expressed as the ratio of the mass of water vapor to the volume occupied by the air-water vapor mixture. The formula for the actual humidity ratio is written as:

$$W = \frac{P_W}{P_a}$$

where,

W = Absolute Humidity

P_W = Mass Density of Water

P_a = Mass Density of Air

Absolute humidity is also known as *specific humidity.* It is expressed in various units such as grains of water per pound of air or pounds of water per million standard cubic feet.

Relative

Relative humidity (RH) is defined as the actual amount of water vapor present as compared to the maximum amount of water vapor the air can hold at a given temperature. As the temperature of the air rises, the amount of water vapor it can hold increases. For example, suppose that the amount of water vapor at 50°F saturates the air early in the morning. The relative humidity is 100 percent. When the temperature rises to 100°F at noon with the same amount of water vapor present, the air is considered dry because it contains 19 percent of the amount of water vapor it is capable of holding. The relative humidity, therefore, is 19 percent. Pressure also has an effect on how much water vapor the air can hold. As pressure increases, the water vapor saturation point decreases, and vice versa. The graph in Figure 8-15 shows the maximum amount of water vapor that air can hold at various temperatures when the pressure is 29.92 inches of Hg.

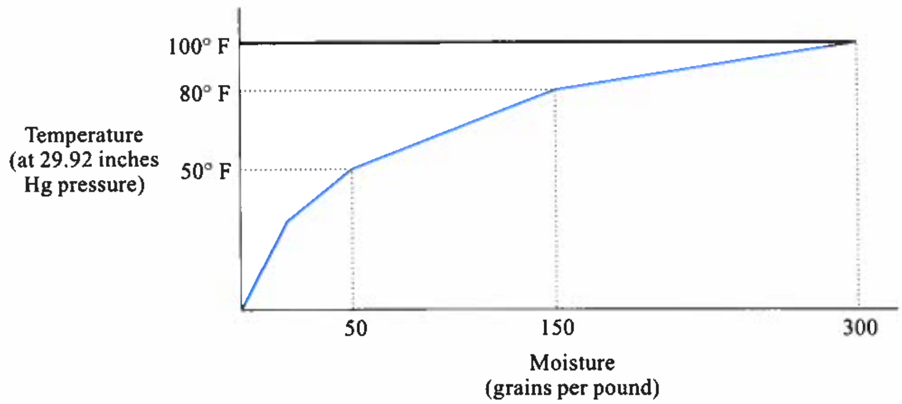


FIGURE 8-15 Maximum moisture content in air at various temperatures

Dew Point

Dew point is the temperature at which the air (or a gas) becomes saturated. When the air is cooled at a constant pressure, condensation of vapor will begin when the dew point is reached.

Absolute Humidity Sensor

The most common type of device used to measure absolute humidity is the *aluminum oxide sensor.*

Aluminum Oxide Sensor

This detection device is the most widely used moisture sensor in gaseous and nongaseous liquid industrial processes. Shown in Figure 8-16, this sensor consists of an aluminum strip that is anodized to form a porous aluminum oxide layer. A very thin permeable layer of gold is deposited over the oxide. Together, these three materials form a capacitor. The aluminum strip and gold layer each form an electrode, and the aluminum oxide is the dielectric. When the sensor is exposed to moisture, water vapor travels through the gold and equilibrates by penetrating into the pores of the oxide. The dielectric constant of the capacitor changes according to the amount of water vapor present. This condition affects the capacitor's value to represent the moisture reading.

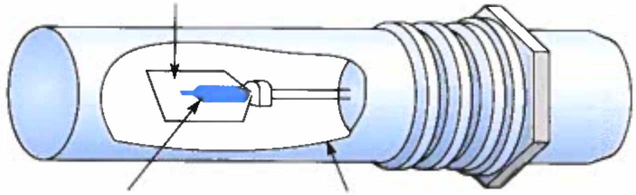


FIGURE 8-16 Aluminum oxide absolute humidity sensor

The aluminum oxide sensor has a wide range of applications. For example, it will detect the presence of undesirably high moisture concentrations. These include:

- Compressed air stream that must be sufficiently dehumidified if the line runs outdoors. Too much moisture causes harmful condensation or freeze-up.
- Natural gas in pipelines contaminated with moisture can develop partial or even total restriction of flow due to the formation of hydrates, a combination of water and hydrocarbon molecules in a state similar to ice. In addition, moisture accelerates pipeline corrosion and reduces the energy value of the gas.

Relative Humidity Detectors

The operation of relative humidity measurement detectors is based on the tendency of a material's physical or electrical properties to change in a predictable manner when exposed to humidity. Three common detection devices are the psychrometric, hygrometric, and electronic capacitance sensors.

Psychrometric Detector

This device uses two identical thermometers. One is called a *dry bulb* and the other a *wet bulb*. The dry bulb is directly exposed to the surrounding air. The wet bulb is covered by a wick that is kept moist. Air is passed over the wick by using one of two methods. Either the wet bulb is whirled in a circular path, or it is stationary and the air is drawn past it by an air exchanger. When the air flows over the wick, evaporation cools the thermometer inside until saturated equilibrium is reached. The drier the air, the more cooling that occurs. Once wet-bulb and dry-bulb temperatures are known, relative humidity can be determined by reading tables, psychrometric charts such as the one shown in Figure 8-17, or data from a computer software program.

Wet/dry bulb psychrometers are very accurate, but they require a high degree of maintenance. Their accuracy diminishes when the RH is below 20 percent.

Hygrometric Detector

This type of detector determines humidity by measuring the change in dimension of hygroscopic materials, such as hair, cotton, paper, or a synthetic wick. Human hair is one of the most common hygroscopic materials used. The hair absorbs moisture from the surrounding air by an amount that is a function of the water vapor present. As the water content in the hair increases, its length increases. Expansion and contraction of the hair cause a pointer or a pen to move, displaying a continuous relative humidity reading. Hygroscopic materials can also be used in conjunction with a humidistat switch to provide humidity controlled capabilities.

Humidity can also cause a change in the physical weight of hygroscopic materials. By measuring the weight as it absorbs or desorbs water, a relative humidity reading can be taken.

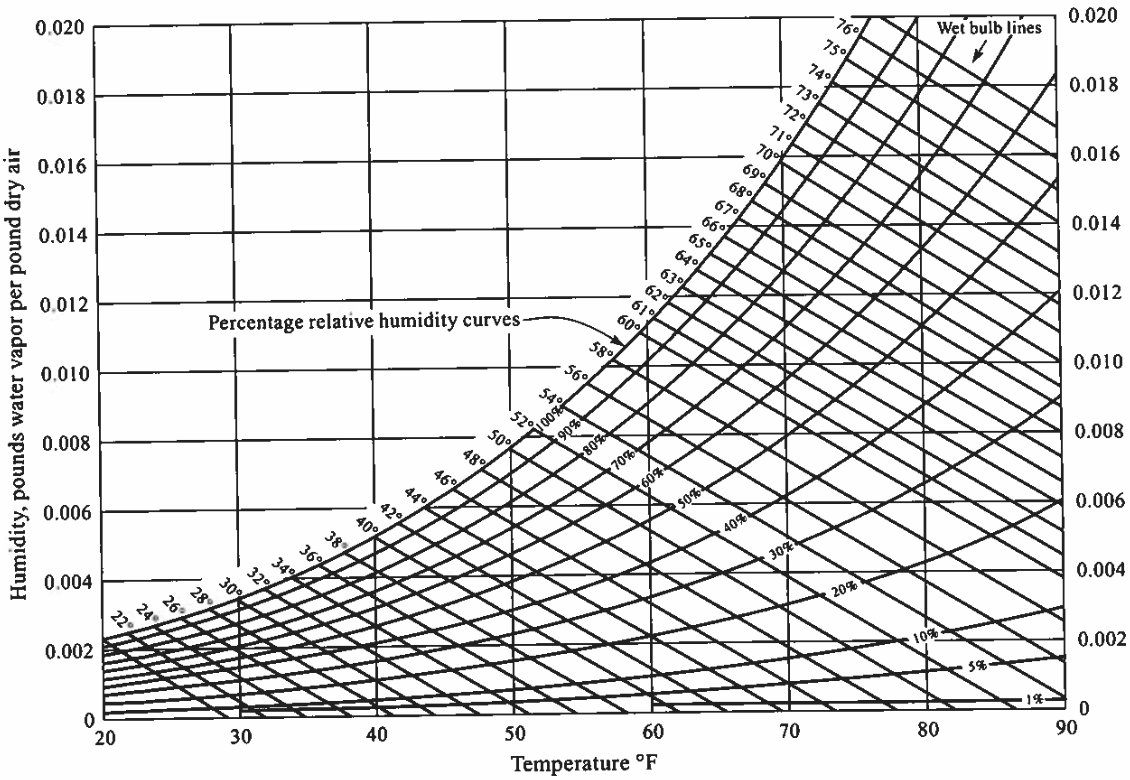


FIGURE 8-17 A psychrometric chart is constructed by using specific humidity, relative humidity, dry-bulb temperature, and wet-bulb temperature

Electronic Capacitance Detector

This type of sensor constitutes a large portion of the RH sensors sold. This device is a small capacitor consisting of a hygroscopic dielectric material placed between a pair of electrodes, as shown in Figure 8-18.

The plates are porous to allow moisture to pass through to the dielectric. The dielectric is typically made of plastic or polymer materials with a dielectric constant ranging from 2 to 15. When no moisture is present, the capacitor's value is determined by the plate geometry (plate size and distance between them) and the plate's dielectric constant.

When the sensor is exposed to humid conditions, moisture in the air is absorbed by the dielectric material. This action causes the dielectric constant to increase, which results in a change of the sensor's capacitance. Relative humidity is also a function of temperature. Therefore, it is necessary to combine a thermistor reading with the capacitance measurement. The sensor's electronics converts both of these measurements into a relative humidity value.

Capacitance sensors are capable of measuring a range of relative humidity with an accuracy of 2 to 15 percent. Because these sensors require considerable time to change capacitance, they tend to be selected for applications where fast response time is not necessary.

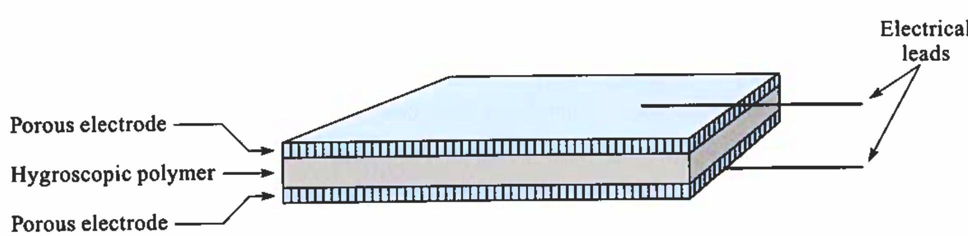


FIGURE 8-18 RH electronic capacitance detector

Dew Point Measurements

Three techniques used to measure dew point are the *manual chilled mirror* (dew cup), *adiabatic expansion sensing*, and the *optical chilled mirror*.

Manual Chilled Mirror

Also known as the *dew cup* technique, this method uses a polished cup made of chromium-plated copper. It is partially filled with acetone or methanol, and a thermometer is placed in the solution. Small cubes of dry ice are dropped into the solution until condensation forms on the outside of the cup. The dew point temperature is measured by reading the thermometer when the condensation begins to appear. This method is a one-time measurement and its accuracy is dependent upon the skill of the operator.

Adiabatic Expansion

This method uses an instrument that draws an air sample into a chamber. The chamber is sealed and then pressurized to a predetermined level. Next, the chamber is unsealed and the air is released, causing a drop in temperature. By measuring the temperature and pressure, the instrument computes the dew point by determining their ratio. This method provides a one-time measurement.

Optical Chilled Mirror Hygrometer

The optical chilled mirror device is capable of providing a continuous on-line humidity measurement over a prolonged period of time. Shown in Figure 8-19, it contains the following elements:

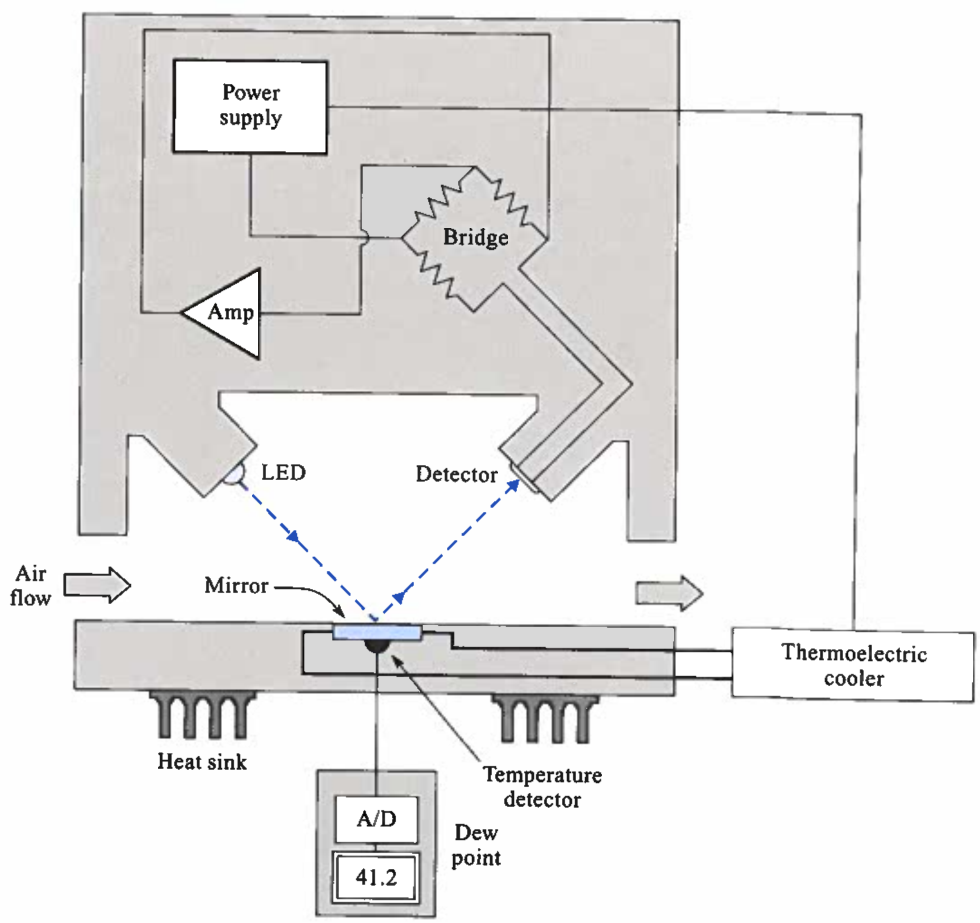


FIGURE 8-19 Optical chilled mirror hygrometer

- Gold or rhodium-plated copper mirror.
- A thermoelectric cooler used to control the temperature of the mirror.
- A high-intensity LED which shines its light on the mirror.
- A phototransistor or an optical detector used to measure the amount of light reflected from the LED off the surface of the mirror.
- The optical detector connected to one leg of an electronic bridge network that is coupled to an amplifier.

A flow of the sample air continuously passes over the surface of the mirror. When the mirror surface temperature is above the dew point, it is dry and highly reflective. Therefore, the maximum light is received by the optical detector. When the thermoelectric cooler reduces the mirror temperature, moisture will condense on its surface when the dew point is reached, causing the light to scatter due to refraction. Therefore, the light received by the detector is reduced. The change in the detector affects the bridge, which provides the feedback signal for closed-loop control. The purpose of the closed-loop system is to maintain the surface temperature on the mirror to within a few degrees of the dew point. This condition is performed by a four-step cycling process.

Step 1: The mirror is rapidly cooled from above ambient to 1.5°C above the last dew point.

Step 2: The cooling rate is decelerated to approach and cross the dew point as slowly as possible to allow dew to form in a uniform manner.

Step 3: When the dew detection is completed, the current through the thermoelectric cooler is reversed. This action causes the mirror to rapidly rise in temperature until it reaches 1.5°C above the previous dew point level.

Step 4: The cooling cycle does not begin until the dew evaporates from the mirror surface and remains dry for a period of time. The mirror is dry for about 95 percent of the time, compared to the 5 percent time duration when the dew is present and the measurement is made. Typically, the measurement cycle is once every 20 seconds.

The temperature of the mirror's surface is measured by a platinum resistance thermometer embedded just beneath its surface. Its temperature is recorded and displayed at the moment the frost appears.

Because dew is on the mirror for only a short time, contamination buildup is kept to a minimum. Also, due to the cycling of the power, the life of the sensor is extended because it is not exposed to excessive heat for prolonged periods of time.

Controlling Humidity

If conditions are too dry, a mist of water is sprayed into the air by a humidifier to bring the moisture up to an acceptable level. If the air is too humid, moisture is removed by using a dehumidifier or an air conditioning unit. The way in which water is removed by both devices is similar. The moist air is blown through a radiator or pipes that are cooled to a dew point temperature. The moisture is removed as condensation forms on the chilled surface areas and then drips into a drainage mechanism.

Humidity Measurement Applications

Humidity measurements and control techniques are required for the following types of production applications:

- Metal production, such as carbonizing, polishing, brazing, sintering, and annealing. Improper humidity levels affect the carbon in these metals and can diminish product quality.
- Moisture affects the integrity and shelf life of certain chemicals such as pharmaceutical products, especially pills or powder.

- Bakeries running large conveyor belts through an oven. Humidity levels outside certain limits cause improper baking.
- For industrial paper dryers, a constant humidity level throughout the drying process must be maintained to ensure batch-to-batch uniformity.

8-5 Sampling Measurement System

Whenever the temperature of the air being tested is above the level to which a sensor can be exposed, it is necessary to cool the air before a reading can be made. One method of achieving this requirement is to use a sampling system, as shown in Figure 8-20.

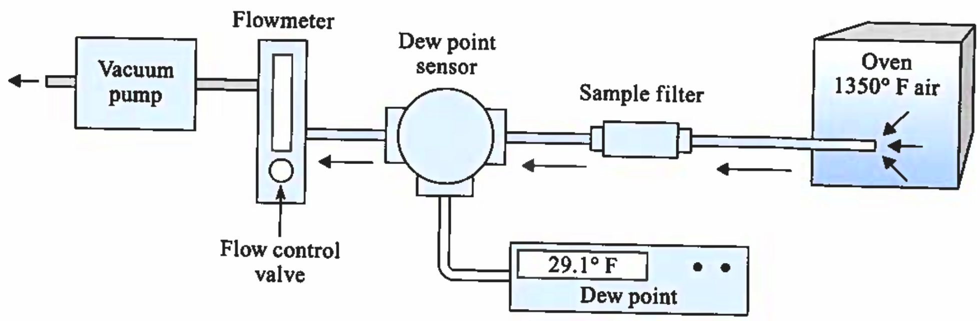


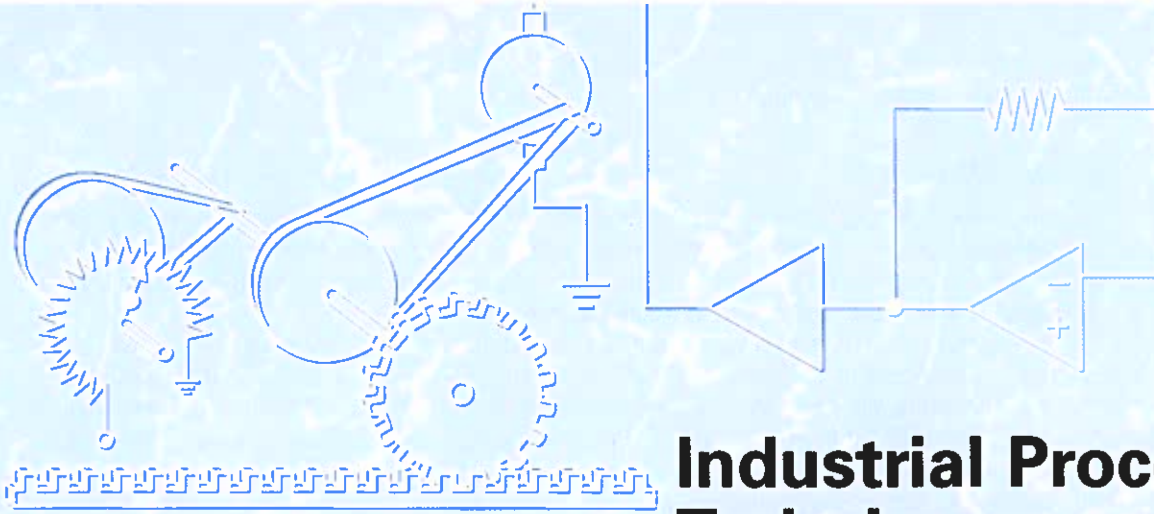
FIGURE 8-20 Sampling measurement systems

The interior of the oven is 1350°F, but the humidity sensor has a maximum rating of 250°F. The only way to measure the humidity of the air is to extract a sample from the furnace. This system consists of a small vacuum pump that draws out the air, a flowmeter that measures the gas flow rate, and a flow control valve that regulates the flow rate. The air sample exits the oven through a stainless steel tube and flows into the humidity sensor. The tube functions as a very efficient heat exchanger. Even though the pipe is only a few feet in length, the sample temperature will be reduced from 1350°F to the ambient temperature which surrounds the tube outside the oven. Before the air enters the sensor, dust and dirt are removed by a filter.

Problems

1. The letter p in the term pH refers to ________, and the letter H refers to ________.
2. If the pH value of a solution is less than 7, it is a/an ____.
   a. base b. acid
3. The pH value of pure water is ____.
   a. 0 c. 7
   b. 1 d. 14
4. An acid solution is neutralized by adding ____.
   a. water b. a base
5. A ____ potential forms on the inside surface of the glass of a pH electrode when the process solution is alkaline.
   a. negative b. positive
6. Water that ____ has the greatest degree of conductivity.
   a. is pure b. contains impurities
7. T/F One factor that affects the conductivity of a liquid is its volume in a container.
8. ____ solutions contain ions.
   a. Acidic c. Conductive
   b. Alkaline d. All of the above
9. Electrode conductivity probes that measure conductivity make measurements at different ranges by ____.
   a. changing the applied voltage
   b. changing the dimensions of the plates
10. A ____ conductivity probe would be more likely to measure the conductivity of a solution with a large concentration of impurities.
    a. capacitive b. inductive
11. ____ gas is present if a hydrocarbon fuel is not completely burned.
    a. Carbon dioxide b. Carbon monoxide
12. The most likely reason why a hydrocarbon fuel does not completely burn is that the ____.
    a. flame is not hot enough
    b. fuel-to-air ratio is not correct

13. T/F A fossil fuel is considered a combustible gas.
14. T/F A specific type of gas can be identified by the light it absorbs at a specific frequency.
15. Static electricity is more likely present in ____ air.
    a. humid
    b. dry
16. What is the relative humidity when the temperature reaches the dew point?
17. The term _________ refers to the property of a material that is capable of absorbing moisture.
18. T/F Absolute humidity refers to the amount of water vapor present at a specific temperature.
19. The wet-bulb and dry-bulb instruments measure ____.
    a. absolute humidity
    b. relative humidity
    c. dew point
20. The dew point is most likely to be reached when the air temperature ____.
    a. increases
    b. decreases
21. T/F The dew cup technique for measuring moisture is used in a closed-loop control system.



CHAPTER 9

Industrial Process Techniques and Instrumentation

OBJECTIVES

At the conclusion of this chapter, you should be able to:

- Describe the characteristics that pertain to the following types of manufacturing processes:

Batch	Chemical Reaction	Polymerization
Continuous	Separation	Product Composition
Mixing/Blending		

- Define the following terms:

Endothermic	Sensitivity	Air-to-Open
Response Time	Static	Span
Precision	Exothermic	Hysteresis
Data Acquisition	Accuracy	Dynamic
Air-to-Close	Zero	Repeatability
Linearity		

- Describe how varying heat and pressure levels affect a process.
- Explain how the following types of instruments and equipment operate:

Heat Exchanger	Agitator	Square Root Extractor
Indicator	Positioner	Final Control Element
Evaporator	Transducer	I/P, P/I, I/V, V/I Transducers
Reactor	Recorder	
Transmitter	Alarm	

- Provide the different types of standard electronic and pneumatic transmission signals and their numerical ranges.
- List the steps required for the calibration process of an instrument in their proper order.
- List the types of control valves, describe their characteristics, and explain applications for which they are used.

INTRODUCTION

The manufacturing industry provides a great diversity of products. The methods of production and types of equipment used to make a product vary greatly from one industry to another. Despite the differences, modern industries rely on the capabilities of automated systems to measure and control the manufacturing process.

In this chapter, instruments used in automated systems and process techniques commonly performed to achieve quality, efficiency and safety standards will be discussed.

The industrial field is production-based. Its function is to transform raw materials into a final product. In the field of *process measurement and control,* raw materials are manipulated through various processes to manufacture goods and provide public services such as electrical energy, or water treatment and purification. These products and services are provided in either *batch processes,* or by *continuous processes.*

9-1 Batch Processes

A large variety of products, such as alcoholic beverages, explosives, pharmaceuticals, liquid detergents, foods, plastics, and metals are produced by the batch process method of manufacturing. These products are made one batch at a time and usually in smaller quantities than the products produced by the continuous method of manufacturing. In batch processing, a sequence of steps is performed similar to the way a food recipe is followed. The product is made by putting ingredients into a vessel, called a *reactor,* and then causing them to react to form a product. The reactor, shown in Figure 9-1, can be described as a large kettle. The vessel is usually closed to keep contaminants from entering the atmosphere. When the *reaction* is completed, the finished product is discharged from the vessel. To ensure product quality, various control requirements must be achieved during the sequence of steps that takes place.

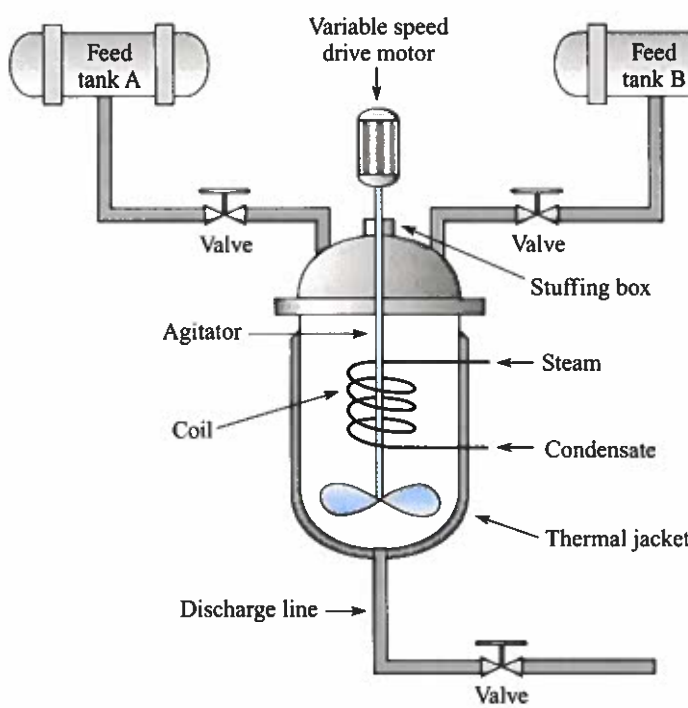


FIGURE 9-1 Batch reactor

Control Requirements

Controlling the Quantity of Raw Materials

In a batch process, exact quantities of raw materials are required for each batch. Measurements can be made by:

- Determining the weight of the ingredients inside the reactor with a pressure sensor.
- Using a level sensor to read the height of the ingredients in the vessel.
- Calculating the volumetric flow rate of a raw material being fed into the reactor by using a flowmeter.

Controlling the Process Variables During the Reaction Cycle

During each step in the process, variables must be controlled. In batch production applications, temperature and pressure are the two most common variables that must be regulated to control the rate of reaction. Applying thermal energy and maintaining the temperature at a certain level is critical to most batch processes. The type of thermal energy applied, whether it be heating or cooling, is determined by the type of ingredients used in the recipe, resulting in an endothermic or an exothermic reaction. Processes that require a source of external heat while forming a product are called **endothermic.** The reaction will not take place unless heat is applied to the raw materials in the vessel. When heat is generated during the reaction phase, an **exothermic** process occurs. In this type of process, a source of cooling thermal energy must be applied to ensure product quality and to prevent overheating. A clogged residential plumbing fixture can be used as an example of why the reaction needs to be kept at lower temperatures. After the drain cleaner solution is applied, a chemical reaction takes place and produces enough heat to damage the pipe. By applying water, the temperature of the solution and the blockage is lowered to a safe level.

With some reactors the thermal energy is applied to the bottom of the vessel. However, this is not a very efficient way to apply the energy to the contents inside. Only the ingredients in contact with the bottom of the tank are directly exposed to the energy source, while the ingredients on top receive the energy from the thermal transfer that takes place along the sides of the vessel, and through the medium itself. Most batch reactors use a thermal jacket, shown in Figure 9-1, that surrounds the sides and bottom of the vessel. By exposing thermal energy to a larger surface area, heating or cooling can be distributed more evenly and efficiently. Thermal energy in the form of heat is supplied by hot water or steam to the jacket. This is what happens in a double boiler used in the kitchen. When cold thermal energy is required, a cold water supply is circulated inside the jacket. In addition to using a jacket, circulation coils placed inside the reactor can be used to speed up the heating or cooling process.

Some endothermic processes require very high temperatures. However, the temperature of the material inside the reactor cannot be brought to a higher level than its boiling point. For example, pure water cannot be raised to a temperature above its boiling point of 212°F, regardless of how much heat is supplied. By increasing the pressure applied to a substance (above the level from the atmosphere), the boiling point is raised, thereby enabling it to become hotter. Pressurizing the reactor under controlled conditions provides a way to elevate the temperature of the material inside, causing the reaction time to speed up. This is the principle of how a pressure cooker operates.

Controlling Each Step in the Sequence

A batch process usually involves a series of sequential steps to form a product. These steps may include feeding, mixing, heating, cooling, reacting, discharging, and then cleaning the vessel after the product is removed. The duration of time, or the rate at which each of these operations occurs, is determined by the requirements of the particular recipe for the process.

Types of Batch Processes

The four basic categories of batch processing methods are:

- Mixing/Blending
- Chemical Reaction
- Separation
- Polymerization

Mixing/Blending

Mixing/blending is an operation that involves combining two or more ingredients together. This method may only require a one-step process of feeding the materials into a tank and then draining the container after a short period of time. To speed up the blending process, a mixing operation may be required by using an agitator to stir the ingredients, as shown in Figure 9-1. Some blending operations require precise control of the time duration for the mixing cycle; this control is performed by a timer. Other types of operations require a precise speed at which the stirring action takes place to control the reaction rate. A variable speed device is used to control the rpm at which the motor drives the agitator blades. Making paint is one example of a mixing/blending operation. In an operation that requires a pressurized condition, a mechanical device called a stuffing box is placed around the reactor's agitator shaft to provide a tight seal.

In some applications, the amount of agitation can be reduced and the mixing time can be shortened by adding heat. This concept can be illustrated by the simple example of making instant coffee. The granules are dissolved more quickly when they are stirred in hot water than when they are stirred in cold water.

Chemical Reaction

A **chemical reaction** is the process of combining two or more materials or reactants to form a product. The reaction usually occurs under the influence of temperature, pressure, agitation, and by introducing a catalyst. A large variety of products, such as fertilizer, antifreeze, and pesticides, are made by chemical reaction processes.

Separation

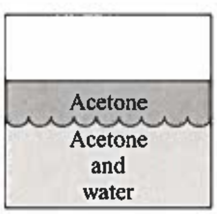


FIGURE 9-2
Separation
of acetone and water

A **separation** operation is opposite to mixing/blending. During the separation process, an ingredient is removed from a mixture. One example of a separator process is shown in Figure 9-2, where acetone is removed from a mixture of acetone and water inside the reactor. Over a period of time, some of the acetone will separate and rise to the top. However, the time duration of this process can be shortened by heating (or cooling) the mixture.

Another type of separation process is crystalization. Crystalization is the formation of a solid material from a solution, vapor, melted material, or solid that is in a different phase of the reaction. Some types of pharmaceuticals are formed through this process.

Polymerization

Polymerization is a process in which a large number of molecules are combined to form a product. For polymerization to take place, temperature, pressure, and a catalyst are supplied under very precise, controlled conditions. Products such as plastics and synthetic materials are made using this type of process.

All four of these processes occur in a batch *reactor.* Some reactors must be made of specific materials. The type of material used to construct the reactor depends on such factors as:

- Its capability to withstand the corrosiveness of the ingredients inside.
- Its capability to not contaminate the contents inside. For example, stainless steel is often used to hold food products.

9-2 Continuous Processes

A large variety of products, such as petroleum, chemicals, paper, plastic garbage bags, and so forth, are produced by the continuous process method of manufacturing. In a continuous process, raw materials are continuously passed through manufacturing equipment at a controlled rate, and the end product is continuously withdrawn. Unlike batch processing, where a relatively small amount of the product is made, continuous processing is designed to manufacture a large volume of a particular product. There are several types of continuous process manufacturing equipment from which products are formed, such as screens and rollers on a paper machine, extruders that shape plastic bags, or an evaporator that processes liquids. To ensure product quality, several variables must be continuously controlled simultaneously by maintaining the process conditions at a constant *setpoint* for each one of them. The stability of the variable must be maintained, despite changes in process conditions. There are several control requirements that must be achieved for continuous processing.

Control Requirements

Controlling the Quantity of Raw Materials

In a continuous process, exact quantities of raw materials are required as they are fed into the manufacturing equipment. These raw materials can be granules, powder, pulp, sewage, water, petroleum, and so on. The quantities of these materials are measured primarily by various types of flow sensors. Flow valves located in piping or at a discharge port of a gravity-fed storage tank are often used to vary the rate at which the raw materials are fed into the process.

Controlling Operating Parameters During the Process

As the raw materials are being fed through the manufacturing equipment, several variables must be monitored and kept at a constant value. For most continuous processing, these variables include: temperature, pressure, level, flow, and product composition.

Temperature The temperature at which a continuous process takes place can be very critical. Some types of processes require heating, and others require cooling. Heat exchangers are often used to transfer the thermal energy (above and below ambient temperature) required for the process.

Figure 9-3 shows the construction of a heat exchanger. It consists of a shell, heads that are removable for maintenance, a tube section enclosed inside the shell, and inlet and outlet ports for both the shell and tube. In this configuration, the product flows through the shell, and the thermal medium from which energy is obtained flows through the tube. Steam or hot water is usually supplied to the exchanger for heating, and cold water is supplied to the exchanger for cooling.

Pressure When the continuous process takes place within a covered vessel, the contents are often pressurized to raise the boiling temperature and shorten the reaction time. By maintaining pressure within a certain range, product quality standards and safety parameters can be achieved.

Level Some continuous manufacturing processes take place inside a vessel. One method used to determine the amount of material that is inside the vessel is to measure the level at which it fills the container. There are several reasons why the level of the contents must be monitored and regulated. If there is not enough liquid to cover a thermal exchanger heating element, it may become too hot and be damaged. Too much material can create a spillage problem by overflowing an uncovered vessel. If the contents become too high in a covered vessel, pressure within the air gap above the medium may also become too high and create an explosion. Various types of level sensors are used to detect high limits, low limits, or the entire depth range of the contents.

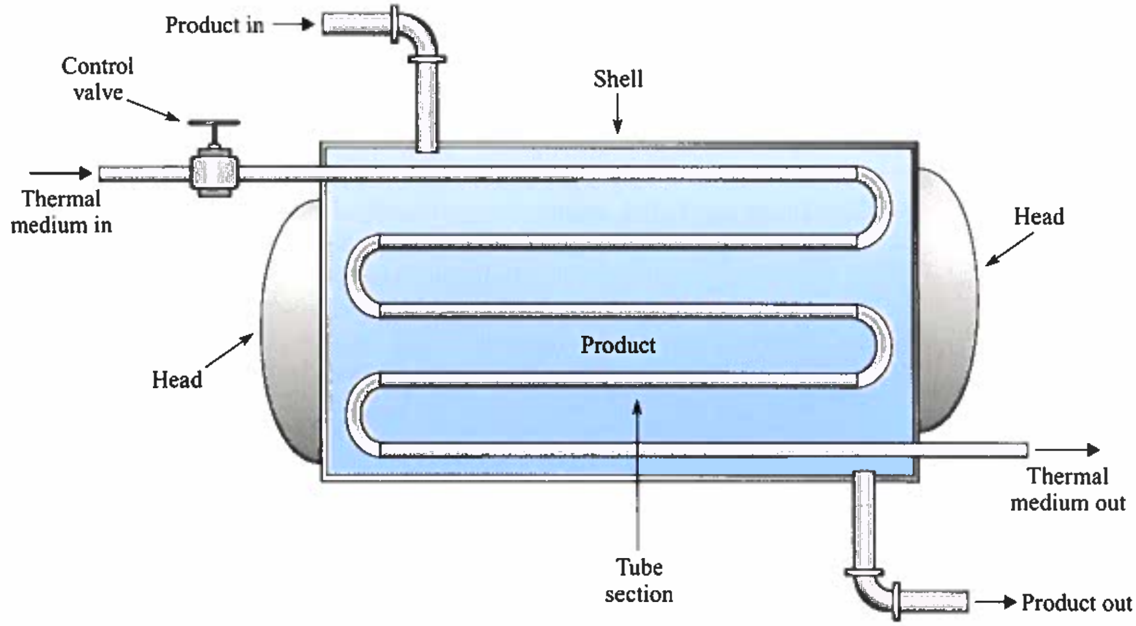


FIGURE 9-3 Heat exchanger

Flow The most common variable in a continuous process application that needs to be controlled is flow. Raw materials are continually fed into the machinery that produces the product. Conditions inside the machinery, such as temperature and pressure, must be at a certain value to control the reaction rate of the product. The temperature is maintained by controlling the flow of steam or fuel, and the pressure level can be regulated by the flow of air from a compressor or vacuum pump that passes through a control valve. In summary, the rate of production and many variables that are essential elements of the process are controlled by flow.

Product Composition As the product stream of multiple ingredients is blended in a continuous process, the ingredients are often mixed, pressurized, heated, or cooled to cause the desired reaction. During this process, the composition of the material must be very precise. The composition refers to the conditions of the product solution, such as the concentration of solids in a liquid, completion of a chemical reaction, or consistency of a mixture. The status can be measured by reading boiling point temperature, or by using a sensor called an *analyzer*. Controlling the composition of a product is also referred to as *analytical control*. The composition is often affected by changing the other variables: temperature, flow, level, and pressure.

The evaporator shown in Figure 9-4 can be used to illustrate how other variables can control the composition of a product. Liquid and paste are fed into a chamber, mixed, and boiled to produce a condensed solution. If the solution becomes too concentrated because the process is altered, the problem can be corrected by increasing the flow rate of the liquid, by decreasing the flow rate of the paste, or by reducing the flow rate of the heat supply that causes boiling to take place.

Some products can be manufactured by using either a batch process or a continuous process. If the volume of the product is small, a company will usually use a batch reactor similar to the one described in Figure 9-1. If the demand for the volume of the same product is large, the company can increase the production output by using continuous process equipment, such as the machine shown in Figure 9-5.

Raw materials from the feed tanks A and B are mixed in an in-line mixer. Because the blended liquid must be heated to a 100-degree temperature to cause a desired reaction, it passes through a heat exchanger. The end product is continuously withdrawn through a discharge port at the bottom of the vessel. If the temperature required for the process were greater than 212°F, the vessel could be pressurized to enable the liquid to be heated above the atmospheric boiling point.

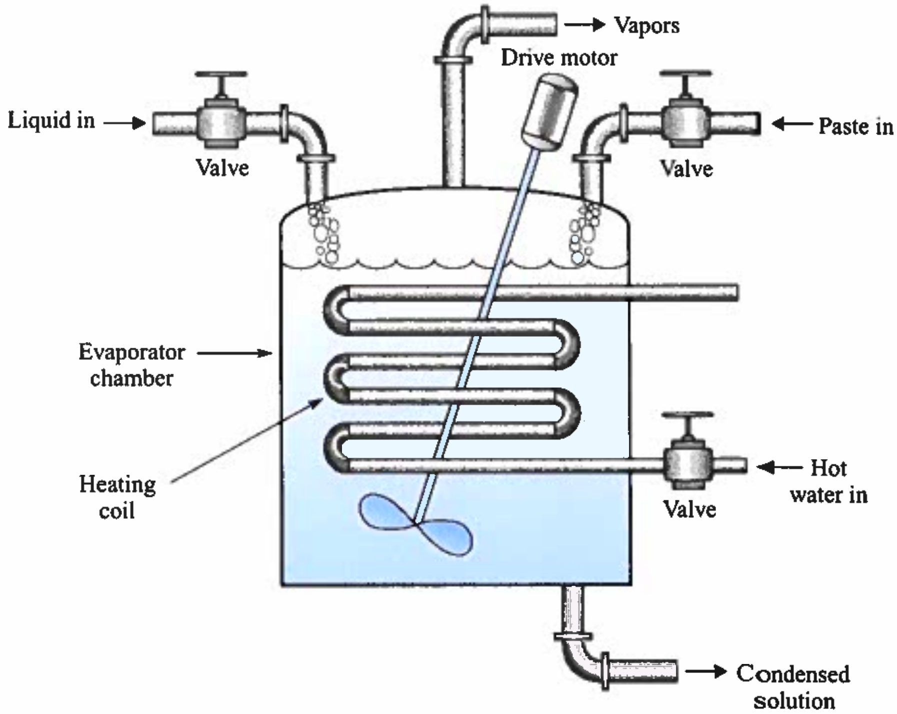


FIGURE 9-4 Heat blending process

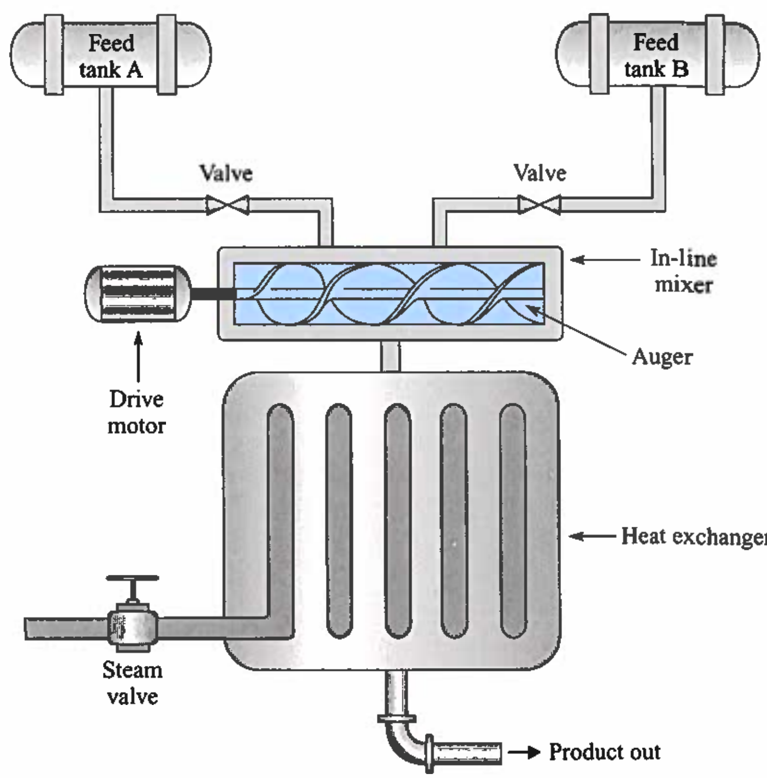


FIGURE 9-5 Continuous process heat exchanger

9-3 Instrumentation

As a product is being manufactured, critical stages of the process must be manipulated to achieve the desired outcome. Modern industrial equipment performs the manipulation function automatically. The control of an industrial process by automatic rather than manual means is called *automation*.

Figure 9-6 shows a block diagram of an automated system. This system performs three functions, the *measurement, control,* and *manipulation* of the process. Each block is a basic element that performs one or more of these functions. The lines between the elements indicate how each block is interconnected and the arrowheads show the direction in which information between them flows. Each block has at least one input and output. The arrowheads that point into the block indicate an input, and the arrowheads that point away from the block indicate the output. This type of block diagram is referred to as a *control loop* because there is a regular circulation of information.

The desired condition of the process variable being controlled is established by adjusting the setpoint value applied to the controller. A second input applied to the controller is the feedback signal, which indicates the actual condition of the process variable. The controller is the "brain" of the control loop. If the feedback signal is different from the setpoint, the controller processes the information and produces an appropriate output to make them the same. The controller output is the input to the final control element, which causes the process to change. The actual process condition is measured by a sensor. The large variety of sensors used to monitor various processes produce many types of output signals. An interface device is used to convert the sensor output into a standard signal that is compatible with the controller. The sensor interface device and its output lines form the feedback portion of the loop. Monitoring instruments connected to the output of the interface device do not perform any of the feedback loop functions. Their purpose is to provide information for the human operator about how the closed-loop system is functioning.

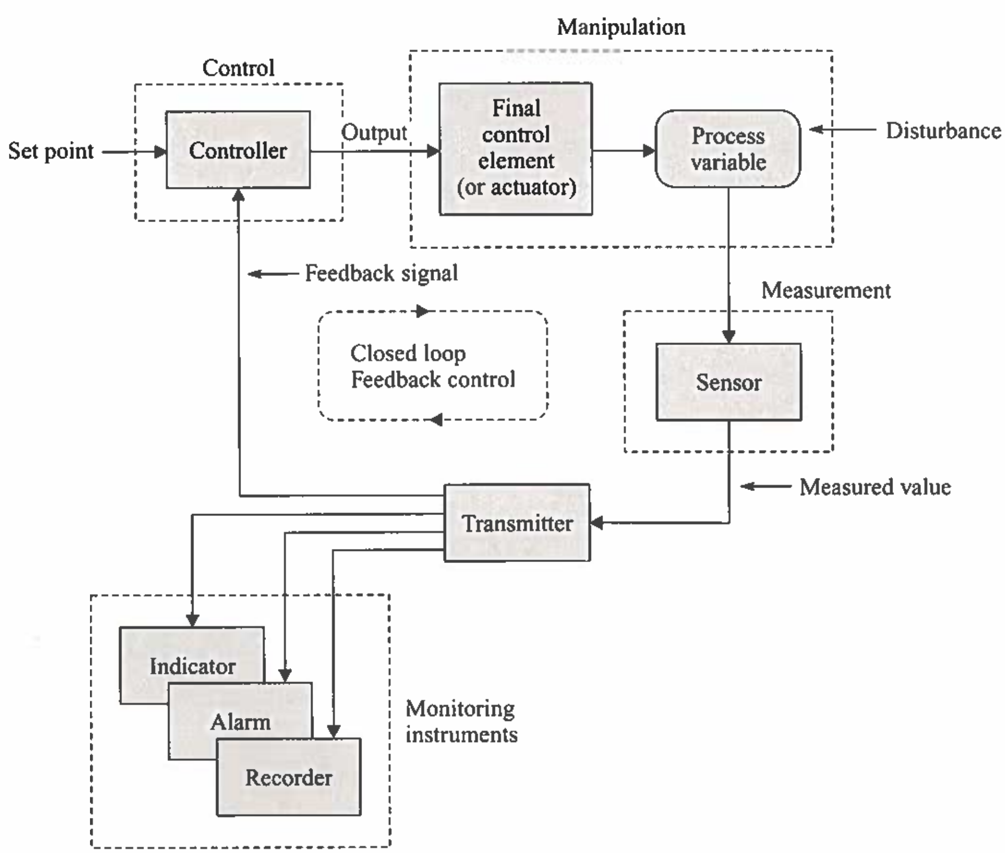


FIGURE 9-6 Block diagram of a closed-loop automated system

By continuously measuring, controlling, and manipulating, the closed-loop system keeps a process variable, such as temperature, pressure, flow, or level, at a condition commanded by the setpoint. If a disturbance causes the process variable to change, the controller will detect this deviation of the feedback signal from the setpoint and cause the final control element to manipulate the variable back to the desired condition.

The functions of the elements in a closed-loop automated system are performed by various instruments, which are referred to as *instrumentation devices*. In most industrial process machines, several different variables must be controlled simultaneously to manufacture a product. A separate control loop is used for each one of them. The control functions of these loops are performed at intermediate stages of the production line to maintain quality-related standards of each variable.

9-4 Measurement Devices (Sensors)

An industrial process loop *begins* with measuring a variable. This function is performed by a *sensor,* which is located in the field near the process. A control loop is effective only if the sensor is reliable.

An ineffective loop can cause the quality of the variable to become unacceptable. The reliability of the sensor is affected by its characteristics, which are classified as either **dynamic** or **static.**

The dynamic characteristic refers to the transient response of the instrument, which is the time during which its output reaches a steady state after a new signal is applied to its input. The static characteristic refers only to the condition of the instrument when it is stable and not changing. The following explanations describe dynamic and static characteristics.

Dynamic

Response Time

Sensors do not respond to changes immediately. It takes a period of time for the sensor to produce the signal that represents the condition that it is detecting. The term **response time** is used to describe the amount of time the sensor takes to respond to a change in the measured variable. The response time is determined by several factors, such as the design of the sensor and the type of variable being measured. For example, flow and level sensors respond almost immediately to any changes that occur. However, temperature sensors take longer because they must physically heat up or cool down when a temperature change takes place until they reach the same level as the measured variable. This effect, known as "temperature lag" or "thermal lag," can take from seconds to minutes when responding to changes. A sensor's proximity to the measured variable also affects the response time. For example, a temperature sensor inside a protection chamber called a *thermowell* will take longer to respond than a sensor directly exposed to the measured medium. Similarly, an air pressure sensor inside a pipe will respond more quickly than an identical sensor connected to the pipe through a long length of tubing. The graph in Figure 9-7 shows a comparison of typical response times for different types of variables.

Since the controller receives an input from the sensor, it cannot react to changes any faster than the response time of the sensing device. Therefore, the response time of the entire loop is affected by the sensor. Response time is a factor that must be considered if a control loop requires a very fast response to changes in the condition of a variable.

Static

Accuracy

The term **accuracy** is used to describe how closely a sensor measures the actual value of a controlled variable. Figure 9-8 is used to illustrate the accuracy of a temperature sensor as it takes five separate readings of a constant temperature. The graph shows several different

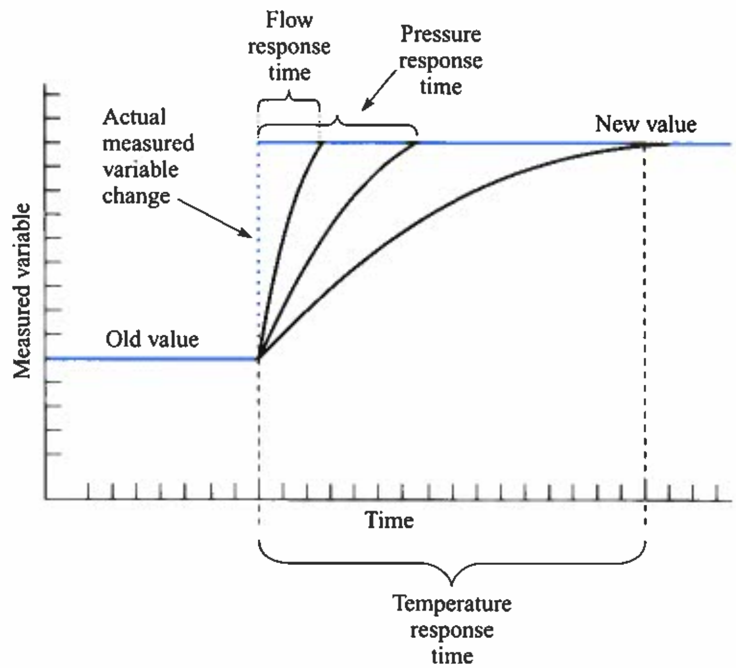


FIGURE 9-7 Response time

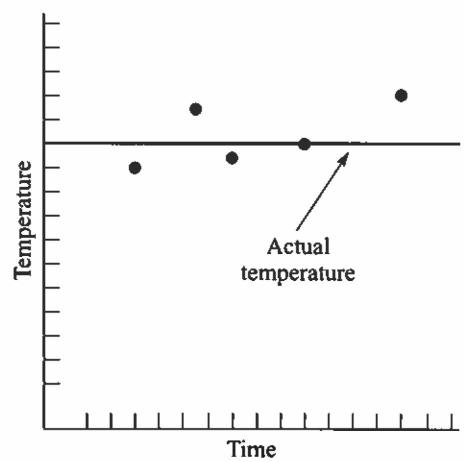


FIGURE 9-8 Accuracy

measurements. If each indication is within a tolerance range as specified by the manufacturer, the sensor is considered accurate.

Precision

The term **precision** is used to describe how consistently a sensor responds to the same input value. Figure 9-9 is used to illustrate the precision of a temperature sensor as it takes five separate readings of a constant temperature. The graph shows several different measurements. Even though the measurements are not exact, they are considered precise because they are consistent. Another term used to describe precision is "repeatability."

Linearity

The sensing device converts a physical quantity of the variable it measures into a signal, such as pneumatic or electrical. With some types of sensing devices, the output produced is not

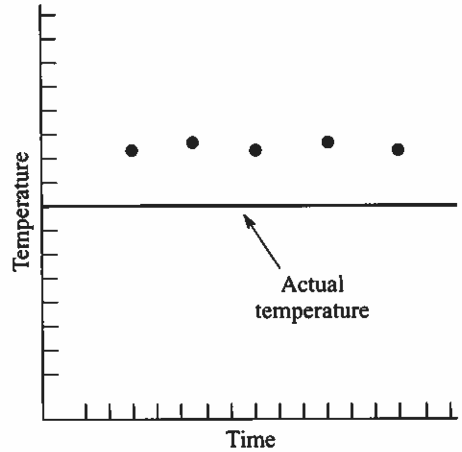


FIGURE 9-9 Precision

proportional to the actual condition measured. Instead, the signal produced is the square of the variable's physical quantity. If the input vs. output of the sensor is plotted graphically, as shown in Figure 9-10, a nonlinear line, or curve, will be produced.

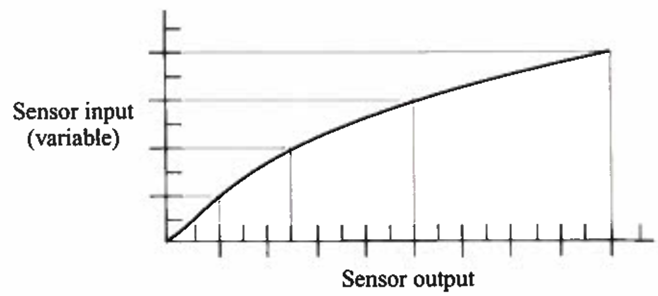


FIGURE 9-10 Nonlinear output of a sensor

Hysteresis

The graph in Figure 9-11 is used to show the **hysteresis** characteristics of some types of sensors. There are two curves identical in shape. The upward and downward arrows describe the way in which the output reading varies as the measured signal applied to its input increases and decreases, respectively. The illustration shows that the instruments produce different output values for equivalent low-to-high and high-to-low input changes. Hysteresis is the dissimilarity between these two curves.

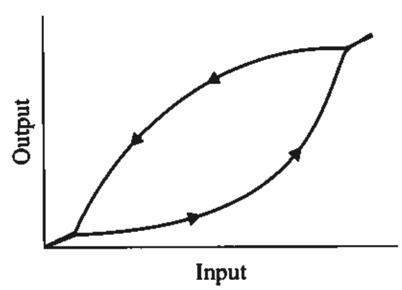


FIGURE 9-11 Hysteresis loop

Sensitivity

The **sensitivity** of a sensor is the ratio of its output change to a change in its input quantity that represents the measurements. The graph in Figure 9-12 illustrates that, if a sensor has

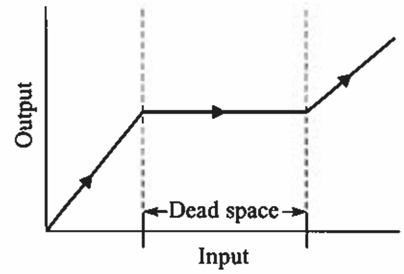


FIGURE 9-12 The dead space of a sensor that has poor sensitivity

poor sensitivity, the sensor will not produce an output change in response to a range of input values. The range is referred to as *dead space*. The dead space will be smaller for a sensor with better sensitivity.

9-5 Feedback Loop Interface Instruments

The sensor is seldom connected directly to the controller. Instead, various interface instruments are usually added to the feedback loop that connects them together. These instruments are the *transmitter* and the *transducer.*

Transmitters

The different variables that are monitored in the process industry and the many conditions under which they are measured require a large variety of sensors to perform this function. Sensors are primarily mechanical devices or electronic instruments, and they produce many types of signals that represent the condition of the controlled variable. For example, they provide a mechanical movement, a varying current flow, a varying voltage, a varying resistance, or a varying capacitance. These outputs are sent to a **transmitter,** which has two functions. First, it converts a signal from the sensor into a standardized signal used in process systems. Second, since the sensor is often positioned at a remote location from the controller, it carries the signal the distance between them. Some sensors produce very small voltages no greater than 1 mV. The transmitter contains an amplifier that boosts the signal high enough to overcome the resistance of long wires. Some transducers have a signal filtering function, which removes a particular band of frequencies within a signal. For example, low-pass filtering may be required to remove the high-frequency noise component in a signal. This noise is any stray voltages that are induced into the sensor's conductor from magnetic lines that develop around motors and other high-current carrying devices located close by. Sensors and transmitters are often combined into one unit.

The most common types of standard signals are transmitted electronically, pneumatically, and optically. Electronic and pneumatic signals are referred to as analog because their values are proportional to the conditions they represent within a standard range. Optical signals are referred to as digital signals because they are either in the "On" or "Off" state condition. In order to represent specific values, a series of On and Off pulses are optically transmitted. Each value is represented by a specific pattern of pulses.

Table 9-1 shows the ranges of standard electronic and pneumatic signals commonly used in the process control industry.

TABLE 9-1 Standard Transmission Signals

Electronic	*Pneumatic*
4–20 mA DC	3–15 psi
0–20 mA DC	
0–10 VDC	

Electronic Signals

Analog electrical signals in a control system are direct current (DC) and can be divided into two categories: voltage and current.

Voltage Signals Voltage signaling is uncommon between transmitters and controllers within process industries. The most common application is to provide an input to display devices, recorders, and occasionally a controller. Voltage signaling is limited to short distance transmission.

Current Signals The most commonly used electronic signals are current signals having current ranges from 4 to 20 mA, and 0 to 20 mA. For signaling using 4 to 20 mA, the transmitter draws about 3 mA, and therefore does not need a separate power supply. In a two-wire configuration, the same leads are used for signaling and to supply the power. The floating-zero-point of 4 mA makes the transmitter easy to calibrate because the lowest setting can be adjusted slightly lower than 4 mA if necessary. For signaling using 0 to 20 mA, the resolution is better than the 4 to 20 mA range. However, its lowest range for calibration is limited to 0 mA. Also, a separate power supply for the transmitter must be provided, which adds to the installation cost. Current signaling is commonly used for short-distance transmission, but exclusively used for long-distance applications.

Pneumatic Signals

Pneumatic 3–15 psi (pounds per square inch) signals are often used for environmental conditions where a spark may cause an explosion.

Calibration

To provide accurate measurements, transmitters should be adjusted so that their output will vary through its full range in proportion to the full range that the controlled variable changes. The procedure of making this adjustment is referred to as **calibration.** The following calibration steps explain this procedure:

Step 1: Determine the full range of the variable being measured. For example, assume the range of a process level being controlled is 10 inches to 90 inches.

Step 2: Select an appropriate level sensor for the application, and then determine the type of analog output signal that is produced by its transmitter. For example, assume a 4 mA to 20 mA transmitter is used.

Step 3: Make a *zero* adjustment on a potentiometer or keypad, which causes an output of 4 mA when the minimum level of 10 inches is measured.

Step 4: Make a *span* adjustment on a potentiometer or keypad, which causes an output of 20 mA when the maximum level of 90 inches is measured.

Note: Span does not refer to the range of current that the transmitter produces. It is the maximum current produced when the variable it represents is at the maximum magnitude.

Step 5: Verify the adjustments by measuring the 0 percent output at 4 mA when 10 inches are detected, a 50 percent output of 12 mA when 50 inches are detected, and a 100 percent output of 20 mA when a 90-inch level is detected.

As time passes, mechanical wear, aging of components, environmental changes such as temperature, humidity or pressure, and exposure to dirt or dust, will lessen the accuracy of the sensor/transmitter. To ensure that correct measurements continue over a period of time, it is necessary to periodically test and make adjustments at timely intervals using the calibration steps.

The calibration procedure should be documented so that a record of the instrument's calibration history is always available.

Transducers

Most batch and continuous process control machines have a large variety of instruments that do not respond to the same types of signals.

To enable these instruments to work together, some type of signal conversion is necessary. Transmitters perform this function and also provide long-distance transmission by using an amplifier. When long-distance transmission is not required, another instrument called a **transducer** is sometimes used to perform the signal conversion function. The following examples show some of the most common types of transducers used in the process control industry.

I/P Transducer

An I/P transducer converts an electrical current signal (I), produced by a sensor ranging from 4 mA to 20 mA, to a pneumatic (P) signal ranging from 3 to 15 psi, both of which are standardized values used in the process control industry.

Pneumatic signals are often used to operate a pneumatic actuator which causes a valve to vary the fluid flow through a pipe. Figure 9-13 shows a control loop which uses an I/P transducer. A pressure regulator supplies 20 psi of air to a transducer located near a pneumatic valve which controls the process flow. The transducer receives an electrical signal from a controller and produces a proportional analog pneumatic signal. For example, if a 4-mA input signal is received, 3 psi will be applied to the valve. Likewise, a 20-mA current signal will cause the transducer to apply 15 psi to the valve.

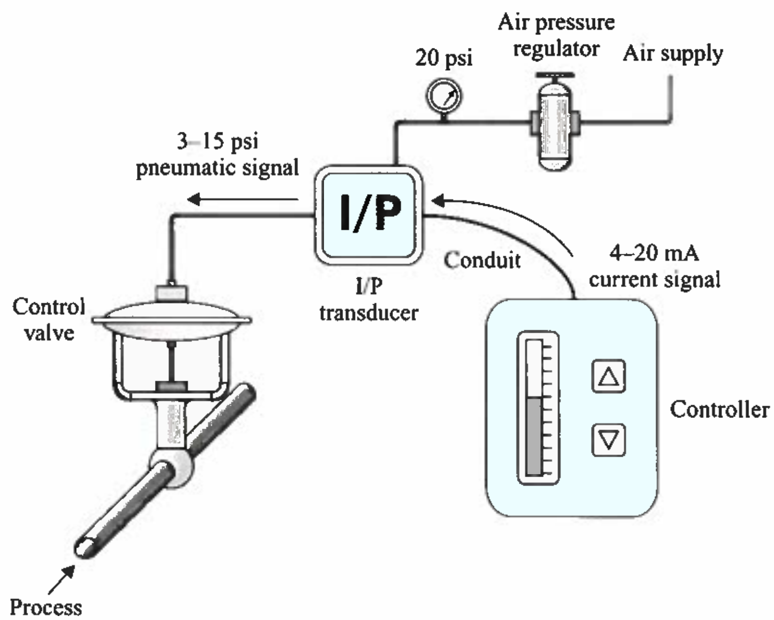


FIGURE 9-13 I/P transducer application

P/I Transducer

A P/I transducer converts a 3 to 15 psi pneumatic (P) signal to a 4 to 20 mA current (I) signal. Figure 9-14 provides an example of how the pneumatic signal is received from a liquid level sensor called a bubbler. Air is fed to an immersed dip-tube vertically inverted with an open end placed close to the bottom. The amount of air that is forced out of the tube is inversely proportional to the level of the fluid. For example, the higher the level, the more difficult it becomes to force air through the end of the tube. As a result, a larger amount of back pressure develops that represents the height of the liquid.

One application of a bubbler sensor is to measure the tank level of a flammable liquid because there are no electrical signals or connections which could create a spark to cause an explosion. The pressure signal is applied to the input of a P/I transducer that is capable of sending a current signal to the controller at a remote location. When the maximum level is detected, the bubbler creates a back pressure of 15 psi that is converted to 20 mA by the P/I transducer. At the minimum level in the tank, a back pressure of 3 psi would be converted to a 4-mA current signal for the controller.

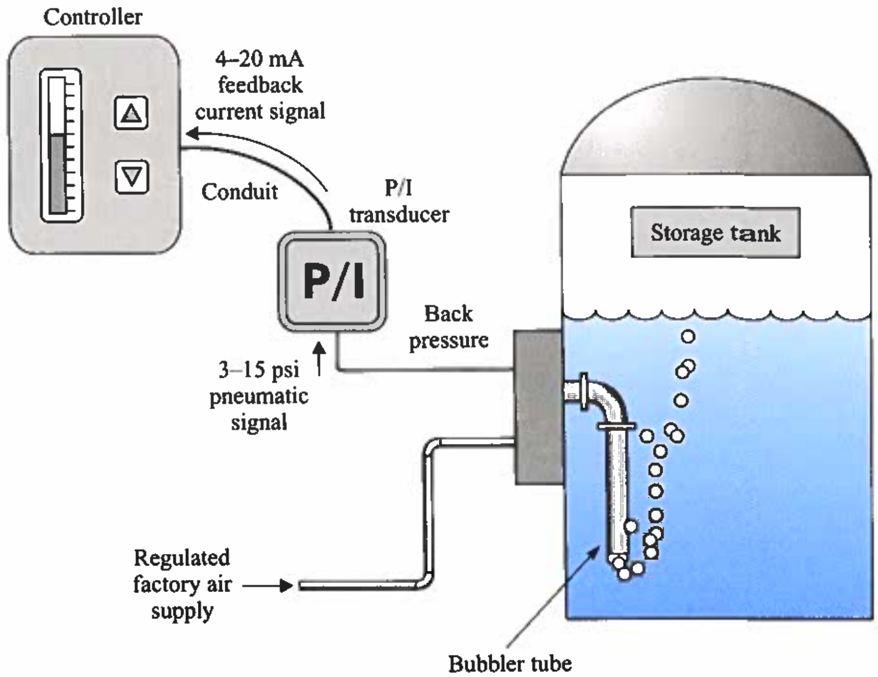


FIGURE 9-14 P/I transducer application

I/E Transducer

Signaling between the transmitter and a number of instruments located in the control room often requires a current-to-voltage (I/E) conversion. This function is performed by an I/E transducer, which converts a 4 to 20 mA current signal to a 1 to 10 VDC signal. DC voltages are often used as input signals to such instruments as a controller, a recorder, or an indicator. Figure 9-15 shows how these devices are parallel-connected when the transducer feeds its output to them simultaneously. The conversion process is achieved by using the voltage drop across an internal resistor as the transducer output, and which is proportional to the current that passes through from the transducer's input terminals.

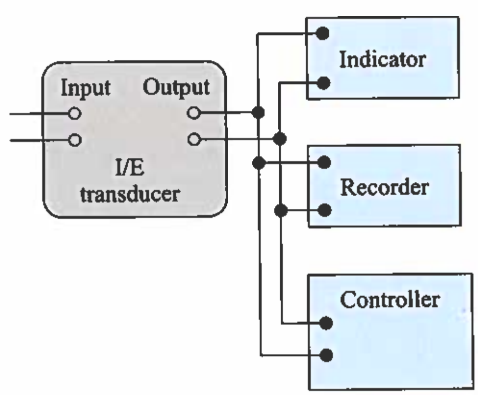
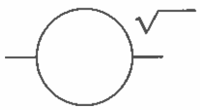


FIGURE 9-15 I/E transducer application

Square Root Extractor

When a fluid passes through the orifice of a flowmeter, the differential pressure that develops across the restriction is nonlinear. Therefore, the magnitude of the signal produced by a differential pressure-type flowmeter is not proportional to the rate of flow. Instead, the flow rate



is proportional to the square root of the pressure drop being measured. To compensate for this condition, it is necessary to linearize, or extract, the square root from the sensor's output. A transducer called a *square root extractor* is placed between the sensor and controller to perform this function. The symbol for this transducer is a circle with a square root symbol.

Analog-to-Digital Transducer

Most signals produced by measuring controlled variables are analog. However, most controllers are computer-based and process digital signals internally. An analog-to-digital (A/D) converter similar to the type described in chapter two makes the conversion. A/D input modules are used by programmable controllers to perform this function, and computers use an I/O board.

Digital-to-Analog Transducer

As the controller processes information, such as comparing the digitized command "setpoint" signal with the measured "feedback" signal, it produces a digitized output that must be converted to an analog signal. This function is performed by a digital-to-analog D/A converter similar to the one described in Chapter 2. D/A output modules are used by programmable controllers to perform this function, and computers use an output card.

9-6 Controllers

The **controller** is the element in a closed-loop system that performs the decision-making function. By comparing a setpoint value that represents the desired condition in a process to a signal from a sensor that represents the actual condition, the controller determines if and how a correction needs to be made. The operations that most controllers perform are simple On-Off control and the more sophisticated PID control. The gain settings are made during a tuning procedure, and a defined control algorithm programmed by the system designer determines how much and how fast the controller output will change in response to an error. The controller's output signal is sent to the final control element, which directly affects the process. There are two categories of controller outputs: *dimensional,* and *nondimensional.* Dimensional outputs are absolute values such as 3–15 psi, 4–20 mA, or 0–10 volts DC. The output value of many controllers is also represented by nondimensional values, which are percentage figures between 0 and 100 percent. For example, a percentage indicates a valve is 70 percent open, or a flow is 50 percent of the maximum rate. By using percentages it is much easier to keep track of the huge diversity of absolute value signal ranges that represent the condition of each variable. Table 9-2 shows how a 0–100% output signal relates to common dimensional output values. The most common types of controllers are briefly described in the following text.

TABLE 9-2 0–100% Output Signal Versus Common Dimensional Ranges

Output Units represented by a percentage	*Output Value for a 4–20 mA signal*	*Output Value for a 0–10 VDC signal*	*Output Value for a 3–15 psi signal*
0%	4 mA	0 V	3 psi
25%	8 mA	2.5 V	6 psi
50%	12 mA	5.0 V	9 psi
75%	16 mA	7.5 V	12 psi
100%	20 mA	10 V	15 psi

Pneumatic Controllers

Pneumatic controllers produce a pneumatic output signal that is applied to a flow control valve. They are usually located in the field and are mounted near the point of measurement.

These controllers are usually found in older systems and are capable of controlling only one loop.

Panel-Mounted Controllers

The panel-mounted controller is a microprocessor-based device which can measure, display, and control temperature, pressure, level, flow, and other process variables. This device is relatively inexpensive and is capable of performing simple On-Off as well as PID-type control operations. A diagram of this type of controller is shown in Figure 9-16.

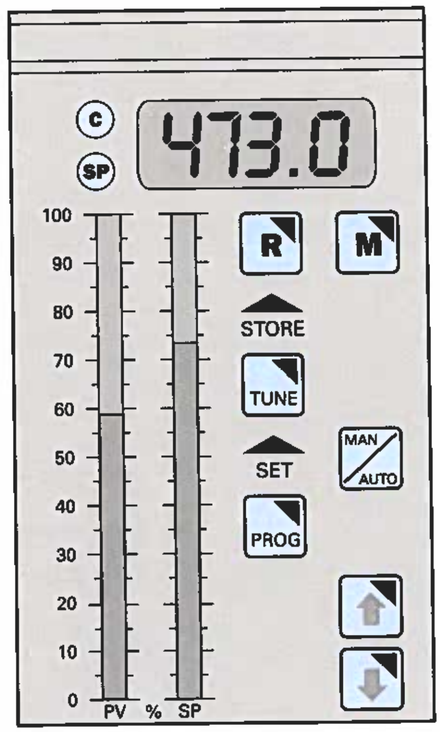


FIGURE 9-16 Panel-mounted controller

Users can select the instrument functionality required from menus, using tactile membrane keys and the high-intensity LED-segment displays.

By pressing the **M** button several modes of operation can be accessed, such as On-Off parameters, PID gain settings, and preset limits that activate an alarm when they are exceeded. The specific values for each mode are shown on the digital display as they are programmed by pressing the up/down arrows after the **PROG** key is pressed. Bar graph indicators on the left display the setpoint (**SP**) value selected and the run time status of the process variable (**PV**) that is being controlled. The **TUNE** button is used for autotuning, which automatically selects the gain settings for each PID mode. The **R** button performs the reset function if the programmer needs to repeat the keypad entries.

An auto/manual button enables the operator to use the controller in either manual or automatic modes. When in manual mode, the control function is performed by the user. In automatic mode, the controller function is performed by the microprocessor-based circuitry.

Personal Computers

The personal computer (PC) can be used for small systems that are easy to control. Software programs provide the control of On-Off, PID, and multiple-loop operations. Some types of software programs show the real-time operations on a graph as shown in Figure 9-17(a), or by a pictorial display on the computer screen which contains a drawing of the actual equipment, as shown in Figure 9-17(b).

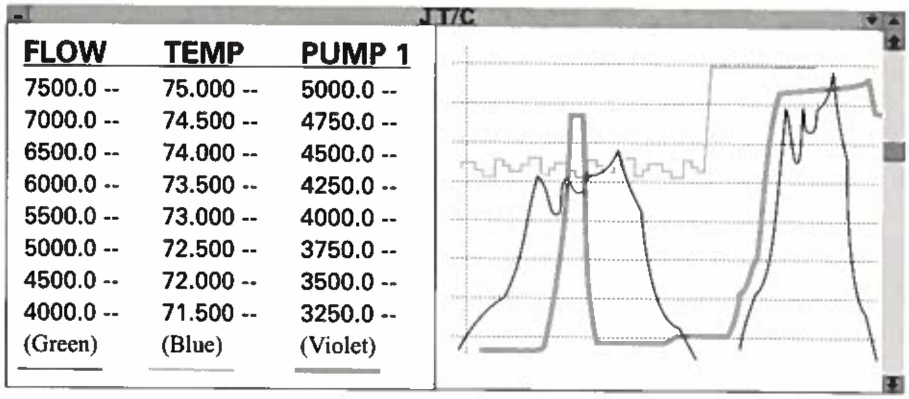


FIGURE 9-17(a) Paperless graph recorder

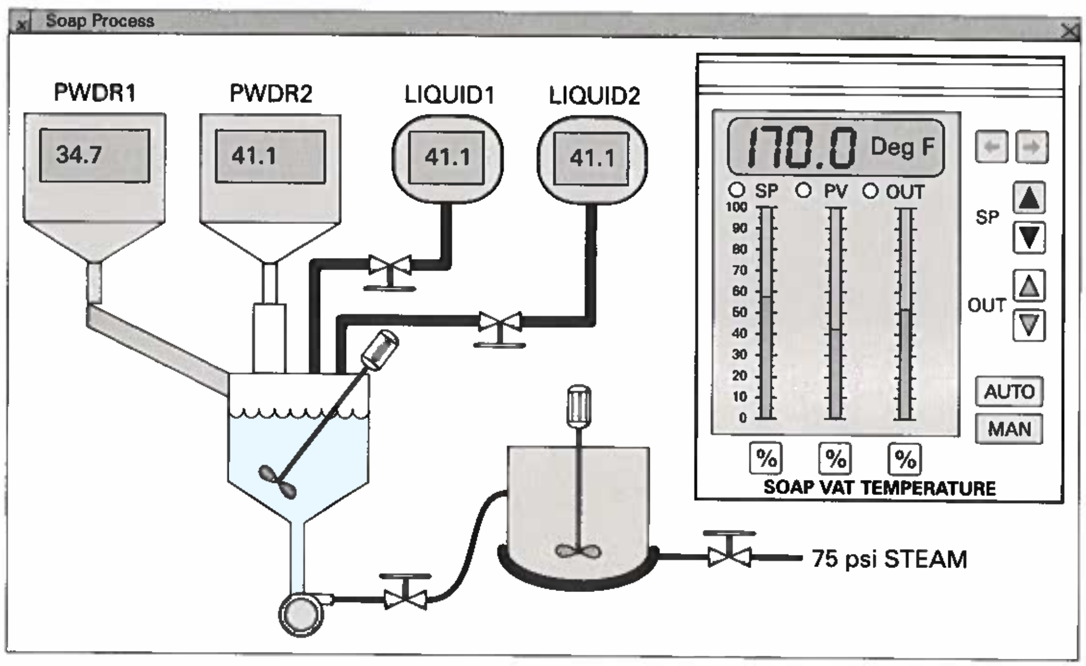


FIGURE 9-17(b) Pictorial computer display

Programmable Logic Controllers

The programmable logic controller (PLC) can perform most control operations for very complex systems. Discrete I/O modules perform On-Off batch operations. Input analog modules are capable of interfacing with sensors and transmitters, and output analog modules can send control signals to final control elements used in a continuous process. The CRT used by the PLC can display the same information as the PC.

Distributed Control Systems (DCS)

Factories that use large production machines have an entire room with a high capacity computer dedicated to performing complex control operations. These computers can control hundreds of control loops, simultaneously enabling them to interact with each other to coordinate each part of the machine, so that it performs the required manufacturing operation as one unit. The computer displays real-time information about each loop on indicators such as numerical displays, bar graphs, meters, and pictorial drawings on computer screens. Operators located at consoles inside the centralized control room observe the display screen to monitor the operation. These computers set off alarms, if an undesirable condition arises, and record historical data for analysis of each control loop at a later time. This data can also include the amount of raw material used, energy consumption required, and the amount of end product made. This information is useful for the accounting department when calculating expenses vs. production and inventory. The DCS also provides diagnostic information about the condition of instruments in the system to assist maintenance personnel with troubleshooting before or after a failure occurs.

9-7 Monitoring Instruments

Various types of instruments are designed to monitor the process control operation. They can be mounted on a control panel or on the controller itself, or can be a dedicated unit. These instruments include *indicators, alarms,* and *recorders.*

Indicators

Indicators are used to display information for the operator or technician. They show data such as setpoint adjustments, the amplitude and polarity of an error signal, or the magnitude of the signal sent to the final control element by the controller. Indicators are placed on the manufacturing equipment at strategic locations in a closed-loop to display the status of variables so that the automatic control action can be monitored. The information they provide is used for deciding whether the system is operating properly, if external adjustments need to be made, or when a machine operation needs to be performed. For example, the responsibility of an operator is to monitor the operation of a machine and to make sure that raw materials are supplied without interruption. Instead of climbing on top of, or around, a machine and its feed tanks, the operator can easily monitor the condition by reading indicators on a centrally located panel.

Figure 9-18(a) shows an analog indicator where a pointer moves across a fixed scale to show a reading. Figure 9-18(b) shows an analog indicator where the scale moves in relation to a fixed pointer. These meter-type indicators are actuated either electrically or pneumatically. The indicator in Figure 9-18(c) is a color bar graph that provides a reading in a similar manner to a thermometer. A digital-type indicator, which displays numbers that represent a measurement, is shown in Figure 9-18(d).

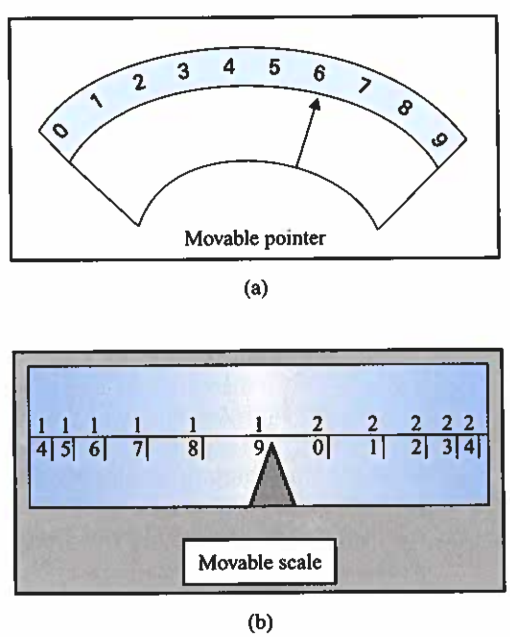
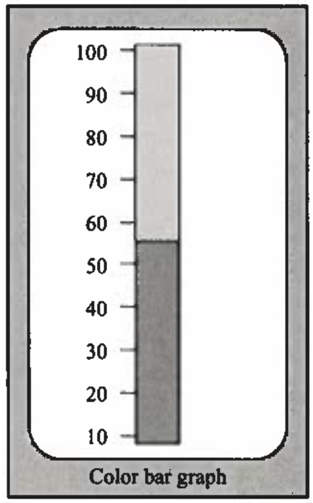
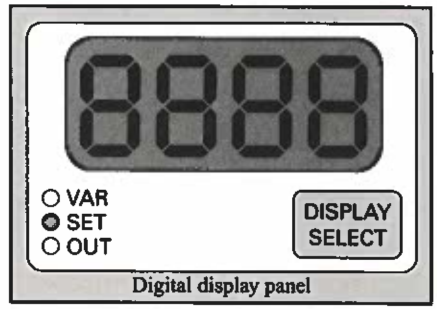


FIGURE 9-18 Indicators



(c)



(d)

FIGURE 9-18 *(continued)*

The most modern method of indication is the display on a computer monitor. Software programs can be written to draw a picture of the machine, which graphically displays the entire operation as it takes place. For example, the amount of raw material in a feed tank is shown and an instruction can be programmed to display a flashing warning—"empty"—when the contents become too low.

Alarms

Control systems can be equipped with a variety of **alarm** features. Their purpose is to warn the operator or initiate some action if an undesirable process condition develops. When a condition falls outside parameters that are programmed into a controller, it activates an alarm. The alarm action may be to turn on a light or electronic sound, to flash a message on the controller's display which describes the problem, or to shut the system down.

Examples of alarm operations are as follows:

1. A deviation alarm, which activates when the controlled variable differs from the setpoint by a certain value.
2. A rate-of-change alarm, which turns on when a controlled variable is increasing or decreasing at a faster rate than desired.
3. A limit alarm, which is initiated if the controlled variable reaches or exceeds a predefined value. For example, the alarm system will turn off a feed pump if the level in a storage tank, to which it supplies a liquid, reaches a certain height.

Recorders

In some types of manufacturing equipment, such as a paper machine, a large number of variables must be continuously monitored and controlled. This information is often recorded to be read and analyzed at a later date. For example, suppose that some bad rolls of paper are discovered by the quality control department. By reading data charts that were recorded while the paper was being made, it may reveal that an operator made a mistake by incorrectly adjusting a valve, or that an engineer's computer program for controlling the machine is faulty. The individuals who caused the problem will be notified so that the same mistake will not be made again. The maintenance department may periodically read the chart to find out if a part is wearing out so that it can be replaced before becoming fully defective. For example, if the temperature of a fluid used in the process is slowly rising, this information may reveal that the orifice through which steam passes inside a valve is becoming larger due to erosion.

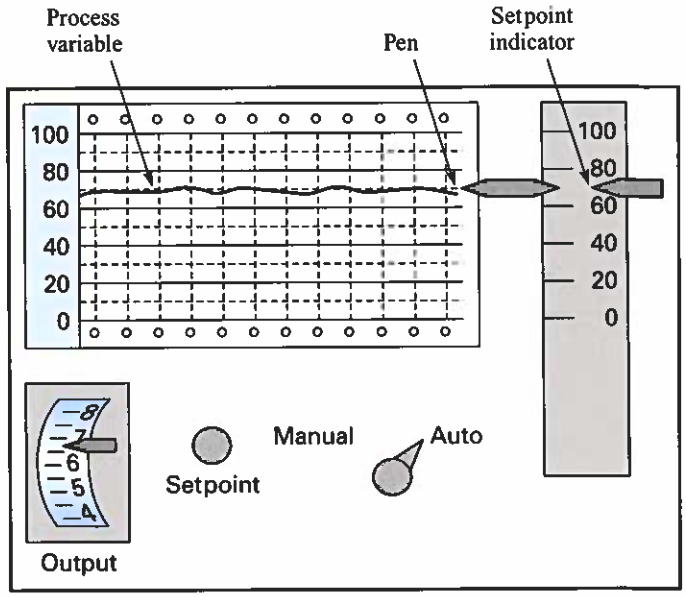


FIGURE 9-19 Strip chart recorder

Recording this type of information is called *data acquisition.* Some plants still use strip chart recorders, where a pneumatic element is connected by a linkage to a stylus. Figure 9-19 shows a chart **recorder** that displays the data on a controller/recorder. A pen that is connected to the stylus is in contact with a chart which is slowly rotated by a motor (at maybe only one revolution per hour). As the variable is sensed by the pneumatic element, the pen draws an ink line to graphically show its status. Modern data acquisition recorders use computers to display a chart recorder on its monitor. Instead of using a roll of paper to store historical data, the information is saved on discs or hard drives. This data can be retrieved at a later time and printed on a data sheet for examination.

9-8 Manipulation Devices (The Final Control Element)

In process control systems, the **final control element** is the device that directly influences the process variable. In a closed-loop system, it changes or maintains the value of the process at the desired point. There are many types of final control elements, such as pumps, motors, fans, compressors, heaters, dampers, and so on. The most widely used final control element for process control, however, is the *control valve.*

The Control Valve

The control valve is a mechanism that regulates the amount of fluid flow by varying the size of the passage through which fluid passes. Remember, the fluid can be a liquid, a gas, or a vapor. The control valve is made up of two distinct parts:

1. The *valve body,* which becomes a part of the main process line by being connected to the pipes through which the fluid in the system passes.
2. The *valve actuator,* which provides the force needed to physically change the size of the flow passage inside the valve body.

The Valve Body

The valve body is the housing that provides inlet and outlet flow connections and contains the internal trim elements. The trim elements are the parts of the valve that are in contact with the controlled fluid. They include a valve restrictor seat. The seat is a stationary element that is fixed to the valve body to form a port. The restrictor is a movable port that opens, closes, or provides a variable restriction at the seat through which the fluid flows.

Control Valve Classifications

A control valve is usually classified on the basis of its *body style* or its *flow characteristics*. *Sliding-stem globe valves* and *rotary motor valves* are the most common and versatile types of flow control valves. Their popularity is the result of their rugged construction and multiple models to select from for satisfying different application needs.

Body Style

Many styles of control valves have been developed through the years. The following summary describes some of the popular designs presently used in the process control industry.

Sliding-Stem Globe Valves

The globe valve is the type most commonly used for controlling the flow of fluids. It gets its name from its globular-shaped cavity located around the port region. Three different types of globe valves are described as follows:

Single-Seated: The single-seated valve is shown in Figure 9-20. It consists of a single plug and seat. The fluid enters the port beneath the seat and creates an upward force against the plug. As long as the pressure from the process line does not exceed the force from the valve stem, tight shut-off will occur. For high pressure applications, the valve plug is located below the valve seat, and the convoluted edge is around the top rim instead of the bottom rim. Also, the valve seat is located on the inlet side of the port and the plug is pushed upward by the stem. This design causes the inlet pressure to push the valve plug upward and aids the force from the actuator.

Double-Seated: The double-seated valve, shown in Figure 9-21, has two plugs and two seats. It is designed so that the line pressure creates an upward force on one plug, and a downward force on the other plug. This configuration creates a balanced condition to allow the valve to be used for applications involving high pressure, fluctuating pressure, or where the valve size is large.

Three-Way: The three-way valve has three external ports connected to three different pipes. It is used primarily for two types of applications, *mixing* (or *bleeding*), or *diverting*. Figure 9-22 shows its configuration for a mixing application. There are two inlet ports through which different fluids enter. Inside the valve body, the liquids converge and then exit the outlet port.

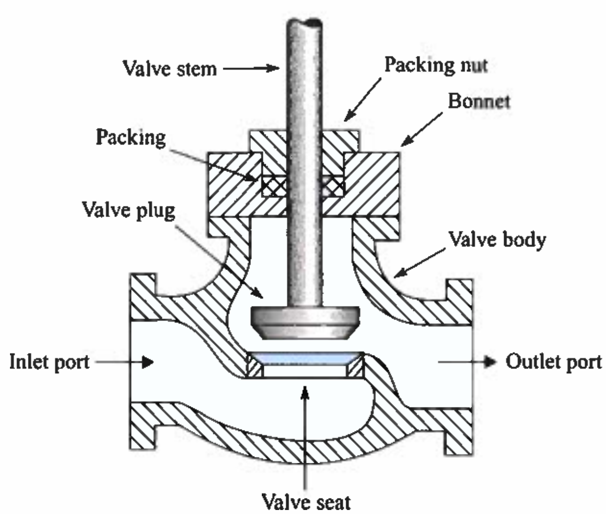


FIGURE 9-20 Single-seated valve

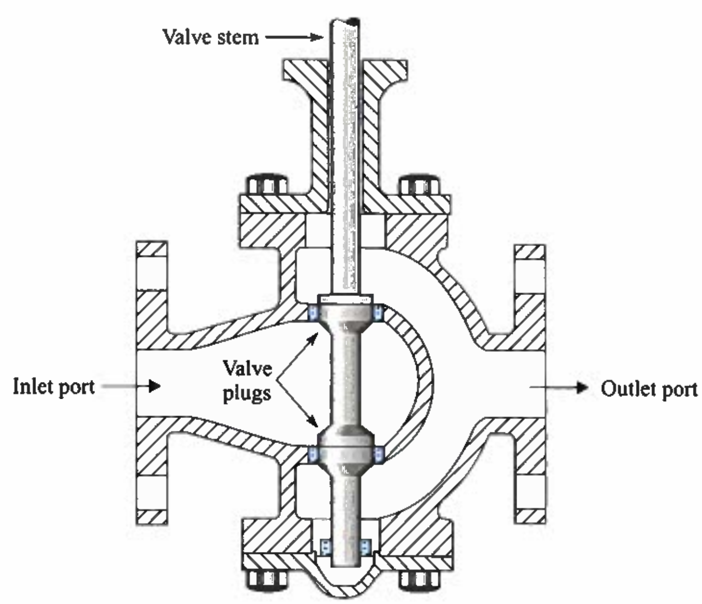


FIGURE 9-21 Double-seated valve

Figure 9-23 illustrates the configuration for a diverting application. The fluid enters an inlet port and splits inside the valve body before it exits two different outlet ports.

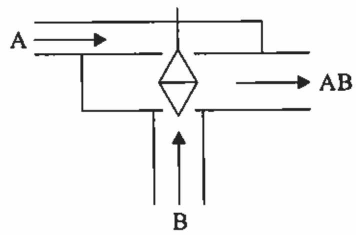


FIGURE 9-22 Mixing

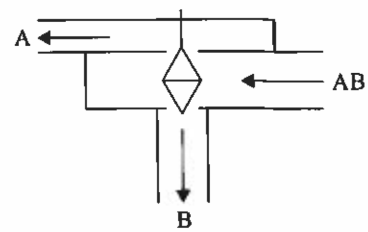


FIGURE 9-23 Diverting

Rotary Motion Valves There are two common types of rotary valves, *butterfly* and *ball*. They get their names from the shape of their restrictors. By rotating on a shaft, the restrictor alters the flow by changing the area through which the fluid passes. They are described as follows:

Butterfly: The butterfly valve contains a vane or a disk restrictor to provide the valve closure, as shown in Figure 9-24. One advantage of the butterfly valve is that the valve body around the restrictor is small. Also, since the fluid passes straight through the valve, there is no accumulation of stock or sludge such as there is with globe valves that have pockets. Butterfly valves are used in applications where high static pressures with small pressure drops across the restrictor are desired.

Ball: The ball valve shown in Figure 9-25 contains a plug that is spherical in shape and has either a v-notch or a circular port. When it is activated, the plug rotates up to 50 degrees. At 0 degree the port is completely open, and at 50 degrees it is completely closed. As the plug turns, it varies the flow from minimum to maximum capacity. Ball valves have the greatest flow capacity of all control valves. They have low maintenance requirements, and they withstand corrosive materials very well. These valves are often used to control fibrous flows such as pulp stock, paper stock, and slurries.

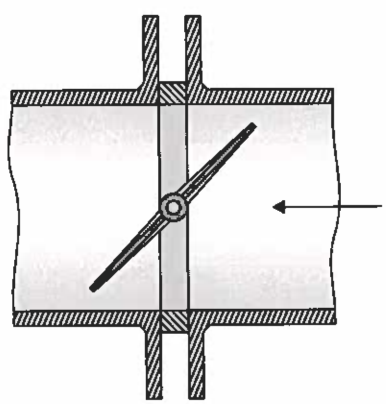


FIGURE 9-24 Typical wafer-type butterfly valve

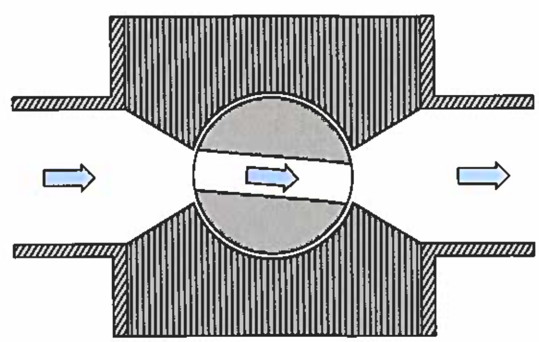


FIGURE 9-25 Flow diagram for a ball valve

Selecting a Control Valve

The result of a survey conducted in recent years has revealed that improper control valves are used in roughly one-third of all installations. When the wrong valve is used, plant efficiency and product quality are degraded. When selecting the proper control valve for a particular application, two factors must be considered: *valve capacity* and *valve characteristics*.

Valve Capacity **Valve capacity** refers to the amount of material that a valve is capable of allowing to pass. Its capacity is influenced by the physical size of the flow passage within the body.

The size of the valve has an effect on the amount of system pressure that is dropped across its inlet and outlet ports. The smaller the valve, the larger the pressure that is developed. The amount of pressure differential needed for good control is a function of the pressure dropped across the valve with respect to the rest of the system. A rule accepted by many designers is that 50 percent of the system pressure should be dropped across the valve. Sizing valves incorrectly can cause them to operate at substandard levels. A valve that is too small creates two problems:

1. The controller of the closed-loop system will usually cause the valve to be fully open because it is not passing enough fluid.
2. Small movements in the valve restrictor may cause a change in flow that is greater than desired.

Historically, most valves are oversized because of inaccurate design procedures, inexperience, or the assumption that using a larger capacity valve than needed will meet all the necessary flow requirements encountered. A valve that is too large creates three problems:

1. The controller of the closed-loop system will cause the valve to always operate at or near the closed position. The result is that the valve plug may slam into or bounce out of the valve seat. Also, excessive seat or valve wear may result from the high velocity flows between their surfaces due to the small amount of passage area.
2. The differential pressure across the valve (relative to the system pressure) becomes small, resulting in sloppy and slow control responses because large movements of the restrictor will cause small changes in flow.
3. Large valves are more expensive than smaller valves.

Valve Characteristics The **valve characteristic** is the relationship of the change in the valve opening to the change of flow through the valve. Figure 9-26 illustrates valve flow characteristics by using a graph. The valve lift position is plotted as a percent of maximum lift along the horizontal axis. The graph shows three characteristic curves that represent the most common operation of control valves used in industry.

The top curve shows the flow characteristics of a *quick open* valve. This valve is used predominately for On-Off control application. A relatively small movement of the valve stem

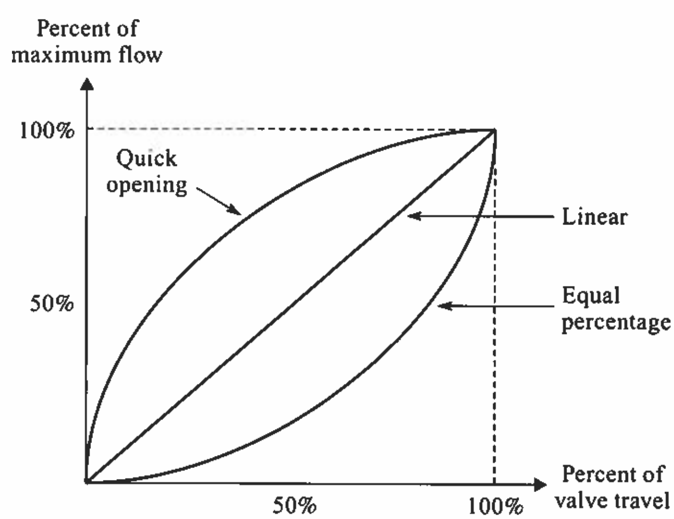


FIGURE 9-26 Characteristic curves of common valves

causes the maximum possible flow rate. For example, the curve shows that a 25 percent stem movement results in a flow rate of 70 percent of the maximum capacity. The middle curve shows the flow characteristics of a *linear* valve. This style of valve has a flow rate that is directly proportional to the position of the valve stem. It is used in applications where most of the process system pressure drop is across its inlet and outlet ports. The bottom curve shows the flow characteristics of an *equal percentage* valve. The name of this valve describes how it operates. A given percentage change in the stem position causes an equal percentage change in the flow. This type of valve is used in applications where the valve pressure is high at low flows, or low at high flows. Its drawback is that, due to its limit of travel, it does not shut off flow completely.

These flow characteristics are based on the differential pressure developed across the valve, which is primarily determined by the shape and size of the housing, ports, and the restrictor. Figure 9-27 shows how the plug in a globe valve is contoured to cause the flow characteristics just described.

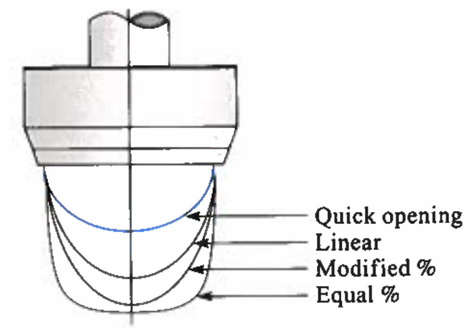


FIGURE 9-27 Contoured plug

Computer programs are now available to help designers determine proper valve sizing and appropriate flow characteristic selection. Also, most vendors and manufacturers provide specialists who can assist designers with the selection process.

The Valve Actuator

The mechanism that physically moves the element, which restricts flow in a control valve, is the *actuator*. There are two types of actuators, the *spring-and-diaphragm* and the *piston*. Because of its dependability and simplicity of design, the spring-and-diaphragm actuator shown in Figure 9-28 is used most frequently. How much the actuator moves the restrictor is determined by the magnitude of a pneumatic or electric control signal. The pneumatic actuator is the most widely used.

In Figure 9-28(a) the air signal from the controller enters the actuator housing above the diaphragm. When the pressure of the control signal increases, the diaphragm (made of rubber or neoprene) is moved downward against a spring with a force equal to the air pressure multiplied by the area of the diaphragm. The diaphragm moves until the spring creates an equal and opposing upward force due to its expansion. At this position, the motion stops and the plug and valve stem to which it is connected are in a balanced state. For each different pressure of a controller signal, there is a corresponding plug position. When there is no air pressure the valve stem is pushed upward by the spring, and when there is 15 psi pressure the valve stem is forced downward. This type of valve is capable of exerting large forces. The amount of force depends on the size of the diaphragm and how much air is applied to it. For example, suppose a force of 100 pounds is required to open or close a valve. This requirement can be achieved by applying 10 psi to a diaphragm with an area of 10 square inches, according to the formula,

$$F = PA$$

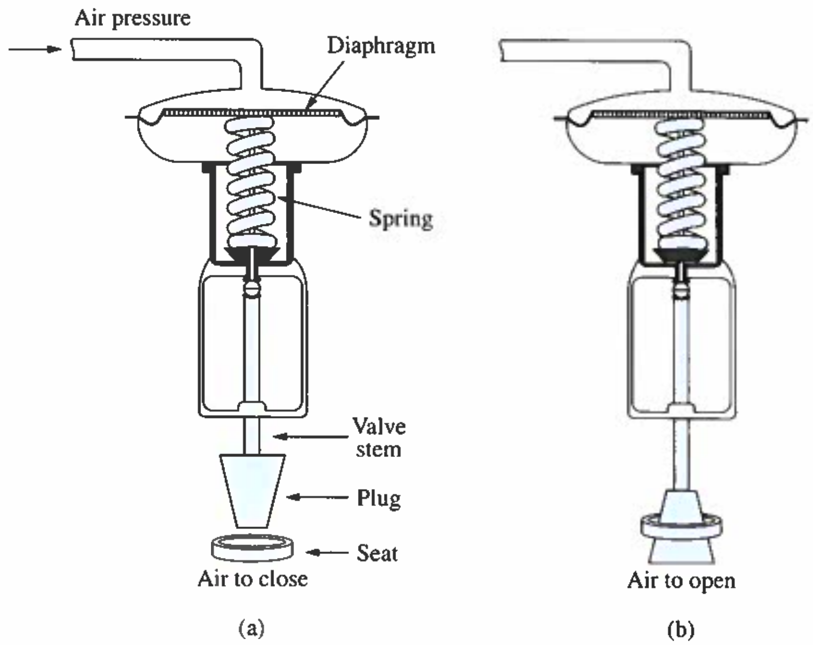


FIGURE 9-28 Valve actuator

Where,

F = Force

P = Pressure

A = Area

EXAMPLE 9-1

Determine if an actuator with a diaphragm 3 inches in diameter is capable of opening a valve fully when 15 psi of air pressure is applied. A force of 50 pounds is required to move the valve.

Solution

$$
\begin{aligned}
F &= PA \\
&= 15 \text{ psi} \times \pi^2 \times r^2 \\
&= 15 \times 3.14 \times 1.5^2 \\
&= 106 \text{ lbs}
\end{aligned}
$$

The 3 inch actuator is large enough to provide the required force of 50 pounds.

There are two different designs of the spring-and-diaphragm valve. Their action is generally defined as either "air-to-close" or "air-to-open." These terms indicate whether the plug will open or close the port at the valve seat when it is actuated by air. The illustrations in Figure 9-28 show how these valves operate. The valve style selected depends on the "fail-safe" position that is required if the control signal, which activates the valve, fails to occur.

To illustrate this guideline, assume that a material in a tank is heated by a heating jacket. The temperature is regulated by the amount of steam that flows through the control valve. If the material in the tank is damaged by overheating, an air-to-open valve will be used. By going to the closed position when the activating signal is absent, the steam is not allowed to pass through the valve to the heating jacket. On the other hand, if the material is damaged when the temperature drops below a certain level, an air-to-close valve will be used. With no activating signal applied to the valve, it will pass steam to the heating jacket and prevent the temperature from dropping.

For applications where pressures exceed the tensile strength of a spring, piston actuators (powered by air in both the upward and downward position) are used. When there is no air supply available, such as in a remote installation, electric actuators are used.

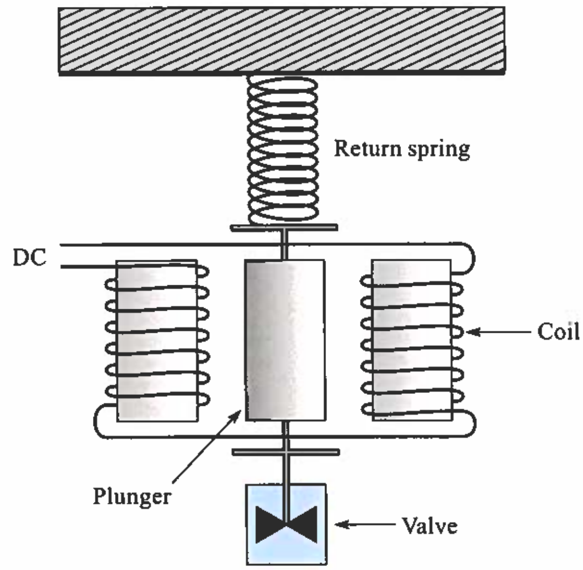


FIGURE 9-29 Using a solenoid

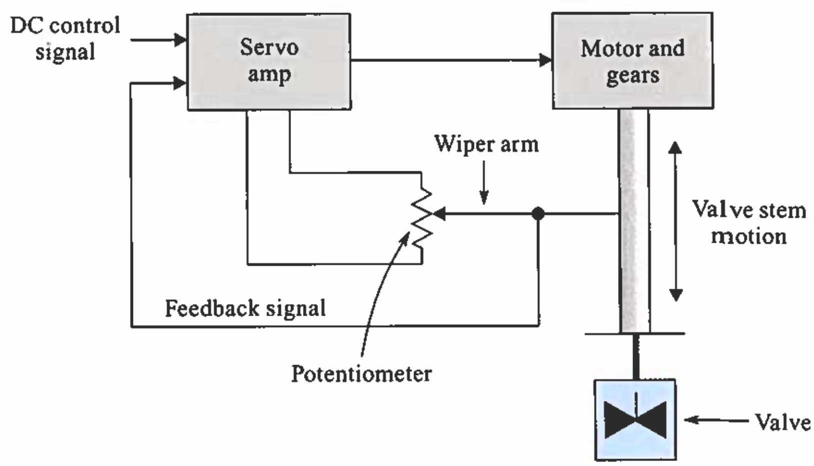


FIGURE 9-30 Using a motor or servomechanism

Actuation using the electrical method is performed two different ways. When performing the On-Off control mode, a solenoid is used to switch the valve, such as the one illustrated in Figure 9-29. When current flows through the coil, a magnetic field is generated, which moves the plunger downward against the spring. When the current stops, the spring pulls the plunger in the opposite direction.

When performing the proportional control mode, a small motor is used to move the valve stem, as shown in Figure 9-30. A DC control signal is applied to a servo amplifier which drives the gear motor to move the valve stem. The wiper arm of a potentiometer, which is attached to the valve stem, moves the valve stem and sends a feedback signal to the servo amplifier. The amplifier drives the motor until there is no longer a difference between the control signal and the feedback signal.

Valve Positioners

To ensure that the valve stem is at the precise position called for by the controller, an auxiliary instrument called a *positioner*, mounted on the top or side of the control valve actuator,

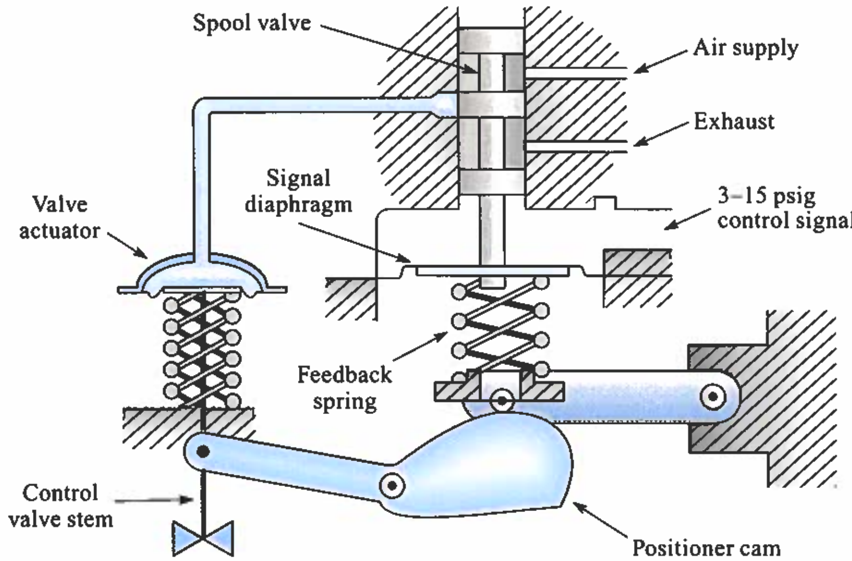


FIGURE 9-31 Force balance positioner

is used. Though they are not always required, positioners are very common because they can improve valve performance. Positioners are used to:

1. Overcome forces within the valve caused by friction or high pressure across the valve.
2. Gain speed and improve the frequency response in the closed loop.
3. Reduce actuator deadband, and reduce the hysteresis effects of the diaphragm-and-spring.
4. Provide linear positioning of the actuator stem when dynamic imbalances are present in a valve.

One type of positioner that uses pneumatic power is the *force-balance* model, shown in Figure 9-31. The control signal is applied to a signal diaphragm that creates a force which is opposed by a feedback spring. The signal diaphragm is physically coupled to a spool valve. When the spool valve is centered, it blocks air flow between the ports of the chamber in which it is located.

Suppose the pressure of the input signal is increased. It pushes the signal diaphragm against the spring and causes the spool valve to move downward. The downward position of the spool valve creates a path between the ports of the air supply and the valve actuator. As the supply air pushes against the diaphragm of the valve actuator, it causes the control valve to open and moves the lever of the positioner cam downward. This action rotates the head of the cam in a counterclockwise direction, which causes the feedback spring to compress. When the pressure on the signal diaphragm from the control signal is equal to the pressure from the feedback spring, the spool becomes centered, the ports close, and the cam stops rotating.

If the pressure of the control signal is decreased, the pressure exerted by the feedback spring becomes greater. This condition causes the spool valve to move upward and create a path between the valve actuator and the exhaust ports. Since the force created by the spring at the bottom of the valve actuator diaphragm is greater than the force created by atmospheric pressure on the top, air is pushed out of the diaphragm chamber through the exhaust port. The result is that the control valve stem moves upward to close the control valve, causing the lever of the positioner cam to move upward. This action rotates the head of the cam in the clockwise direction, which causes the feedback spring to decompress. When the pressure on the signal diaphragm from the control signal is equal to the pressure of the feedback spring, the spool valve becomes centered, the ports close, and the cam stops rotating.

DC and AC Motors

In many process control applications, an electric motor is the actuating device that powers a mechanical load. For example, in the food processing industry, motor driven stirrers are used to mix different ingredients that are blended together.

DC motors are often used in applications that require precise variable speeds with high torque capabilities. For example, they are used to turn the auger in an extruding operation. AC motors are used to power the majority of machines in industry. For example, they are used to drive a pump that forces liquids to flow through pipes. However, AC motors turn pumps at a constant speed, making it necessary to use control valves to vary the flow rate. In this application the motor runs at its full speed continuously and much energy is wasted when the control valve reduces the flow. In other applications, the control valve is replaced by a variable frequency drive, which changes the flow rate as it varies the speed of the motor driving the pump.

Problems

1. Which of the following statements describe the control requirements that must be achieved to ensure product quality? ____
   a. Quantity of raw material
   b. Controlling the process variable during the reaction cycle
   c. Controlling each step in the sequence
   d. All of the above
2. List the four types of batch processing methods.
3. Separation occurs when a mixture is ____.
   a. heated
   b. cooled
   c. both a and b
4. List five types of variables that are commonly controlled during a continuous process.
5. ____ thermal energy is supplied to heat exchangers.
   a. Hot
   b. Cold
   c. Both a and b
6. The boiling point of a liquid can be increased if the pressure of the container in which it is held is ____.
   a. increased
   b. decreased
   c. both a and b
7. In some applications, ingredients can be mixed in a shorter amount of time by ____ heat.
   a. adding
   b. reducing
8. In which of the following types of processes is material added to a vessel at the same time it is removed from the vessel? ____
   a. Batch
   b. Continuous
   c. Discrete parts manufacturing
9. In process control applications, the setpoint is typically ____.
   a. changed frequently
   b. kept constant
10. The reliability of a sensor is determined by which of the following characteristics. ____
    a. Response time
    b. Accuracy
    c. Precision
    d. All of the above
11. The term ____ is used to describe how consistently a sensor responds to the same input value.
    a. accuracy
    b. precision
    c. reliability
12. The ____ characteristic of a sensor refers to the time at which its output reaches a steady state after a signal is applied to its input.
    a. static
    b. dynamic
13. The two functions of a ____ are to convert the output of a sensor into a standardized signal and to send a signal to a distant location.
    a. transducer
    b. transmitter
14. The value for a standard transmission current signal is ____ when it is zeroed during calibration.
    a. 3 mA
    b. 4 mA
    c. 15 mA
    d. 20 mA
15. The value for a standard transmission pneumatic signal is ____ when it is spanned during calibration.
    a. 0 psi
    b. 3 psi
    c. 15 psi
    d. 20 psi
16. An I/P transducer converts ____ to ____.
    a. an input signal
    b. watts
    c. current
    d. pressure
17. The purpose of a square root extractor is to ____.
    a. multiply the magnitude of a signal
    b. linearize a signal
    c. remove noise from the signal
18. T/F When in the manual mode, the controller performs the decision-making process.
19. T/F Information obtained from recorders can be used to help troubleshoot a malfunction.
20. A term used to describe the process of storing historical data is referred to as ____.
    a. historical data
    b. data acquisition
    c. data history
21. The most widely used final control element for process control is the ____.
    a. AC drive
    b. electric motor
    c. control valve
22. The ____ control valve is recommended for high pressure application.
    a. single-seated
    b. double-seated
    c. butterfly

23. ____ valves have the greatest flow capacity of all control valves.
    a. Single-seated
    b. Three-way
    c. Butterfly
    d. Ball

24. If a control valve is sized too ____, small movements in the valve restrictor may cause a change in flow that is greater than desired.
    a. small
    b. large

25. If the valve should block flow when a control signal fails to occur, a ____ control valve should be used.
    a. air-to-close
    b. air-to-open

26. Which of the following functions is/are performed by valve positioners? ____
    a. Overcome frictional forces
    b. Increase the reaction speed of a valve
    c. Reduce deadband and hysteresis
    d. Provide linear positioning
    e. All of the above

27. How much force is exerted on the 4 inch diameter diaphragm of a valve actuator if 12 psi of air pressure is applied?

CHAPTER 10

Instrumentation Symbology

OBJECTIVES

At the conclusion of this chapter, you should be able to:

- Define a P&ID.
- Identify various instruments by the shape of balloons that represent them.
- Identify and interpret functional identifiers in balloon symbols.
- Describe how tag numbers pertain to an instrumentation loop.
- Describe the function of line symbols.
- Identify the symbols for various actuators and valves.
- Read a simple loop on a P&ID.
- Describe the various types of information on a title block.

INTRODUCTION

In the field of electronics, schematic diagrams use symbols and lines to show which components are in a circuit, and how they are connected. Likewise, in the field of process control, drawings called **Piping and Instrumentation Diagrams,** or simply **P&IDs**, are used. P&IDs are a standard format used in all types of process control fields, such as the petroleum, food, or utility industries. These drawings contain more information than just symbols and lines. Circles, letters, lines, numbers, and symbols are used to indicate which devices are included in a system, how these devices are arranged, where they are located, and which function they perform in the process. A thorough understanding of these diagrams will help the operator or technician monitor processes, do routine work more efficiently, and save time troubleshooting.

10-1 General Instrument Symbols

Figure 10-1(a) shows *general instrument* (or functional) *symbols.*

Individual Instruments

To indicate an individual instrument in a process control diagram, a circle called a *balloon* is used. The balloon contains letters, lines, and numbers that identify its location and its function in the process, and further specifies whether it is used to measure, indicate, record, or control the process variable. A circle by itself indicates a discrete stand-alone instrument, such as a transmitter, sensor, or alarm. If the symbol is a circle in a square, the instrument is described as a

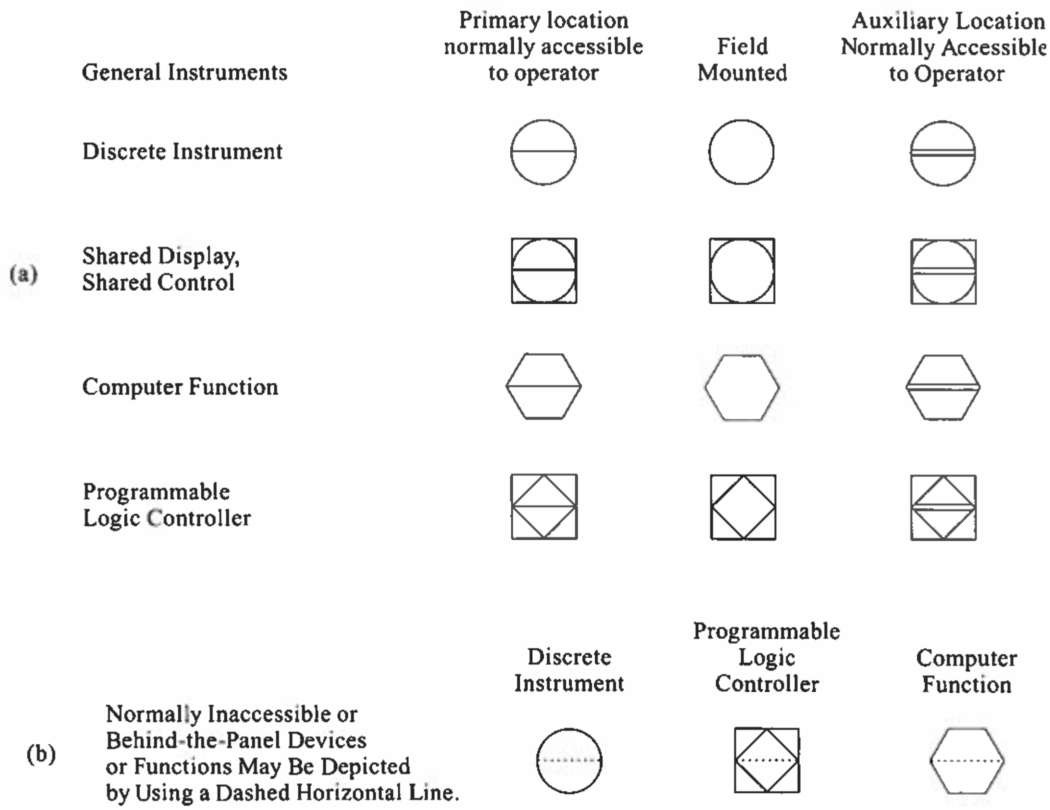


FIGURE 10-1 (a) and (b) General instrument or functional symbols

shared device, which means that, in addition to performing its specific function, it also displays or controls the process variable. If a hexagon is used instead of a balloon, it indicates a computer function. A programmable controller is identified by a diamond inside a square.

Figure 10-1(a) also shows that some symbols are divided in half by a single horizontal line, a double horizontal line, or are without any lines. These lines, or absence of lines, indicate how the instruments are mounted, or where they are located. A symbol without a horizontal line designates that it is installed in the field near the point of measurement or near the final control element. A single solid line indicates the instrument is mounted on a panel board in a control room usually among other instruments. Therefore, they are easily accessible to the operator or for routine maintenance. Double lines specify that the instrument is at an auxiliary location, away from the process.

Symbols with a single horizontal dashed line in Figure 10-1(b) denote an instrument located behind a panel, which may not be easily accessible.

10-2 Tag Numbers

Since there may be many different instruments used in a process, an alphanumeric code is placed inside each symbol to identify it. These instrument identifiers are called **tag numbers.** The code provides a variety of useful information about each instrument. Letters, called **functional identifiers,** are located in the top portion of the symbol. The sequence of letters designates the internal function.

1st Letter: The first letter denotes the measured or the initializing process variable. For example, **P** indicates pressure, **T** is temperature, **F** represents flow, and **L** means level.

2nd Letter: The second letter tells the function of the instrument. For example, **I** represents indicate, **R** is for record, **C** indicates control, and **T** means transmit.

When there are three or four letter identifiers, the second letter provides additional information about the first letter. For example, if **PDI** is used, **D** changes the measured variable, pressure (**P**), to differential pressure. The **I** represents an indicator, which means that the instrument displays differential pressure. An example of a four-letter identifier is **PDAH**, which indicates that the instrument is a differential pressure alarm that **P** is activated when the pressure is too high. A list of standard functional identifiers is shown in Table 10-1.

EXAMPLE 10-1

Use Table 10-1 to determine:

Question: What a balloon with the letters TR indicates?

Answer: A temperature recorder

The numbers located in the bottom portion of the symbol are the **loop identifier.** A loop consists of one or more instruments arranged to measure and control a process variable. The loop ID identifies the loop where the instrument is located. All of the instruments in one loop are given the same loop number, regardless of the function or location of the instrument. When an instrument is used in two or more loops, it should be assigned the number of the most predominant loop. Figure 10-2 shows instruments used in a loop that measures and controls a flow process variable. In addition to providing specific information about each instrument contained in the loop, the number may also indicate a location within the plant or at another building. In some situations, tags and numbers are physically listed on the outer surface of the instrument encasement. This information makes it possible to verify which device in the field is the one designated on the diagram.

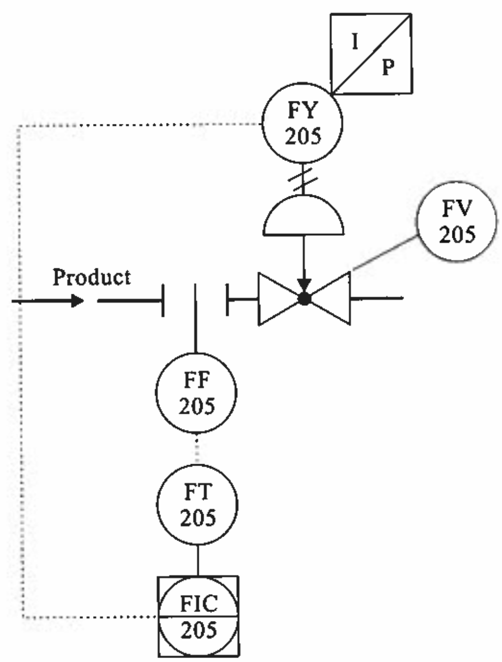


FIGURE 10-2 A P&ID of a closed-loop flow process system

In summary, the symbols, along with the letters and numbers inside them, provide the following information about the process system:

1. Identify the measured variable controlled by the loop.
2. Identify the function of the instrument.
3. Show how the instrument is mounted.
4. Identify the loop number of the location where the operation is performed.

TABLE 10-1 Functional Identifiers

	First Letter		Succeeding Letters		
	Measured or Initiating Variable	*Modifier*	*Readout or Passive Function*	*Output Function*	*Modifier*
A	Analysis		Alarm		
B	Burner, Combustion		User's Choice	User's Choice	User's Choice
C	User's Choice			Control	
D	User's Choice	Differential			
E	Voltage		Sensor (Primary Element)		
F	Flow Rate	Ratio (Fraction)			
G	User's Choice		Glass, Viewing Device		
H	Hand				High
I	Current (Electrical)		Indicate		
J	Power	Scan			
K	Time, Time Schedule	Time Rate of Change		Control Station	
L	Level		Light		Low
M	User's Choice	Momentary			
N	User's Choice		User's Choice	User's Choice	User's Choice
O	User's Choice		Orifice, Restriction		
P	Pressure, Vacuum		Point Connection		
Q	Quantity	Integrate			
R	Radiation		Record		
S	Speed, Frequency	Safety		Switch	
T	Temperature			Transmit	
U	Multivariable		Multifunction	Multifunction	Multifunction
V	Vibration, Mechanical Analysis			Valve, Damper, Louver	
W	Weight, Force		Well		
X	Unclassified	X Axis	Unclassified	Unclassified	Unclassified
Y	Event, State	Y Axis		Relay, Compute	
Z	Position, Dimension	Z Axis		Driver, Actuator, Final Element	

10-3 Line Symbols

The symbols in a P&ID are interconnected by lines. Instead of using just solid lines, such as those used in an electronic schematic diagram, different types of lines are used. They differ in various ways to indicate if they are pipes, lines that pass specific types of signals, and to show how the instruments are connected to the process and to each other. These lines may be solid or broken; their relative thickness may differ; or various markings may be added.

Figure 10-3 shows the different types of line symbols used in P&ID diagrams.

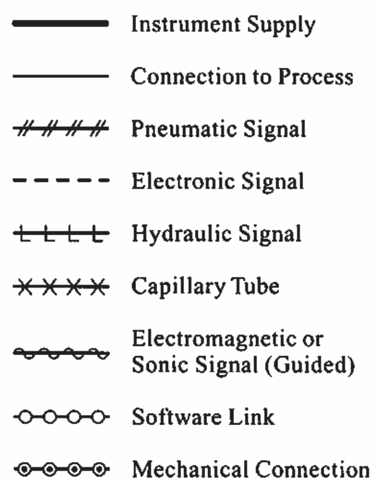


FIGURE 10-3 Line symbols

Solid Bold Line: The thick solid line shows the pipes (referred to as process piping) that contain the process material such as steam, raw materials, or the final product.

Solid Fine Line: The thinner solid line indicates that an instrument is connected directly to the process. For example, Figure 10-4 shows how a field mounted pressure orifice transmitter is connected directly to the process within the pipe.

Other types of line symbols on a P&ID drawing represent signal lines that carry electronic, pneumatic, or optical information that are called signal lines, carry information between two instruments electrically, through pneumatics, or by several other methods. They include:

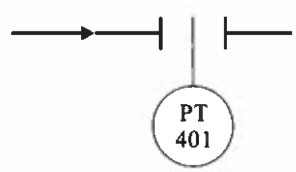


FIGURE 10-4 A thin solid line indicates an instrument is connected directly to the process

Solid Fine Line with Double Diagonal Markings: This line carries pneumatic signals. An example of this type of connection is a transmitter that sends a pneumatic signal to a controller to indicate flow detected by a differential pressure sensor. The amount of pressure indicates how much the controller should vary the flow.

Dashed Line: A dashed (broken) line between two instruments indicates an electronic signal. These lines are usually preferred for carrying signals long distances.

Solid Fine Line with L's: A solid fine line with L's spaced apart represents a tube that passes a signal using hydraulic fluid.

Solid Fine Line with X's: A solid fine line with X's spaced apart represents a capillary tube. Capillary tubing is connected to a filled thermometer that measures the temperature of a process. The tube contains a fluid, which expands and contracts when subjected to temperature changes. The pressure the fluid exerts is often applied to a transmitter that converts the pressure to a proportional electrical signal.

Solid Fine Line with Sine Waves: A solid fine line with sine waves spaced apart represents electromagnetic transmitted signals.

Broken Fine Line Connected with Circles: A set of several fine lines connected with circles represents a software link.

Broken Fine Line Connected with Circles That Contain a Dot: This line symbol represents a mechanical connection.

In general, one signal line is used to indicate the connection between two instruments, even though more than one line may be used to make the physical connection.

10-4 Valve and Actuator Symbols

In P&ID drawings pictorial symbols are used to show valves and the actuators that position them. Squares, triangles, and circles are used to show the different types of valves, dampers, and actuators that control the flow of fluids. Figures 10-5 and 10-6 show symbols for common types of valves and dampers used in process control applications.

Control Valves

Control valves are positioned by the movement of the valve stem, either by a linear motion or a rotary motion.

Linear Motion Valves

Globe Valve: The globe valve shown in Figure 10-5a, is used in many industrial applications that require the tightest possible shutoff. In most applications, these valves are installed so that the flow tends to close the valve, and will shut off in the event of failure.

Three-way Valve: The three-way valve in Figure 10-5b is designed to divert fluid flow into two separate streams. Similar valves are designed to converge two streams into one.

Angle Valve: The angle valve in Figure 10-5c are single-seated valves with special body configurations to suit specific piping or flow requirements, such as turns or bends in which globe valves cannot be used.

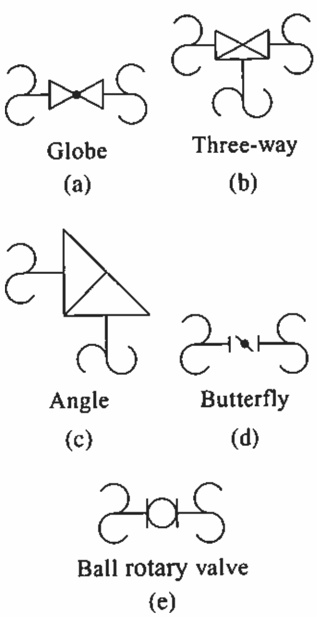


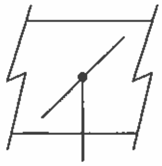
FIGURE 10-5 Valve symbol

Rotary Motion Valves

Butterfly Valve: Shown in Figure 10-5d, the butterfly valve uses a rotating vane to provide closure to flow. Most often, they are used in applications with low or modest pressure.

Ball Valve: The ball valve shown in Figure 10-5e contain a plug that is spherical in shape with a port through which the fluid flows. At zero degrees, the port is fully open and maximum fluid flows. The flow decreases as the ball is rotated. Ball valves require minimum maintenance and have the greatest flow capacity of all control valves.

Dampers: Dampers are rotary action devices used to vary the volumetric flow rate of gas or air. Shown in Figure 10-6, they are typically used in heating, ventilation, and air conditioning systems.



Damper or louver

FIGURE 10-6 Flow actuator

Actuators

An actuator is a component that is used to position another component, usually a final control element such as a valve or damper. There are many types and styles of actuators. Some are manual, but most are automatic. The type selected is usually based on the specific characteristics that best suits a particular application.

Most linear motion valves are positioned automatically by a pneumatically-activated diaphragm. The symbol for this type of actuator is shown in Figure 10-7. The diagram shows the actuator connected to a globe control valve. Notice that a fine line with two diagonal dash markings is used to indicate a pneumatic input signal to the diaphragm. A balloon included with the symbol has a tag number inside to identify the type of valve used and its function. Valves usually have a V in their functional identifier. The diagram indicates that a flow control valve is in temperature control loop 401.

Actuators can also be activated electrically. One example is a solenoid, which is identified by a square with an S inside the box, as shown in Figure 10-8(a). Another electrically activated actuator is a rotary motor, which is identified by an M inside a circle, as shown in Figure 10-8(b). The symbol for a manually activated valve is a T connected to the valve body (Figure 10-8(c)).

On the line between the actuator and valve body is an arrow that describes the valve's failure mode. Failure modes indicate the position of the valve when the signal to the actuator fails to be applied, usually because of a malfunction. An arrow that points upward, as shown in Figure 10-9(a), indicates a failure of the control signal that will cause the valve to be fully open. An arrow pointing downward, as shown in Figure 10-9(b), indicates a fail closed valve.

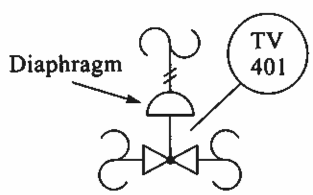
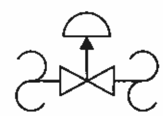


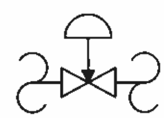
FIGURE 10-7 Pneumatic activated diaphragm symbol

(a) (b) (c)

FIGURE 10-8 Identifiers for various actuators



Fail open
(a)



Fail closed
(b)

FIGURE 10-9 Symbols that show the failure mode of a valve

10-5 Reading a Single Loop

The information provided on instrumentation symbology in this chapter is only a fraction of the amount of information on the subject. An entire manual is needed to provide a complete listing of the material. However, enough information has been given to read simple drawings, such as the one that contains a control loop for a heat exchanger application in Figure 10-10. The following steps illustrate how a P&ID provides information about the type of process variable used and how instruments work together to control the process:

Step 1: The tag numbers on the component symbols indicate that the portion of the P&ID is loop 401.

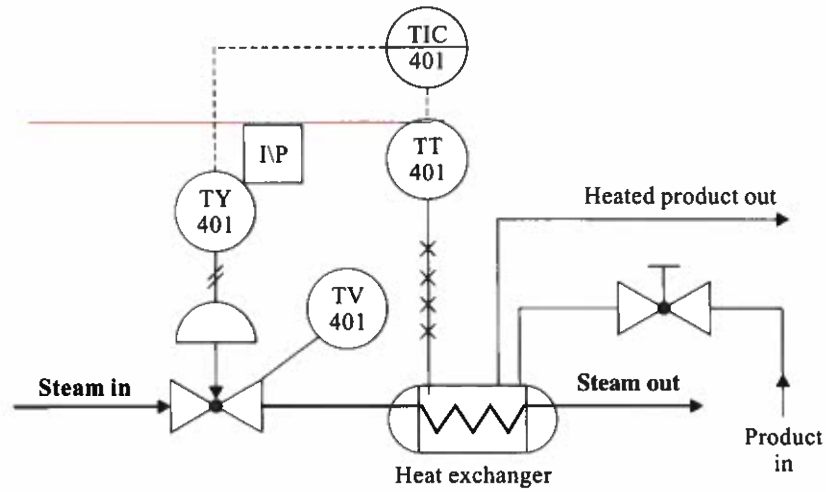


FIGURE 10-10 Control loop (401) for a heat exchanger application

Step 2: The first letter of each functional identifier is a **T,** which means that it is a temperature loop.

Step 3: The instrument connected to the heat exchanger for measuring temperature is a transmitter, which is labeled with a **T** as the second letter of the functional identifier. The balloon has no line inside its symbol, which indicates that it is field mounted. The line with X's indicates that a capillary tube sends a signal from the exchanger to the transmitter. A dashed line that extends from the output of the transmitter indicates that it produces an electrical signal.

Step 4: The electrical signal from the transmitter is sent to an instrument that performs two functions, indication and control: each of these two functions is identified by the second and third letters (**IC**) of the functional identifier. The solid line inside the balloon tells that it is board mounted. The controller sends out an electrical positioning signal, as indicated by the dashed line extending from the left of the symbol.

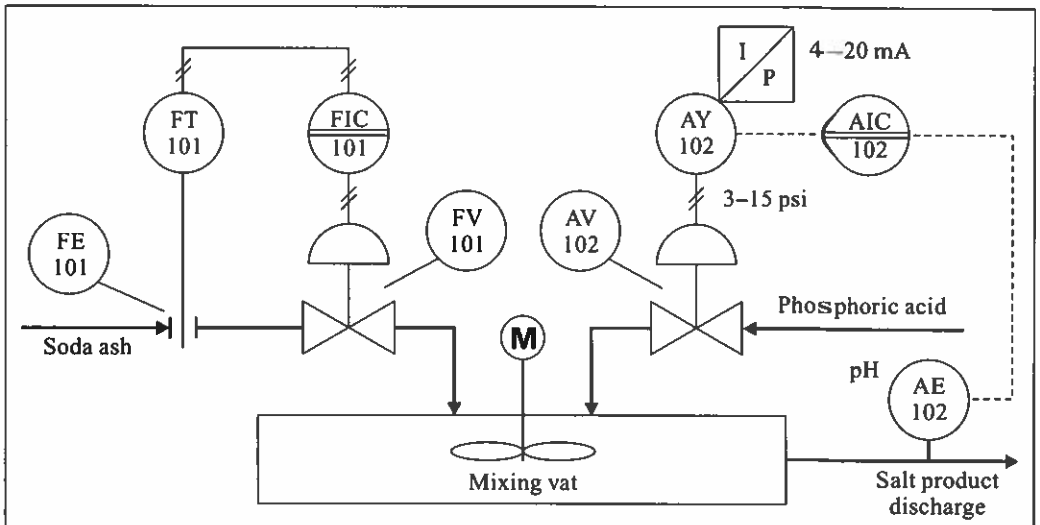
Step 5: Since the actuator that varies the steam through the flow control valve is actuated pneumatically, a transducer is required to convert the electrical signal from the controller to a pneumatic signal. This function is performed by the I/P transducer. The transducer function is described by the second letter (**Y**) inside the balloon. The current-to-pressure conversion is identified by the small square, located in the diagonal position to the balloon, containing the letters I/P. The fine solid line with diagonal markings between the transducer and the actuator shows that it is a pneumatic line.

Step 6: The half circle symbol of the actuator indicates that it consists of a pneumatically controlled diaphragm. The arrow that points downward between the actuator and globe valve symbol tells that it is a "fail closed" type of valve.

10-6 Information Block

Besides the symbols and lines shown on the diagram, additional information about the system may be provided at the bottom of the drawing, as shown in Figure 10-11.

The Title Block: This section, shown in Figure 10-12, is located in the lower right-hand corner of the drawing. It provides the title and the drawing identification number. The ID number should be checked to prevent problems resulting from work being done to the wrong system. On this sample, three signatures are required for validation. Additional information about the drawing may be included in other documentation.



In loop 101, soda ash flows into the mixing vat. The flow is detected by an orifice flow sensor, which is shown connected directly to the process. It sends a pneumatic feedback signal to a flow/indicator/controller mounted behind the panel. FIC 101 sends a pneumatic signal to a diaphragm which controls the valve that regulates flow.

In loop 102 an analyzer sensor that monitors pH sends an electrical signal to an indicator/controller. An analyzer transducer converts the electrical signal from the controller to pressure, which causes a diaphragm to change the valve that controls the flow of phosphoric acid.

FIGURE 10-11 An information block example

ACME PROCESS CORP.	
MIXING SYSTEM #1	
DRAWN BY:	DATE
CHECKED BY:	DATE
APPROVED BY:	DATE
SHEET NO. 1 of 1	DRAWING NO. 3250-7A

FIGURE 10-12 The Title Block

Revisions: This supplement in Figure 10-13(a) provides information about any changes that have been made to the original drawing.

Material List: This supplement in Figure 10-13(b) contains a complete list of the components that are on the P&ID diagram. It also includes a list of numbers for ordering parts when they need to be replaced.

Notes: Descriptive information about the diagram may be included in the form of notes. There are two types of notes, *general* and *local.* General notes pertain to the diagram, as shown at the bottom of Figure 10-11, or to the process system as a whole. Local notes contain information about an instrument or area of the diagram rather

REVISIONS					
REV #	DATE	DESCRIPTION	BY	CH'K	APRV

(a)

MATERIAL LIST			
TAG #	MANUFACTURER	MODEL	PART #
TV-302	FISHER	513RP	61121-41
PV-309	MASONEILAN	47-21134	54378-39
FIC-301	FOXBORO	130M	22447-12
PT-309	FISHER	4157	61247-33
TT-302	FOXBORO	45P-F2	22336-19
LV-305	FISHER	667F7	62458-20
PIC-308	MOORE	528M	14436-38
TIC-302	MOORE	528M	14436-38
LIC-305	FOXBORO	130M	22447-12
LT-305	TAYLOR	4807A	43741-80
LT-307	TAYLOR	4807A	43741-80
FV-308	MASONEILAN	48211-35	54267-37

(b)

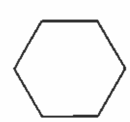
FIGURE 10-13 (a) Revisions; (b) material List

than the whole system. They are usually included on the diagram, and in some cases a line connects the note to the instrument or area to which it pertains.

If there is too much information to fit on the drawing, a local note will refer the reader to another document where it is located.

Problems

1. Which of the following types of information about instruments are not provided on a P&ID? ____
   a. Which type of device b. Location of devices
   c. Function of the device d. How devices are arranged
   e. None of the above
2. The lines, letters, and numbers of a balloon identify the instrument's ____.
   a. Location
   b. Function in the process
   c. Specific operation
   d. All of the above
3. Double lines inside the balloon indicate that the instrument is ____.
   a. mounted on a panel b. field mounted
   c. mounted at an auxiliary location
4. A single line inside the balloon indicates that the instrument is ____ .
   a. mounted on a panel b. field mounted
   c. mounted at an auxiliary location
5. The following symbol indicates a computer function which is ____ mounted.



6. A broken line inside a balloon symbol indicates that the instrument is ____ .
   a. field mounted b. inaccessible to the operator
   c. panel mounted

7. The ____ letter of a functional identifier indicates the type of measured variable.
   a. 1st b. 2nd
   c. 3rd
8. Which symbol represents a stand-alone instrument? ____
   a. Circle b. Square
   c. Hexagon d. Diamond
   e. All of the above
9. A general instrument symbol without a horizontal line indicates that it is ____ .
   a. installed in the field b. board mounted
   c. located behind a panel d. at an auxiliary location
10. Draw a shared instrument that is located at an auxiliary location.
11. A general instrument symbol that is a circle within a square indicates that it ____ .
    a. performs a measuring function
    b. displays or controls the process variable
    c. both a and b
12. T/F All of the instruments in one loop are given the same loop number.
13. A tag number consists of a ____.
    a. functional identifier b. loop number
    c. both a and b
14. Identify each letter of the following functional identifier, PDI.
15. T/F The term *process piping* refers to a pipe through which the process variable flows.
16. Which of these line identifiers represent an electronic signal? ____


A


B


C

D

17. A pneumatic line is represented by which of the following identifiers? ____

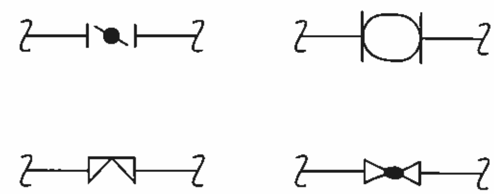

A

B

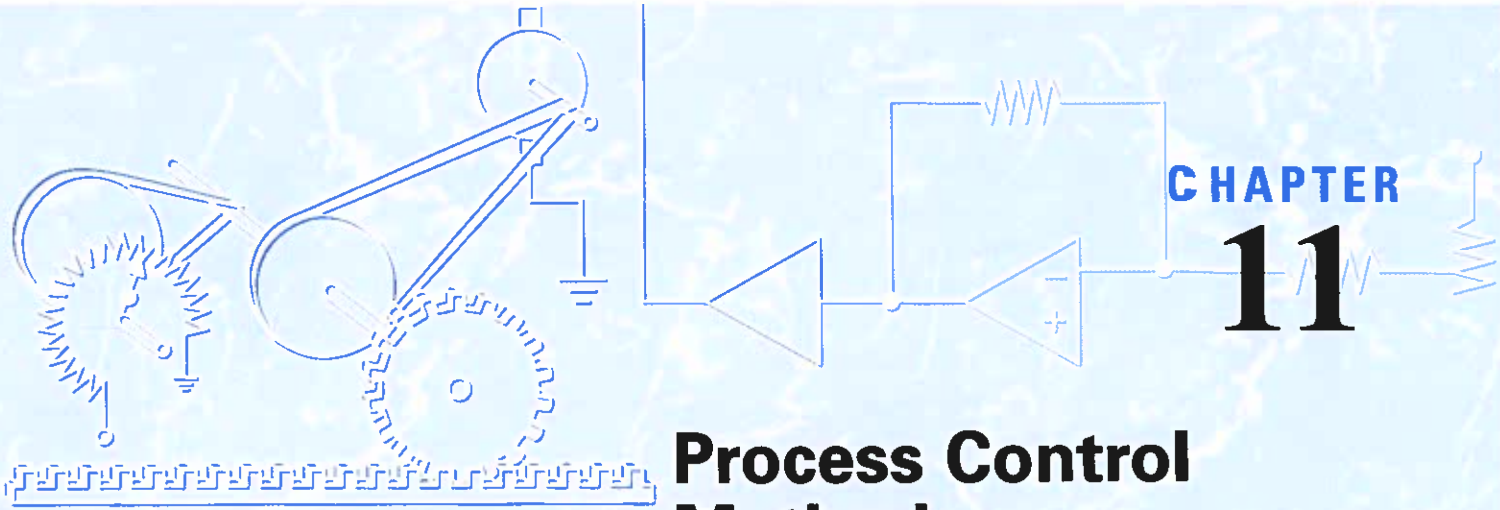

C


D

18. Which of the following devices are considered actuators ____ .
    a. diaphragm b. piston
    c. solenoid d. all of the above
19. A valve symbol with an arrow pointing upward indicates that it is a fail ____ device.
    a. open b. closed
20. Which of the following symbols represents a globe valve? ____



21. The device that positions the final control element is the ____ .
    a. damper b. valve
    c. actuator d. all of the above
22. A line symbol with individual circles spaced apart represent a/an ____ .
    a. pneumatic signal b. electronic signal
    c. capillary tube d. software link
23. A general instrument symbol with TV inside a circle indicates it is a ____ .
    a. variable transmitter b. valve in a temperature loop
    c. volume transducer
24. What does the word *panel mount* refer to?
25. Which of the following types of information are on the title block? ____
    a. Diagram number
    b. The total number of P&ID sheets
    c. The name of the person who created the drawing
    d. All of the above



CHAPTER 11

Process Control Methods

OBJECTIVES

At the conclusion of this chapter, you should be able to:

- List the operational characteristics of an open-loop system. Include the elements, and the signals they produce.
- List the operational characteristics of a closed-loop system. Include the elements, and the signals they produce.
- Define the following terms:

Primary Element	Manipulated Variable	Time Proportioning Method
Heat Exchanger	Controlled Variable	Amplitude Proportional Method
Feedback Loop	Measured Variable	
Final Control Element	Load Demand	
Disturbance		

- Identify which types of elements in an open- or closed-loop system are defined as instrumentation devices.
- List the factors that contribute to the dynamic response of a single-variable control loop.
- Define the following terms associated with the dynamic response of a control loop:

Step Change	First Order Time Lag	Time Constant
Time Lag	Pure Lag	Head Pressure
Dead Time	Static Inertia	

- Explain the operation and characteristics of an On-Off control system, and describe the function of the deadband.
- Describe the operational principles and characteristics of the following continuous control modes:

Proportional	Integral	Derivative

- Describe the operating principles and characteristics of the following advanced control techniques and give a practical application of each one:

Cascade	Ratio
Feed-Forward	Adaptive

- Define the following terms associated with various control techniques:

Proportional Gain	Remote Controller	Secondary Feedback Loop
Offset	Controlled Flow	Wild Flow
Reset Rate	Proportional Band	Hysteresis
Rate	Sensitivity	Deadband
Primary Feedback Loop	Integral Time	
Reset Time	Derivative Time	

INTRODUCTION

Many different operations are performed in an industrial machine to manufacture a product. For example, fluids flow through pipes at a certain rate, ingredients fill a vat to a required level, heat is applied to a vessel to cause a chemical reaction, or a vacuum pressure is applied to a confined tank to extract its contents. Each one of these operations is referred to as a *process*. Many of these individual processes are combined and run simultaneously to produce a finished product of a desired quality as rapidly and inexpensively as possible. To satisfy these requirements, each process must be precisely controlled, often by some type of automatic control device. The automatic operations performed by an industrial manufacturing machine are referred to as *process control*.

11-1 Open-Loop Control

Process control operations are performed automatically by either open-loop or closed-loop systems. If the process is controlled only by setpoint commands, without feedback measurement signals, the system is referred to as **open-loop.**

Open-loop control is used in applications where simple processes are performed. Timing functions are often the key factor used to control the operation. Examples of open-loop process machines are cafeteria dishwashers, commercial laundry machines, and printed circuit board burn-in chambers. This equipment runs through a series of timed cycles, which are activated by controller devices such as relay ladder logic hardware, sequential drum controllers, programmable controllers, or computers.

The advantage of open-loop systems is that they are relatively inexpensive. Their main drawback is that without a feedback loop, there are no control capabilities to make corrections if the process deviates from its required state.

11-2 Closed-Loop Control

Closed-loop automatic control systems are more effective than open-loop systems. With the addition of a feedback loop, they become self-regulating. The diagram in Figure 11-1 is used to illustrate the operation of a temperature-type process control closed-loop system. It shows a *heat exchanger,* which is used to heat a liquid to a temperature of 100°F. A source of steam supplies the thermal energy to the exchanger. The amount of steam that passes through a control valve determines the temperature at which the liquid is heated. The *primary element* (sensor) is used to detect the condition of the *controlled variable,* which is the temperature of the liquid leaving the exchanger. The sensor's output, which is called the *measured variable,* is conditioned by a transducer/transmitter into a standard signal before it is sent to the controller. The controller compares the feedback signal to the setpoint, and an error signal is developed if there is a difference. The controller uses the error signal to make computations to determine which type of *control signal* to produce at its output. The control signal is sent to the *final control element* (which is the control valve). This valve varies the steam flow into the exchanger. The steam is the *manipulated variable* that causes a change in the controlled variable. These actions of *measuring, comparing, computing,* and *correcting* go on continuously.

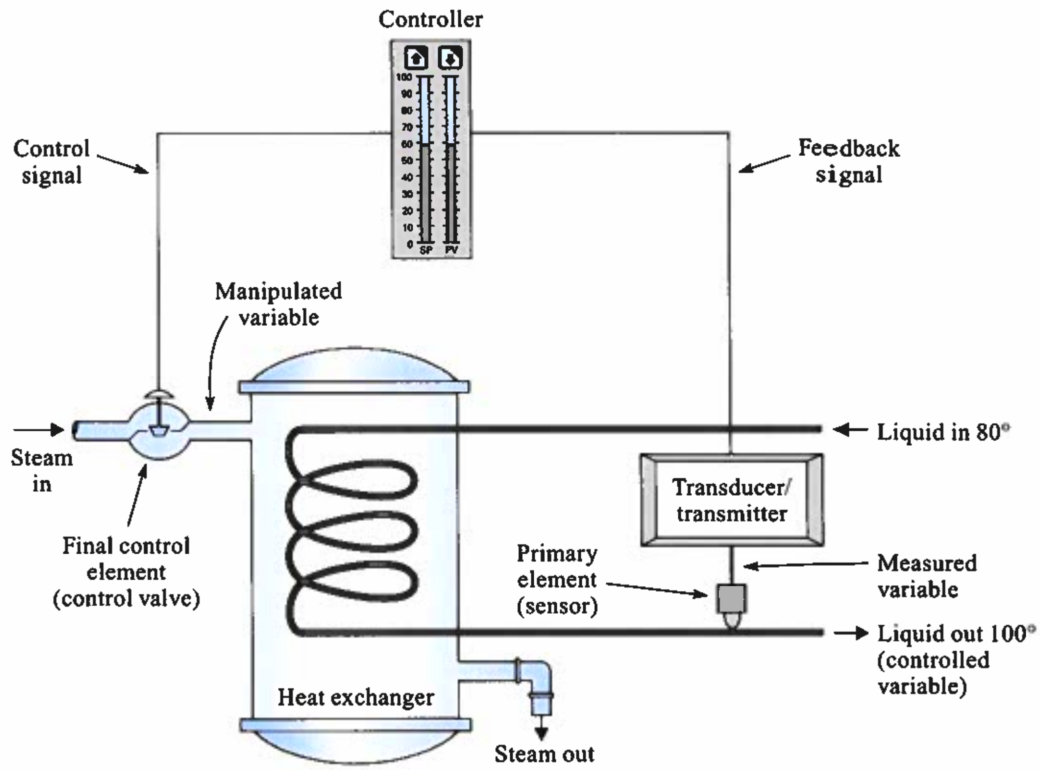


FIGURE 11-1 Closed-loop temperature process control system

Process Behavior

The primary objective of process control is to cause a controlled variable to remain at a constant value at or near some desired setpoint. The term *variable* refers to the fact that an element varies when an influence to which it is exposed causes the variable to change. A change can happen when only one of the following conditions occurs:

- A disturbance appears
- Load demands vary
- Setpoints are adjusted

When a change does occur, the objective of the process control system is to return the controlled variable to the setpoint as quickly as possible.

The behavior of a process system can be examined by observing the controlled variable's response after one of these influences abruptly changes. Referred to as a **step change,** it takes place over a small time interval and is plotted on a time graph (Figure 11-2(b)) as a vertical line.

Figure 11-2(a) shows how step changes develop in an actual application. The flow of fluid through a pipe system is the process. The fluid flow rate leaving the valve is the *controlled variable.* The position at which the valve is set is considered the *setpoint.* The flow rate governed by the position of the flow restrictor inside the valve is the *manipulated variable.* The demand for fluid downstream from the valve is the *load,* and the variance in upstream pressure is considered the *disturbance.*

Figure 11-2(b) is a time graph that shows how a setpoint change, disturbance, and a load variance affect the controlled variable. Flow, the controlled variable, is plotted on top by a measurement device such as a strip chart recorder. At time 1, the flow rate increases when the valve position is opened wider, while the upstream pressure remains constant. At time 2, with the valve position unchanged, the flow rate decreases because the upstream pressure drops. The flow rate would decrease in a similar fashion if the demand for fluid decreased downstream, while the upstream pressure and the valve position remained constant.

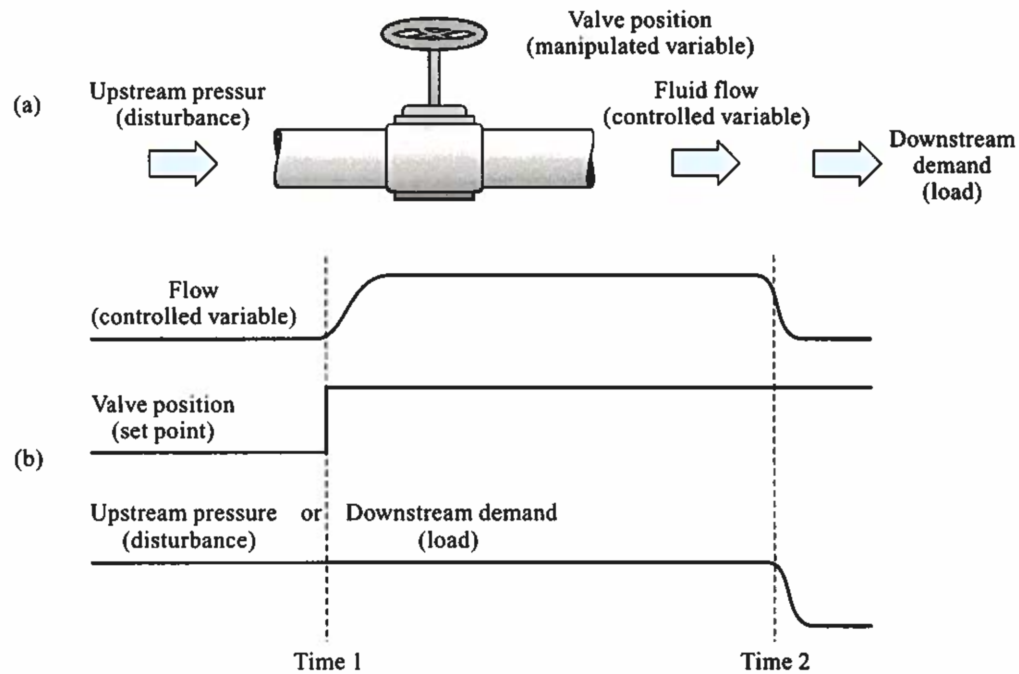


FIGURE 11-2 (a) A pipe system; (b) graphic illustration of process behavior

11-3 Single-Variable Control Loop

Several process variables are typically controlled simultaneously in a machine that produces a product in the process industry. Usually, only one individual *feedback loop* is required to control each variable. Referred to as a *single-variable control loop,* it consists of the following elements:

- Measuring Device (Primary Element)
- Transducer/Transmitter
- Controller
- Final Control Element

These elements are also referred to as *instrumentation* devices.

When a step change takes place, there is not an immediate response by the control loop. The correcting action takes time. A measure of the loop's corrective action, as a function of time to the deviation, is referred to as its **dynamic response.** There are several factors that contribute to this delay.

Response Time of the Instruments

All instruments have a **time lag.** This is the time duration from when a change is received at its input until the instrument produces an output response. Time lag also includes the time duration as a signal passes from one instrument to the next. The following six factors contribute to the time delay caused by instruments:

- Response time of a sensor
- Time lag of the transducer
- The distance the feedback signal must travel from the transducer to the controller
- The time required for the controller to process information
- The distance the control signal travels from the controller to the final control element
- The time lag of the final control element

Pure Lag of the Controlled Variable

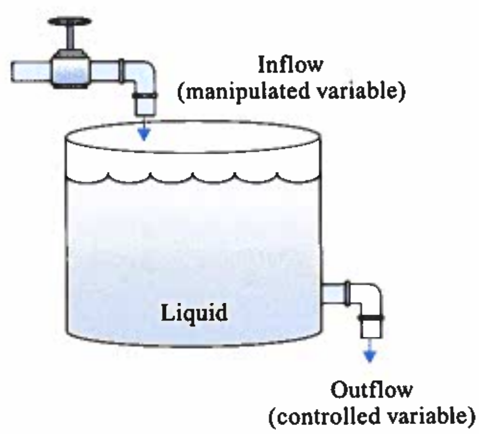
The controlled variable itself may contribute to the reaction time delay of the loop. For example, when a step change occurs, the loop reacts by causing the manipulated variable to be altered. The result is that the energy applied by the actuator, to the controlled variable, either increases or decreases. However, due to the static inertia of the material from which the controlled variable is made, it opposes being changed and creates a delay. Eventually energy overcomes resistance and causes the process to reach its desired state. The delayed reaction is referred to as **pure lag.**

One factor that affects the pure lag time, is the capacity (physical size) of the controlled variable. If the controlled variable has very little mass, the process will react instantly to a step change. A second factor, which can affect the pure lag time, is the physical properties of the controlled variable. For example, the temperature of a solvent will change more rapidly than an equal quantity of pure water when exposed to an equivalent thermal energy change. Another factor that can affect pure lag is the chemical properties of the controlled variable. For example, the hardness of water will affect the reaction rate when pH adjustments are made.

One common method used to analyze the pure lag of a controlled variable is to introduce a step change and observe the results. The storage tank in Figure 11-3(a) is used to describe such a response test, and the graph in Figure 11-3(b) illustrates the behavior.

The tank is being supplied with a liquid at a given rate, while liquid flows out through a drain line. The inflow is the manipulated variable and the outflow is the controlled variable. The rate of outflow is determined by the amount of *head pressure* influenced by the depth of the water. Suppose the setpoint change causes the rate of inflow to increase abruptly, as shown at time T_1 on the graph. The volume of outflow does not immediately increase by the same amount as the new rate of inflow. Instead, it gradually increases as a result of the head

(a)



(b)

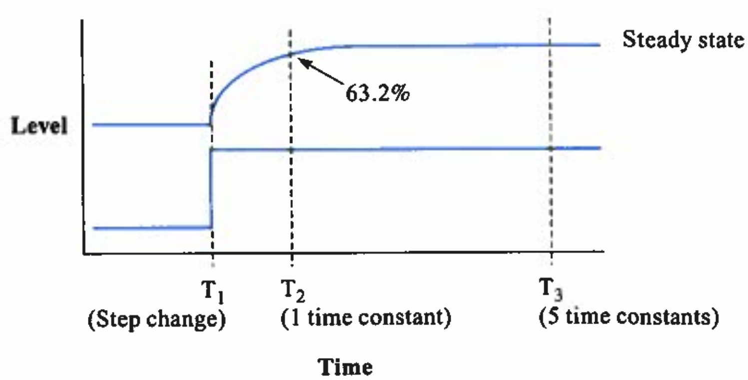


FIGURE 11-3 An illustration of pure lag of the controlled variable: (a)tank system; (b) graph

pressure that builds up from the accumulation of liquid within the tank. Eventually, equilibrium occurs when the liquid reaches a higher level, causing the head pressure to make the outflow equal the increased rate of inflow.

The graph shows that the rate at which the controlled variable changes is rapid at first, and then tapers until it reaches its new steady state. During the time it takes the controlled variable to change 63 percent of the new steady state, it is defined as one time constant. The 63 percent figure is based on a mathematical model that is commonly used to describe the dynamic behavior of physical objects being exposed to an energy change. After five time constants, a new state is reached. This type of single-loop control delay is referred to as *first order time lag.*

Dead Time

Another factor that contributes to time lag is **dead time.** This is the elapsed time between the instant a deviation of the controlled variable occurs and the instant corrective action begins. A process in which the density of a fluid is regulated can be used to illustrate dead time. The liquid enters the pipeline in Figure 11-4(a), and the fluid density is measured by a sensor/transmitter some distance downstream. If the composition of the fluid at the point of entry changes, there will be a time lapse before it reaches the point of measurement. The amount of time that elapses is based on the distance between the two points and the speed of flow. The diagram in Figure 11-4(b) graphically shows the effects of first order time lag plus dead time.

Delays are inherent to each of these factors and cannot be avoided. However, the reaction time can be substantially reduced by maximizing the operation of an instrument in the control loop in two ways:

1. *Select a controller* with operational features that provide the kind of control action needed for a particular process.
2. *Properly tune* the controller to optimize the regulation of the process.

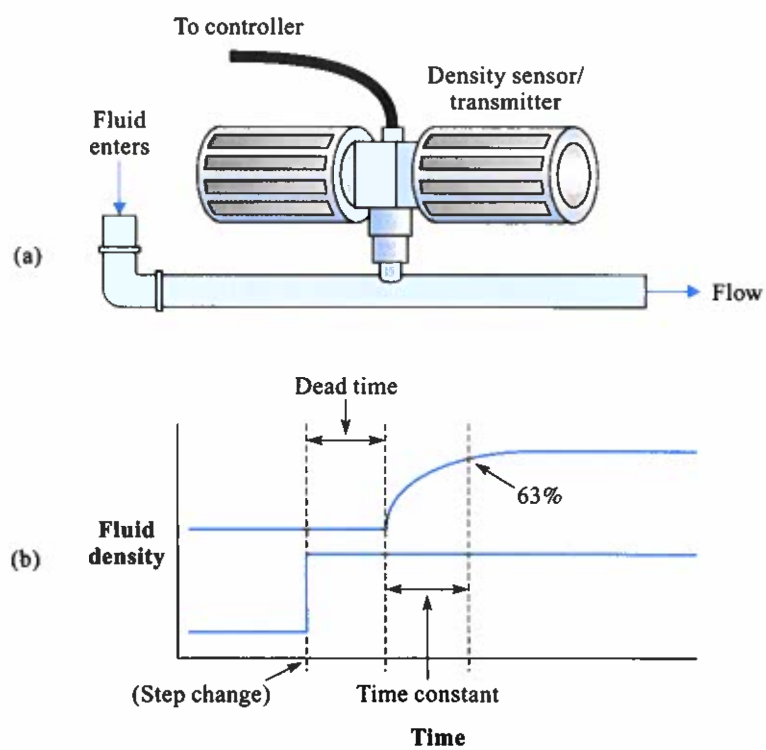


FIGURE 11-4 First order plus dead time

11-4 Selecting a Controller

Controllers are designed to operate by using different control modes. Each of these modes has specific characteristics that provide different types of control action. These control modes are:

- On-Off
- Proportional
- Integral
- Derivative

The mode or combination of modes, which are selected by the design engineer, is determined by the requirements of the process.

11-5 On-Off Control

In some types of process applications, the controlled variable changes very slowly. For example, the temperature of a large mass is difficult to raise or lower rapidly. Therefore, delays due to time lags in the control loop are unavoidable and, as a result, are usually tolerated.

The type of control mode often used for slow acting operations is the one that provides *On-Off* action. This kind of action controls a final control element that has only two conditions, *fully on* or *fully off*. The controller cannot move the final control element to any intermediate position between the two extremes. One example of such a control system is a refrigeration unit. The controller compares the temperature (controlled variable) to the setpoint. When the temperature increases above the setpoint, the controller turns a compressor (final control element) fully on. As the temperature lowers below the setpoint, the compressor is turned off. The controlled variable cycles above and below the setpoint, as shown in Figure 11-5(a).

One drawback of this system is that the rate at which the final control element switches on and off can be very high. This condition can result in excessive wear to equipment.

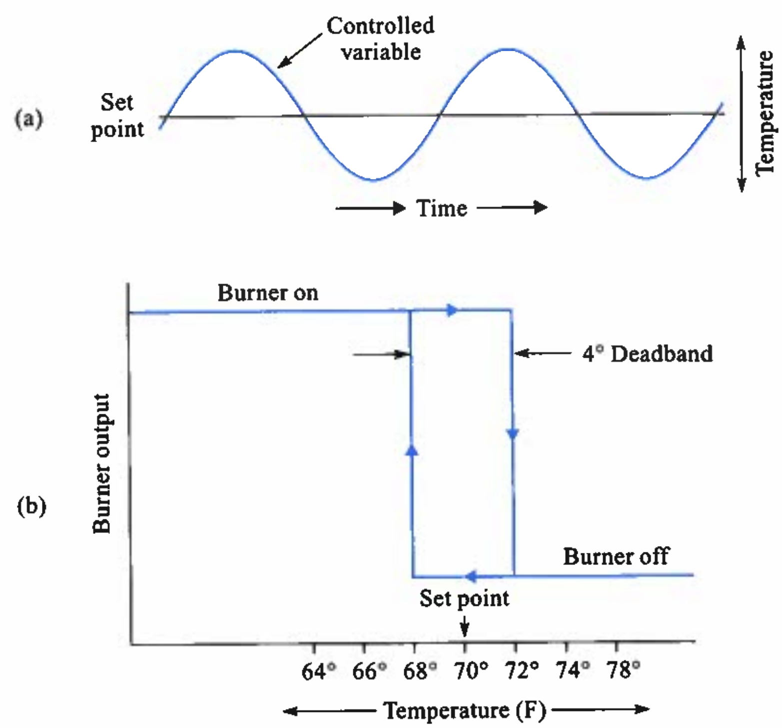


FIGURE 11-5 On-Off control: (a) cycling; (b) deadband

To reduce the switching rate, an On-Off differential, or *hysteresis,* is programmed into the controller. Also referred to as a *deadband,* it causes the controller to produce its on and off signals at different values around the setpoint. For example, a home heating thermostat may have a deadband of 4 degrees. If the temperature setting is 70 degrees, the furnace turns on at 68 degrees and turns off at 72 degrees, as shown graphically in Figure 11-5(b). The drawback of using a deadband is that the controlled variable will deviate from the setpoint by a larger amount than a system that does not use this method.

Another type of an On-Off system is the tank, shown in Figure 11-6(a), that stores a liquid. It contains two capacitance probe sensors (as primary elements), a flow valve (as the final control element), and a controller. The level of the liquid is the controlled variable. One sensor detects the high-level limit and the other detects the low-level limit. As the fluid leaves the tank, the level lowers until it falls below the low-level sensor. When the controller detects a signal change from the sensor, it opens the valve. Since the inlet flow rate is greater than the outlet flow rate, the level in the tank rises. When it reaches the high-level sensor, the controller detects its signal change and causes the valve to close. Figure 11-6(b) graphically shows the action of the final control element and the controlled variable in relation to time.

On-Off controllers are also used in applications that limit the condition of a controlled variable. One example is a safety system that prevents a steam boiler from exploding by not allowing the temperature to rise above a certain level. The controller is programmed to close a fuel valve and activate an alarm if the high-limit temperature is reached. The alarm stays on and the boiler remains shut down until the controller is manually reset.

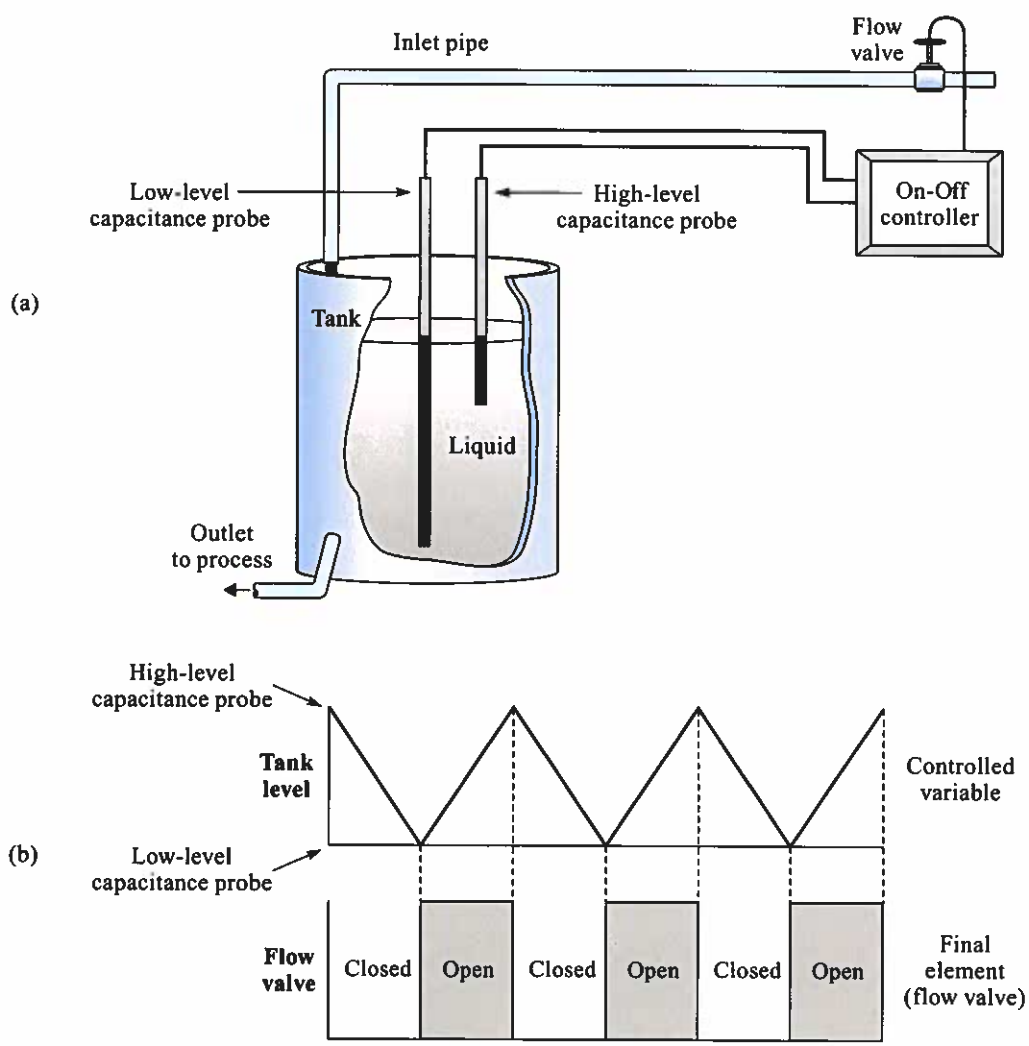


FIGURE 11-6 On-Off level control: (a) tank storage; (b) operation graph

The advantages of the **On-Off control** are that it is the least expensive closed-loop system and the easiest to design. Its limitation is that it cannot vary the controlled variable with precision. Its control action is to switch when extreme conditions exist, causing the final element to only turn fully on or fully off, and the controlled variable to oscillate around the setpoint.

Case Studies—Using Different Control Modes

This chapter contains four case studies about a small chemical company which produces a specially blended product that is sold in bottles. Each study describes how the company uses different control modes to maintain the quality of its product as its production output capacity demand grows.

Case Study 1: On-Off Control

To produce the product, raw materials are made one batch at a time. Bulk materials and liquids are combined in a large tank shown in Figure 11-7. A heat jacket that surrounds the tank is fed with steam because, for proper blending to occur, the temperature of the ingredients must be maintained at 80 degrees. If for some reason the temperature should rise above 85 degrees, one of the ingredients would become overactive and the product would be out of tolerance. On the other hand, if the batch is allowed to cool below 75 degrees, blending will be incomplete and the product will have to be reprocessed or discarded.

To regulate the flow of steam to the jacket, an On-Off controller, shown in Figure 11-8(a), is used to open or close the valve. The desired operating temperature, or setpoint adjustment, establishes the temperature at which the controller causes the steam valve to open or close. The setpoint of 80 degrees is adjusted by a knob, and the setting is displayed by the green

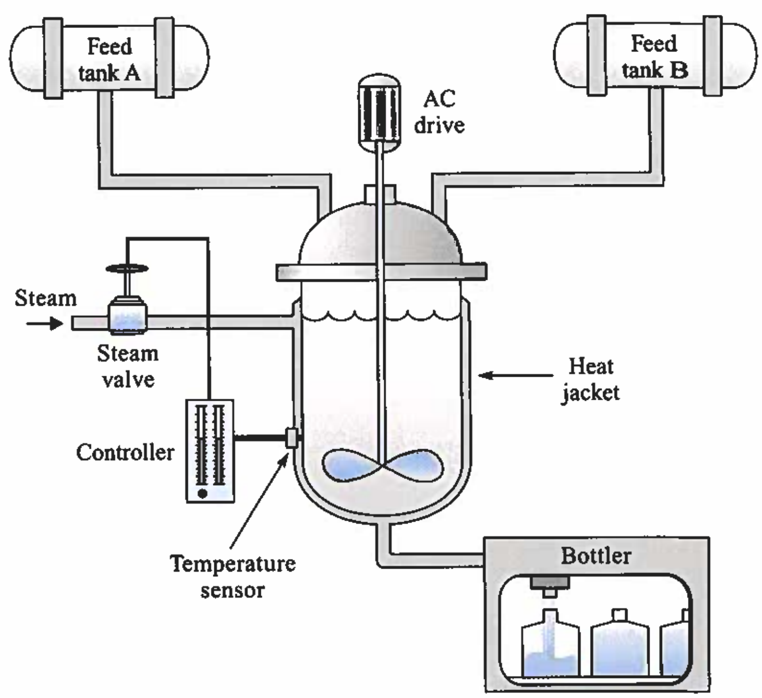


FIGURE 11-7 Batch mixer

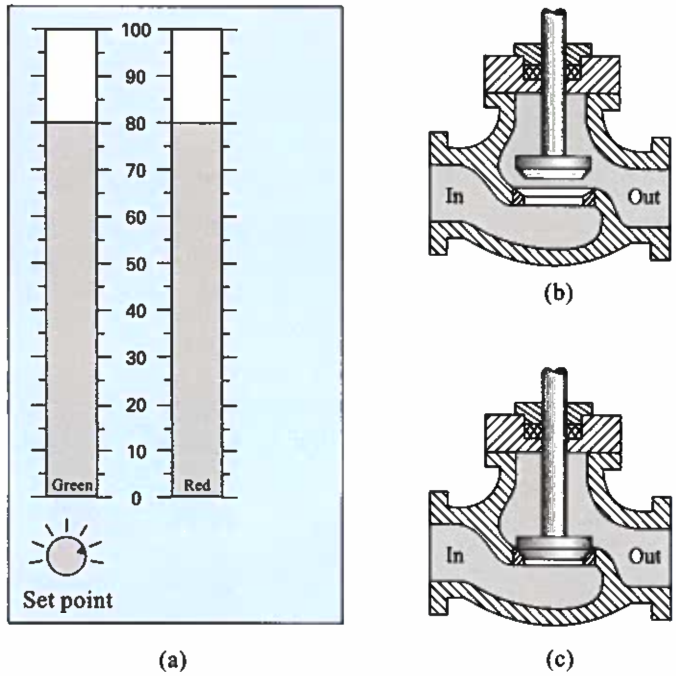


FIGURE 11-8 On-Off controller and steam valves

indicator on the left. The actual temperature is measured by a sensor and is displayed by the red indicator on the right.

At start-up, the ingredients in the batch are at a cool temperature. This condition causes the controller to open the steam valve, as shown in Figure 11-8(b). Steam enters the jacket surrounding the tank. As the batch is heated, the red indicator moves upward. When the red indicator reaches setpoint, the controller closes the steam valve, as shown in Figure 11-8(c).

Before the batch cools, its temperature rises to slightly above 80 degrees due to steam trapped within the jacket. When the batch cools, the indicator moves downward until the controller opens the valve. The heating cycle is then repeated. A continuous record of the temperature is shown by the graph in Figure 11-9. Note that the variations are well within the limits of plus or minus 5 degrees.

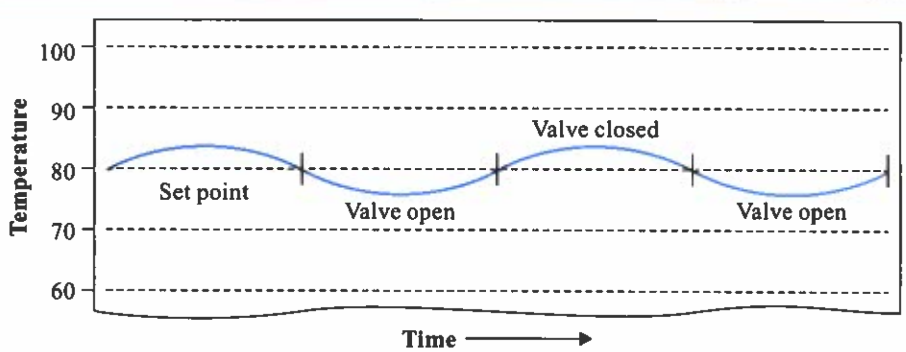


FIGURE 11-9 Chart recorder displaying the On-Off control mode operation

11-6 Continuous Control

On-Off control is suited to situations in which it is only necessary to keep a process variable between two limits. For continuous processes where the variable is required to be kept at a particular setpoint level, it becomes impractical. The controlled variable can be maintained only if the final control element is varied continuously over the entire range of its output. Systems that provide this function use any one, or a combination, of *proportional, integral,* and *derivative* control actions.

Proportional Mode

A proportional controller produces an output signal with a magnitude that is proportional to the size of the error signal (E) it is correcting. The error signal is the difference between the measured variable and the setpoint (desired value). A small error will cause the output to change by a small amount. Conversely, a large error will cause a larger output change. The output of the proportional controller moves the final control element to a definite position to attain a desired value of the controlled variable.

The proportional action can be accomplished in two different ways, by the *time proportioning* method, and by the *amplitude proportional* method.

Time Proportioning

Time proportioning is a method in which the output at the controller is continually switched fully on and fully off. The average voltage produced is varied by changing the ratio of signal on to signal off. The ratio produced by the controller is determined by how much the measured variable differs from the setpoint. If the measured variable equals the setpoint, the output On-Off ratio is 1:1, as shown in Figure 11-10(a). This ratio indicates that the on-time and off-time are the same. If the measured variable is below setpoint, the on-time will be longer than the off-time, as shown in Figure 11-10(b). The ratio increases as the error signal increases, producing a higher average output voltage. When the measured variable is above setpoint, the on-time will be shorter than the off-time, as shown in Figure 11-10(c); thus producing a smaller average voltage. For example, assume the output DC voltage of the controller is 10 volts. When the controller is set for 100 percent, the output is on all of the time and the average voltage produced is 10 volts. If the controller is set for 60 percent, the output is switched on for 60 percent of the time and the average voltage is 6 volts (10 volts $\times$ 0.6 = 6 volts). When the controller is set for 0 percent, the output voltage is not on at all, and the average voltage is 0 volts.

Amplitude Proportional

The **amplitude proportional** method is the most common technique used to produce a proportional signal. The magnitude of the signal is proportional to the size of the error signal. The analog signal produced by a controller is either a variable voltage or a variable current.

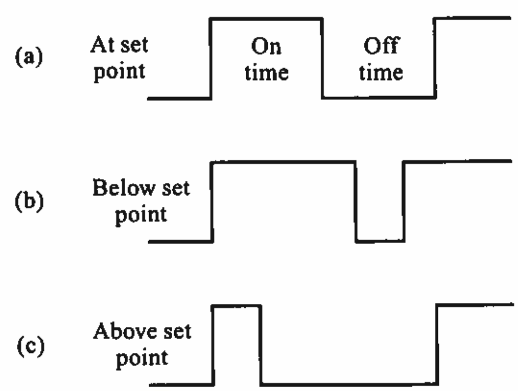


FIGURE 11-10 Time proportioning signals produced by a controller

The controller also has the capability of amplifying the amount at which its output changes in proportion to the change applied to its input. There are two ways to refer to the amplification of a proportional controller: *proportional gain* and *proportional band.*

Proportional Gain **Gain** is the ratio of change in output to the change in input, as described mathematically by the following formula:

$$\text{Gain} = \frac{\text{Percentage Output Change}}{\text{Percentage Input Change}}$$

A float mechanism that regulates the level of fluid in a tank is used in Figure 11-11 to show the concept of gain. Referring to the gain formula, the liquid level represents the input, and the amount of fluid that flows through the inlet flow valve is the output. Suppose the load demand is increased by increasing the opening of the drain valve. The result is that the liquid level drops 5 percent. To prevent the level from dropping any farther, the flow valve opens by 5 percent and increases the inlet flow 5 percent. According to the formula, the gain is 1.

$$\text{Gain} = \frac{5\%\ \text{Output Change}}{5\%\ \text{Input Change}} = 1$$

By repositioning the float along the rod toward the pivot point, as shown by Figure 11-12, the proportional gain is increased. Suppose that a load demand drops the level of the tank by 25 percent, from half to one-fourth of its capacity. With the new float alignment, the inlet

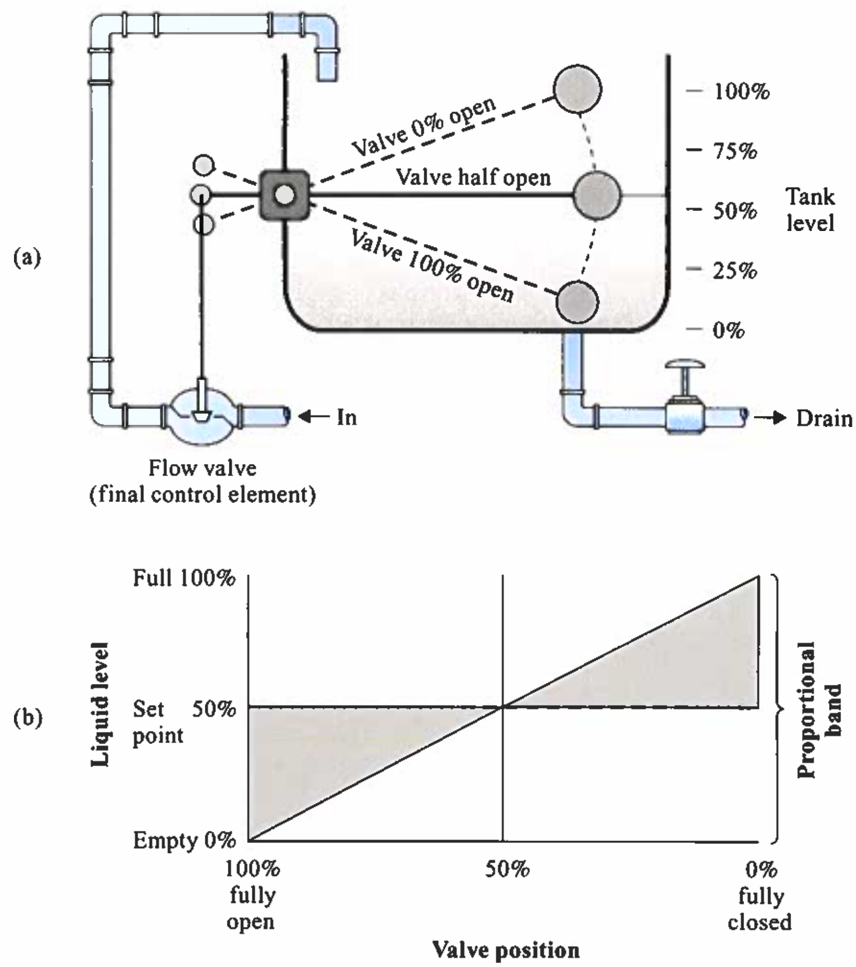


FIGURE 11-11 Level control at a gain of 1

(a)

(b)

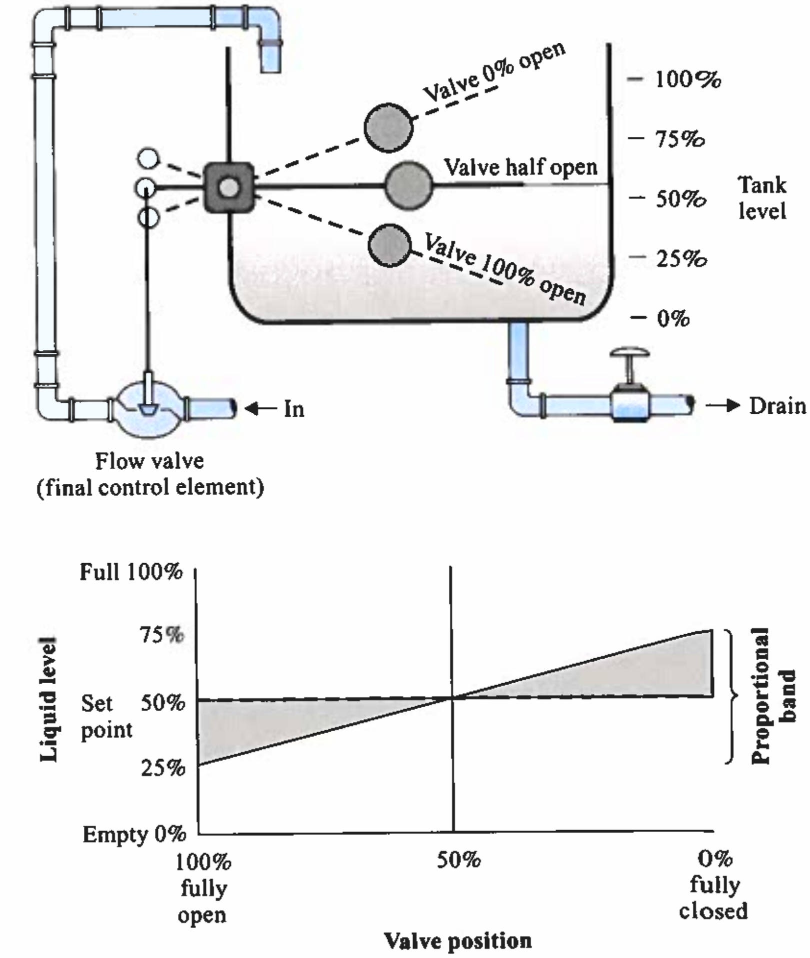


FIGURE 11-12 Level control at a gain of 2

valve changes 50 percent from the half-open to the fully-open position, and the flow of inlet fluid increases. Therefore, the gain is 2.

$$\text{Gain} = \frac{50\%\ \text{Output Change}}{25\%\ \text{Input Change}} = 2$$

With a gain of 2, the controller responds to controlled variable changes with a greater output change than when the gain is 1. The result is that the process variable is restored to a desired value more quickly.

Proportional Band Amplification is also expressed as **proportional band (PB).** Proportional band is defined as the percentage change in the controlled variable that causes the final control element to go through 100 percent of its range. The proportional band can be determined mathematically by using the following formula:

$$\text{PB} = \frac{\text{Controlled Variable \% Change}}{\text{Final Control Element \% Change}} \times 100$$

The width of the proportional band determines how much of a controlled variable change is required to cause a given amount of movement by the final control element. For example, to cause a final control element to move 100 percent, a controller with a proportional band of 100 requires that the controlled variable change twice as much as one with a proportional band of 50. The float mechanism in Figures 11-11 and 11-12 can be used to make this comparison.

The float mechanism in Figure 11-11(a) that has a gain of 1 and the graph in Figure 11-11(b) are used to illustrate a proportional band of 100. The system is designed to maintain the level of the tank at 50 percent (half full) by keeping the valve exactly half open. When the level is 0 percent (completely empty) the valve is 100 percent (fully open). As the level rises, the valve begins to close. When the liquid reaches a level of 100 percent (completely full), the valve is 0 percent (fully closed). This example shows that with a proportional band of 100, a 100 percent change in the controlled variable causes the final control element to move 100 percent through its range. The mathematical representation of this example is:

$$PB = \frac{\text{Controlled Variable \% Change}}{\text{Final Control Element \% Change}} \times 100$$

$$PB = \frac{100\%}{100\%} \times 100 = 100$$

The float mechanism in Figure 11-12(a) that has a gain of 2 and the graph in Figure 11-12(b) are used to show a proportional band of 50. As in Figure 11-11, this mechanism is also designed to maintain the level at 50 percent of full capacity when the valve is half open. However, if the level rises to 75 percent, the valve closes to 0 percent; or if the level lowers to 25 percent, the valve opens to 100 percent. This example shows that with a proportional band of 50, the final control element is moved 100 percent through its range when the controlled variable changes only 50 percent of its designed range. The mathematical representation of this example is:

$$PB = \frac{\text{Controlled Variable \% Change}}{\text{Final Control Element \% Change}} \times 100$$

$$PB = \frac{50\%}{100\%} \times 100 = 50$$

Proportional action only occurs above and below the setpoint within the proportional band. The setpoint is located at the midpoint of the range of values in the proportional band. Outside the proportional band, the controller functions as if it is in the On-Off mode. When the controlled variable is below the proportional band, the final control element is fully on. When the controlled variable is above the proportional band, the final control element is fully off. Within the proportional band however, the final control element is turned on at an amount that is proportional to the difference between the measured variable and setpoint.

Gain and proportional band are two different ways by which an adjustable amplification setting is made to the controller. Both values determine the amount at which the output changes in response to an input change. A larger gain, or smaller PB, causes a greater output response to an input change than a smaller gain, or larger PB. The following formulas show how to convert between gain and PB values:

$$PB = \frac{1}{\text{Gain}} \times 100$$

$$\text{Gain} = \frac{1}{PB} \times 100$$

Note: Proportional band is in percent.

Sensitivity A common term used to describe a controller's ability to respond to input changes is **sensitivity.** The larger the gain or the narrower the PB, the more sensitive a controller is to input changes. The proportional controller can be too sensitive. If the float in Figure 11-12 is moved closer to the pivot point, the valve position will change too much in response to a small change in level. If the level drops below setpoint, the valve will open fully and allow an inrush of liquid, causing the level to rise too high. This situation makes the valve fully close, and results in the liquid dropping below setpoint again. Since the system (and the controlled variable) constantly oscillates above and below setpoint, its operation is similar to On-Off control.

Proportional control is adequate when the inertia of the process is relatively large, the process reaction rate is relatively slow, and the process lag and dead time are relatively small. All of these characteristics permit the use of high gain (narrow PB) and provide fast corrective action for small-to-moderate load changes.

Case Study 2: Proportional Control

As the sales of the company product grow, blending tanks are added to increase production. Eventually, there is no space left in the plant for additional tanks, and no surrounding property on which to increase the size of the building. The plant's maximum output peaks at 10,000 bottles a day. One day a reliable customer offers a long-term contract which will generate an order for 20,000 items per day.

Instead of building a completely new plant at another location, the chemical company decides to remodel the existing building and installs a continuous process machine to increase production. With the new machine, raw materials at a precise flow rate will be fed into an in-line mixer, as shown in Figure 11-13. An auger will provide rough

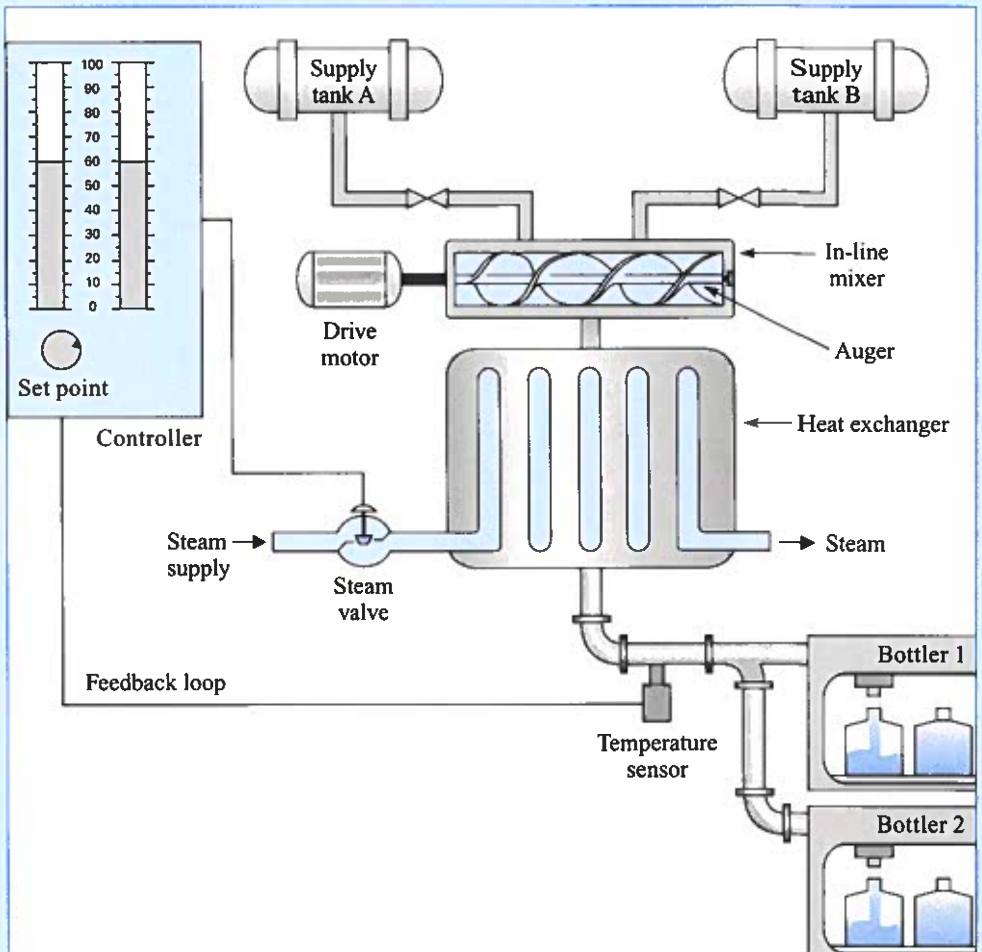


FIGURE 11-13 A continuous process mixing/blending operation using a heat exchanger

blending, but the final blending will be performed by being heated to 80 degrees as the ingredients flow through a heat exchanger. The blended end product will then flow through a pipeline to two automatic bottling machines.

To control the temperature, the engineers install an On-Off controller. When the installation is complete and the process starts, they observe that the metering of the raw material and the machine's mixing operation is highly successful. However, as the controller turns on and off and fully opens or fully closes the steam valve, the temperature in the heat exchanger cycles first to 90 degrees, and then decreases to 70 degrees. The reason why the temperature in the heat exchanger fluctuates too much is because the rate of heating is too rapid. This condition develops because the mass of liquid in the heat exchanger is too small to absorb the energy change from the steam as it varies in temperature.

The engineers determine that if the valve is slowly adjusted until just the right amount of steam is admitted to the heat exchange, the temperature can be held within the desired range. This control action can be performed by using the proportional mode of the controller. By sending an output signal to open or close the valve to a position proportional to the temperature, the controller can maintain the heat at a more constant level.

Figure 11-14(a) shows the controller that provides proportional action. The magnitude of proportional action is adjusted by the dial called *gain*. With a high gain setting, a small temperature change causes a large valve adjustment. A low gain adjustment will cause the valve to move only a small amount. The controller also has a meter which displays the polarity and magnitude of the error. If the temperature is below the setpoint, a negative signal is generated and is displayed by the meter shown in Figure 11-14(b). If the temperature is above the setpoint, a positive error signal is generated and displayed by the meter shown in Figure 11-14(c).

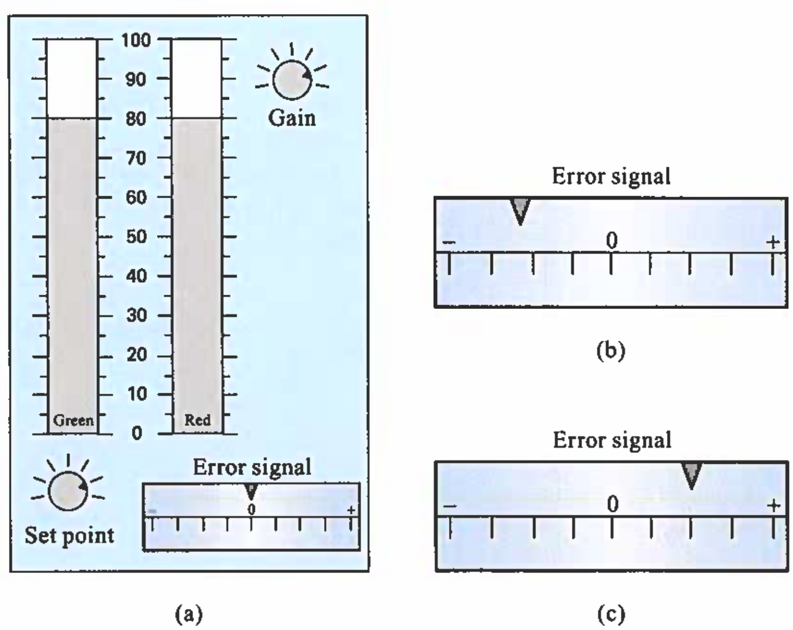


FIGURE 11-14 (a) Proportional controller; (b) indicator showing a negative error signal; (c) indicator showing a positive error signal

Integral Mode

When the setpoint valve position in Figure 11-15 is exactly 50 percent of its full flow rate capacity, suppose a load change occurs from an increase of the outflow through the drain pipe. As the level drops, the float mechanism causes the opening of the inflow valve to increase. When the inflow equals the new outflow value, the system stabilizes. However, the level is below setpoint, as shown by the diagram. This error, a constant difference between setpoint (SP) and the controlled variable (CV), is called **offset.**

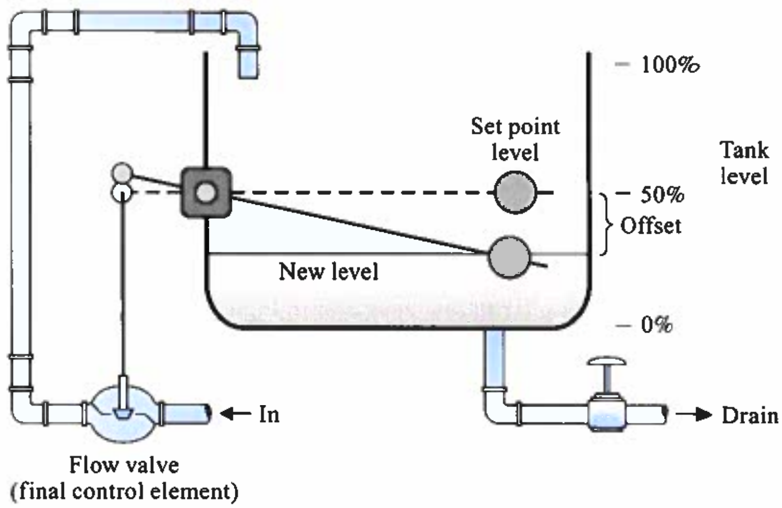


FIGURE 11-15 Offset example

Some systems cannot tolerate offset. They require that the controlled variable return to its original value. To eliminate offset, an **integral** function is added with the proportional mode to the controller. To perform the integral action, the controller senses that there is a difference between the SP and CV. As long as an error exists, the integral mode continuously causes the controller to adjust its output until the offset returns to zero. It performs this function by either adding to or subtracting from the controller output. The longer the error exists, the greater the integral becomes.

The graphs in Figure 11-16 show the functions of the proportional and integral actions in response to a gradual load change with a time duration of one minute. During the first

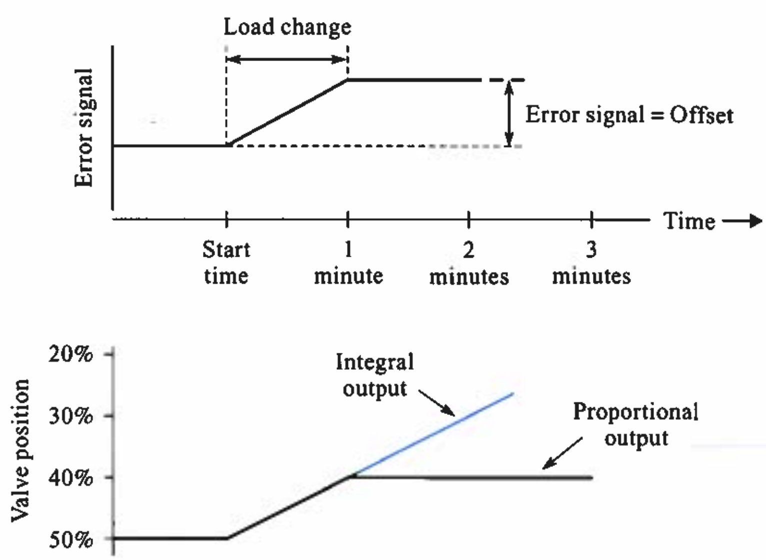


FIGURE 11-16 Proportional and integral action

minute, the proportional output increases as the load changes. At one minute, the load stops changing and the proportional output stops increasing. However, there is an offset and the integral mode continues to increase the amplitude of the controller's output. The result is that the final control element is adjusted until the controlled variable returns to the setpoint.

To better understand this concept, examine the tank system in Figure 11-15. When the system stabilizes after a load change, the new level is lower than the desired height of 50 percent. By manually moving the float toward the pivot point, an action that simulates an increase in controller gain, the valve opens farther and causes the inflow to become greater than the outflow. Eventually, the liquid rises and returns to its desired level, causing the offset to become zero. At this time the float should be moved back to a position that causes the inflow and outflow to equal.

Moving the float and increasing the gain while there is an offset represents the integral action. Moving the float back away from the pivot point when the level returns to the setpoint illustrates how the integral function expires when there is no longer an offset. Controllers perform the integral action automatically by using electronic circuitry or microprocessor-based devices.

Integral is also referred to as *reset*. The term *reset* is derived from the way in which the integral action periodically adds to the controller's output by repeating the previous proportional action, as shown in Figure 11-17. Suppose the proportional action causes a 10 percent output change from 50 to 60 percent. If offset exists after the proportional action is finished, line A shows that the reset function repeats the 10 percent increase once each minute. Therefore, after each minute the controller's output increases 10 percent. Line B shows that by doubling the reset gain on the controller, two repeats per minute occur, causing a 20 percent change each minute. The result is that the adjustment of the final element is doubled and causes the time duration of the offset to be reduced by half.

Integral adjustments that affect the magnitude of the controller's output are labeled three ways:

Gain: Expressed as a whole number

Reset Rate: Expressed in repeats per minute

Reset or Integral Time: Expressed in minutes per repeat

Reset Rate and Reset Time are reciprocals of each other, as shown by the following formula:

$$\text{Reset Rate} = \frac{1}{\text{Reset Time}} \qquad \text{Reset Time} = \frac{1}{\text{Reset Rate}}$$

For example, a reset rate of 10 repeats per minute is equal to an integral time of 0.1 minutes per repeat (6 seconds).

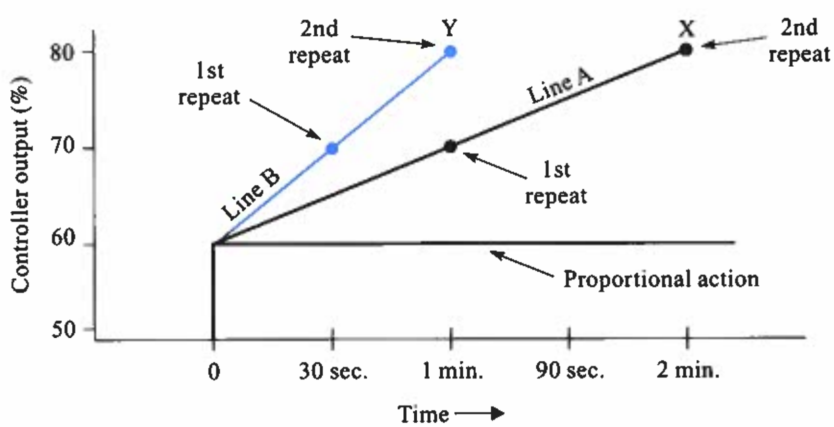


FIGURE 11-17 Reset action

The integral mode is used in process applications where the load varies slowly, but by a large amount. The magnitude of integral should be large if the proportional gain is smaller (wider bandwidth) than when the proportional gain is larger (narrower bandwidth).

Case Study 3: Proportional-Integral Control

As the ingredients flow through the exchanger at a rate required to fill one bottling machine, the proportional controller is able to keep its temperature within the required range. When a second machine is started, the flow through the heat exchanger is doubled. However, the valve is positioned at that moment to only emit enough steam to heat one machine. Therefore, the product temperature drops when the second machine is added. The proportional controller senses the change and gradually increases the opening of the valve. When the temperature levels off it is below the desired setpoint and an offset condition exists. To open the valve beyond that which is dictated by proportional action, it is necessary to add the integral mode function to the controller. As long as the error signal is present, the integral action causes the output of the controller to slowly increase. Eventually the valve opening becomes large enough to pass the correct amount of steam, which allows the temperature to return to setpoint.

Once that happens, the error signal becomes zero and the integral action stops. The integral action is adjusted by the reset knob on the controller shown in Figure 11-18. To obtain optimal performance, the engineer determines that the optimal setting for proportional is 5.5 and 1.5 for integral. Integral action is again required to eliminate an offset condition when the second bottling machine is shut off and the first machine remains in operation.

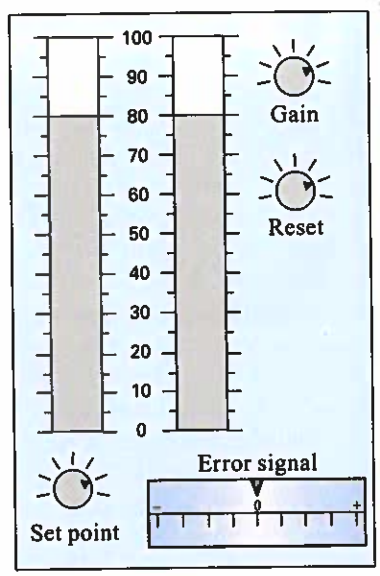


FIGURE 11-18 Proportional-integral controller

Derivative Mode

If the setpoint or load changes suddenly, the controlled variable (CV) will deviate from the setpoint (SP) and create an error signal. The faster the initial rate of change, the farther the CV is apt to move away from the setpoint. In some process applications, this situation is

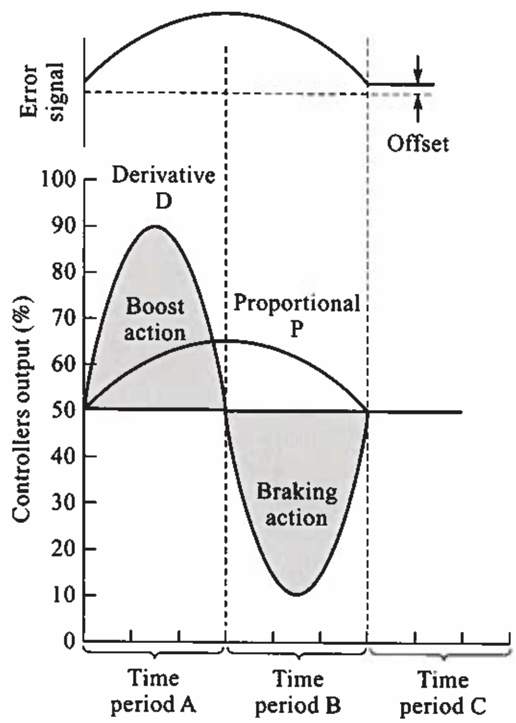


FIGURE 11-19 Proportional-plus-derivative action in response to an error signal

undesirable. If the proportional gain is increased to minimize this condition, the CV will likely overshoot and oscillate. This situation may not be acceptable because a product could be ruined if the tolerance of its condition is exceeded during the overshoot or peak of each oscillation. Instead of increasing the proportional gain to reduce the error signal, the **derivative mode** of the controller is used. The derivative function produces a response as soon as it senses that the CV is changing relative to SP. The response action is to produce a signal that adds to or subtracts from the amplitude of the proportional output. If the error is constant, there is no derivative action. Figure 11-19 shows how the derivative mode reacts to a load change. The top portion of the graph shows the error signal, and the bottom portion shows the proportional and derivative outputs of the controller. During the first half of time period A, the load change causes the process error to increase by almost 15 percent. The proportional mode with a gain of 1 causes the controller output to increase from 50 to almost 65 percent, as shown by line P. The derivative mode shown by line D adds to the proportional signal and causes the controller output to increase from 50 to 90 percent. The result is that the final element makes a large change, which causes a quick system response that prevents the controlled variable from deviating any farther from the setpoint. At the middle of time period A, the rate that the error signal is increasing begins to drop off, and the derivative output begins to decrease. At the end of time period A, the error signal stops changing and the derivative output goes to zero.

At the beginning of time period B, the error signal starts returning to zero and the proportional output reduces by the same amount. The derivative action responds to a reduction of the error signal by reversing its polarity, as shown by line D. During the first half of time period B, the amplitude of the derivative increases as it subtracts from the proportional output. The resulting decrease in controller output provides a braking action as the CV approaches SP. During the second half of time period B, the amplitude of the derivative output decreases and the amount at which it subtracts from the proportional output diminishes. This action minimizes overshoot, a condition where CV goes past the SP value. At the beginning of time period C the error stabilizes, the derivative signal goes to zero, and the proportional output is a small constant value that is unable to overcome the offset.

The derivative mode is used when the controlled variable lags behind an alteration of the final control element and an error signal develops. This condition might occur in a slow acting process control application, such as regulating the temperature of a liquid in a large tank. If, for example, a new setpoint setting is made, the static inertia of the liquid does not allow its temperature to change immediately after the final control element is altered. The result is that a lagging condition develops. The derivative mode can be used by the controller to minimize the error signal that develops from this condition. An example of where derivative control would not be used is in a fast acting application, such as an air flow control system. Whenever a new setpoint setting is made, a flow control valve changes and immediately alters the flow rate of the air. Since the response of the system is very fast, a lagging condition does not develop and the derivative action is not required. Instead, a two-mode controller (PI) is used.

The derivative mode adjustment is called **derivative time.** Its setting determines the extent to which the derivative action changes the controller's output. A derivative time setting of two minutes will cause a response twice as fast as a setting at one minute.

There are several limitations to the derivative mode:

- The derivative mode is never used alone, but in combination with proportional or proportional-plus-integral.
- Derivative action is unable to remove the offset present in proportional control. This offset is a steady-state error, which means that it is a "constant." Therefore, since there is no rate of change that occurs, the derivative action produced is zero.
- Derivative control is unsuitable for systems that are exposed to noisy environments. Noisy signals contain high-frequency components which are amplified by the derivative action. These amplified signals will appear at the controller output and may cause unwanted changes by the final control element.

Derivative control is beneficial in two types of process applications:

1. Those that have large and rapid load changes in a slow response system. The derivative mode enables the controller to respond more rapidly and position the final control element more quickly than is possible with only proportional action.

Case Study 4: Proportional-Integral-Derivative Control

Whenever the second bottling machine is started the load change condition it creates is too sudden for proportional-integral control action to operate effectively. The controller does not increase the opening of the valve fast enough, which causes the temperature to rapidly drop out of the tolerance range. Before it eventually rises back to the setpoint value, 50 bottles are off-standard and have to be thrown out.

To open the valve more quickly, the derivative function mode is added to the controller. With this feature, the magnitude of the controller's output temporarily increases while it detects a fast error change. As the signal causes the opening of the valve to become larger, more steam is added to the heat jacket and the temperature rises more quickly. The derivative action ends whenever the temperature levels off and the valve returns to the position dictated by proportional and integral action. The amount of derivative action is adjusted by the rate knob on the controller, shown in Figure 11-20. A setting too low causes the system response to be sluggish, such as when only proportional-integral action is used. A setting too high causes the temperature to become too high by overshooting.

Derivative action also causes the system to respond more quickly when the second bottling machine is shut off.

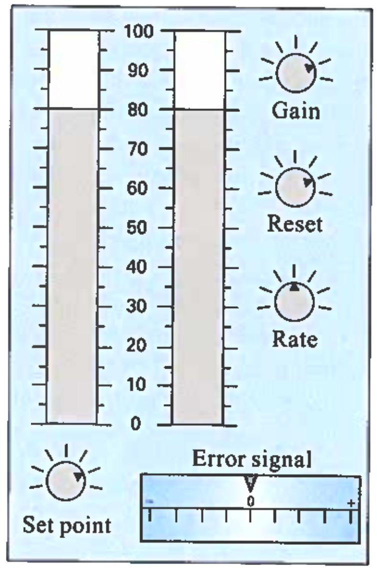


FIGURE 11-20 Proportional-integral-derivative controller

However, the rate time setting must be relatively low, otherwise the controller may overreact and cause an unstable condition of the system.

2. Those in which systems are subject to frequent start-ups, such as batch processes.

Each of the three continuous control modes has specific characteristics that can be advantageous in a control system. Table 11-1 provides a summary of how different mode combinations are used for various applications.

TABLE 11-1 Proportional, Integral, and Derivative Mode Summary

Mode Combinations	*Function*	*Applications*
Proportional (P)	To provide gain	For small set point or small load changes
Proportional-plus-Integral (PI)	To eliminate offset	For large and slow set point or load changes
Proportional-plus-Derivative (PD)	To speed up response and minimize overshoot	For sudden set point or quick load changes in a slow response system
Proportional-Integral-Derivative (PID)	To speed up response, minimize overshoot, and eliminate offset	For large and sudden set point or load changes in a slow response system

11-7 Advanced Control Techniques

Nearly all control systems are based on the principle of feedback control. The function of the control loop is to maintain the controlled variables as close to the setpoint as possible. By incorporating the characteristics of all three PID modes into a single loop, the degree of control may be adequate for most situations. However, some complex manufacturing applications often require more advanced control to ensure a more precise control of the process. There are four of these techniques frequently used: *cascade control, feed-forward control, ratio control,* and *adaptive control.* Cascade and feed-forward control techniques provide a faster and tighter response than PID control because they detect disturbances when they occur and begin correction early to overcome the effects of dead time and process time constants. Ratio and adaptive control techniques are used to accommodate unique process and measurement situations.

Cascade Control

A single-loop feedback control system is designed to respond to changes in the controlled variable. In some types of applications that have long time constants, such as with temperature-related processes, the reaction time to disturbance is not fast enough. For example, Figure 11-21 shows a continuous process where two liquids are mixed and then slowly passed through a

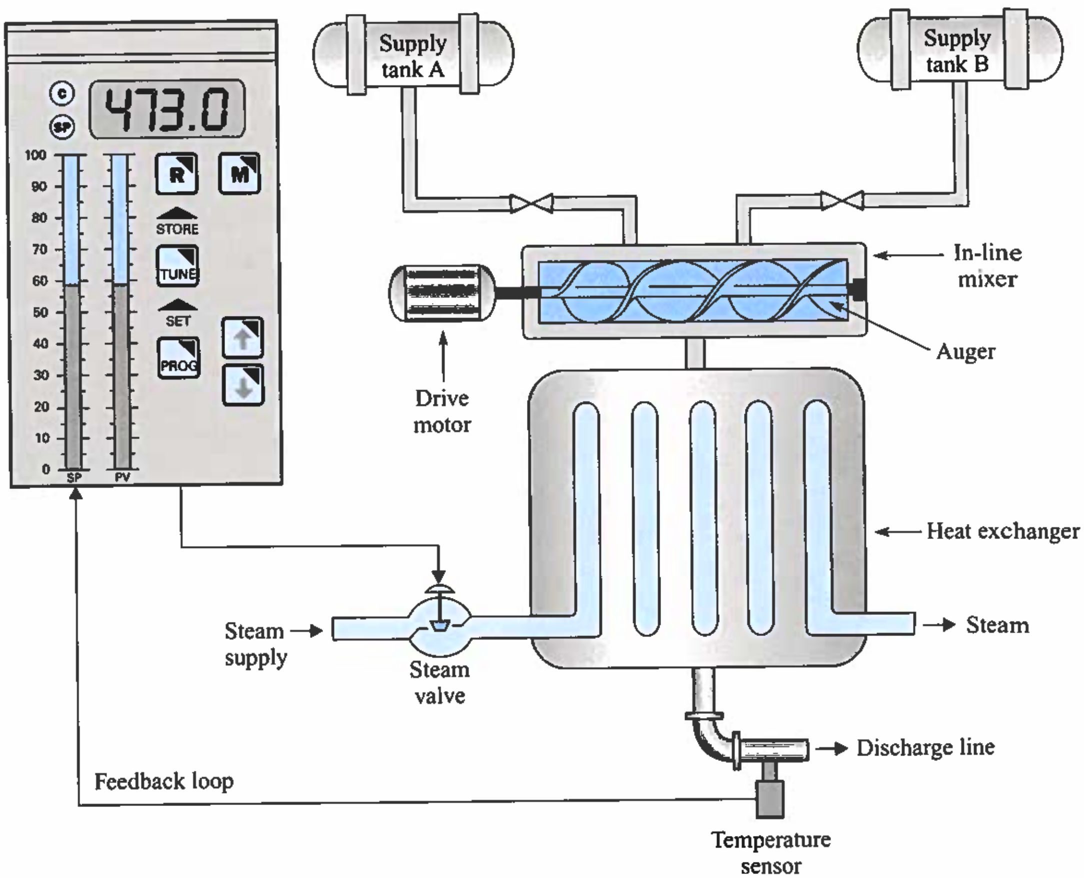


FIGURE 11-21 Single-loop controller

heat exchanger. To cause the desired reaction, the temperature of the liquid inside the exchanger is 100 degrees. The heat applied to the exchanger is supplied by a steam line network that runs throughout the plant. The steam is produced by a boiler, which also produces pressurized steam to heat the facility and provides energy for several other production machines.

As some of the machines are turned on and off, or when their load demands vary, the requirement for steam changes, which causes the pressure to fluctuate. If the pressure drops, the temperature of the steam will lower. If the pressure increases the temperature of the steam rises. The fluctuation of the steam pressure can cause the temperature of the liquid inside the exchanger to vary as much as 5 degrees.

Suppose that a machine upstream in the boiler supply line is turned on and draws a large amount of steam. This situation causes the pressure in the line to decrease and the steam temperature inside the heat exchanger to drop. Due to the static inertia of the process liquid, it opposes a temperature change and creates a delay (pure lag) as the liquid retains thermal energy. Several minutes must pass before the liquid lowers to the same temperature as the steam. As the controller detects a lower liquid temperature from the sensor located at the discharge line, it causes the steam valve to open by a larger amount. The increase in steam causes the temperature inside the exchanger to rise. Another pure lag develops as several minutes pass before the liquid rises to the same temperature as the steam.

The lagging effect in the transfer of thermal energy from the steam to the liquid can be undesirable, especially if the temperature drops below a level that does not provide an adequate chemical reaction. The lagging effect in the exchanger shown in Figure 11-21, is due to the control method used in its design. In the system, the controller responds to changes in the controlled variable (the process liquid) instead of the upset that took place in the manipulated variable (the steam). The process can be controlled more quickly by monitoring both the controlled and the manipulated variables. A *cascade control* system that uses two additional components, a sensor and a controller, to form a *second feedback loop,* performs this function.

The diagram in Figure 11-22 shows the configuration of a **cascade control** system. The inner loop, which monitors the manipulated variable (steam pressure), is referred to as the secondary feedback loop. The outer loop, which monitors the controlled variable (liquid temperature), is referred to as the *primary feedback loop*. The primary controller used in this loop compares the setpoint temperature of the liquid to its actual temperature supplied by the thermal sensor. However, instead of directly positioning the control valve, its output becomes a setpoint signal for the secondary controller. Because the secondary controller

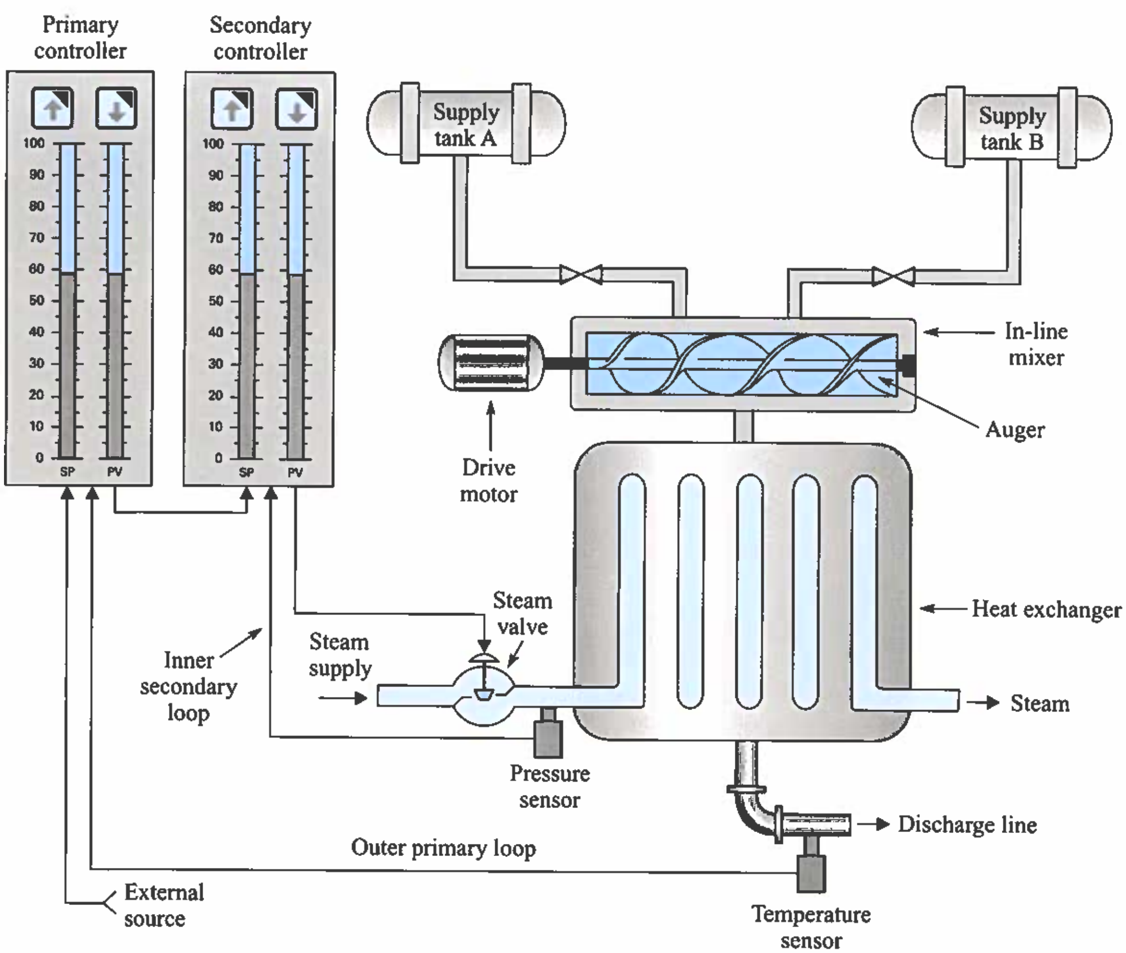


FIGURE 11-22 Cascade control system

has the capability of receiving its setpoint from an externally applied source, it is referred to as a *remote controller.* In addition to its setpoint input, it receives a feedback pressure signal from the sensor placed inside a steam chamber going into the heat exchanger. Based on the results when comparing the setpoint and feedback signal of the inner loop, the secondary controller positions the final control element (steam valve). There are two conditions which will cause the secondary controller to reposition the steam valve. First, if there are any fluctuations in steam pressure, an error signal develops due to the difference between the changed feedback signal and the stable setpoint signal. The result is that the valve position changes, which causes the steam pressure going into the heat exchanger to return to the desired level before the temperature of the liquid is substantially affected. The other condition that causes the secondary controller to adjust the valve is when the setpoint signal it receives from the primary controller varies. This situation occurs if there is a system setpoint change made to the primary controller, or the feedback signal from the outer loop varies due to a disturbance or load change of the controlled variable (liquid) temperature. Either situation creates a new error signal at the primary controller's output, which is fed to the secondary controller as a different setpoint.

In summary, the secondary control loop reacts quickly to changes in steam pressure. The secondary loop always causes a faster final control element reaction to changes in its variable than when variances occur in the primary loop. In addition, by only using the proportional mode in each control loop, cascade control often results in faster, more precise performance than with single-loop PID control systems. When tuning a cascade control system, always tune the secondary loop first. The proportional band of the secondary loop should always be narrower (higher gain) than the proportional band (lower gain) of the primary loop. To be effective the time constant of the inner loop should always be three to ten times faster than the time constant of the outer loop.

Feed-Forward Control

Feedback systems work on the principle that the process must deviate from setpoint before control action is applied. Figure 11-23 is used to illustrate this concept. A liquid passes through the tube section of a heat exchanger which raises its temperature to a required level before it is discharged. The outflow, which is the controlled variable, is fed to a mixing tank for further processing. The heating medium is steam, which passes through the shell of the exchanger. The steam is the manipulated variable. A control valve is used as the final control element to vary the flow of steam, and therefore the heat that is transferred to the product. The sensor located in the outlet line reads the temperature of the controlled variable. If a disturbance causes the outgoing fluid to deviate from setpoint, the controller causes the valve to vary the amount of steam that passes through until the situation is completely corrected. However, while the corrective action takes place, an erroneous product is being produced. Some processes cannot tolerate any deviation from setpoint. For example, if the temperature of the liquid that leaves the heat exchanger is too high when it enters the mixer, the resulting product will separate. If the temperature of the liquid is too low, the end product will be lumpy.

By measuring a variable that enters a process and by taking corrective action if it is affected by a disturbance, a deviation of the controlled variable from setpoint is reduced or eliminated. The operation of **feed-forward control** is based on this principle.

Figure 11-24 shows how the feedback heat exchanger system can be modified to perform feed-forward control. Under stable conditions, the system is tuned so that, as the fluid passes through the exchanger, its temperature is raised from 80 to 100 degrees. To maintain this operation, the temperature of the incoming fluid must be at 80 degrees, and the flow rate must be precisely controlled. One way the operation is disrupted is when the flow rate is constant but the temperature of the incoming fluid drops to 76 degrees. Since the exchanger is calibrated and tuned to raise the fluid's temperature 20 degrees, the outgoing fluid temperature will be only 96 degrees. Another way the operation is disrupted is when the incoming fluid is the required 80 degrees, but the flow rate increases. Since the fluid passes through the exchanger more quickly, the time during which the heat is transferred from the steam to the liquid is shortened and its temperature is lower when the liquid is discharged. The feed-forward system reduces each type of disruption by using two sensors. One measures the temperature of the

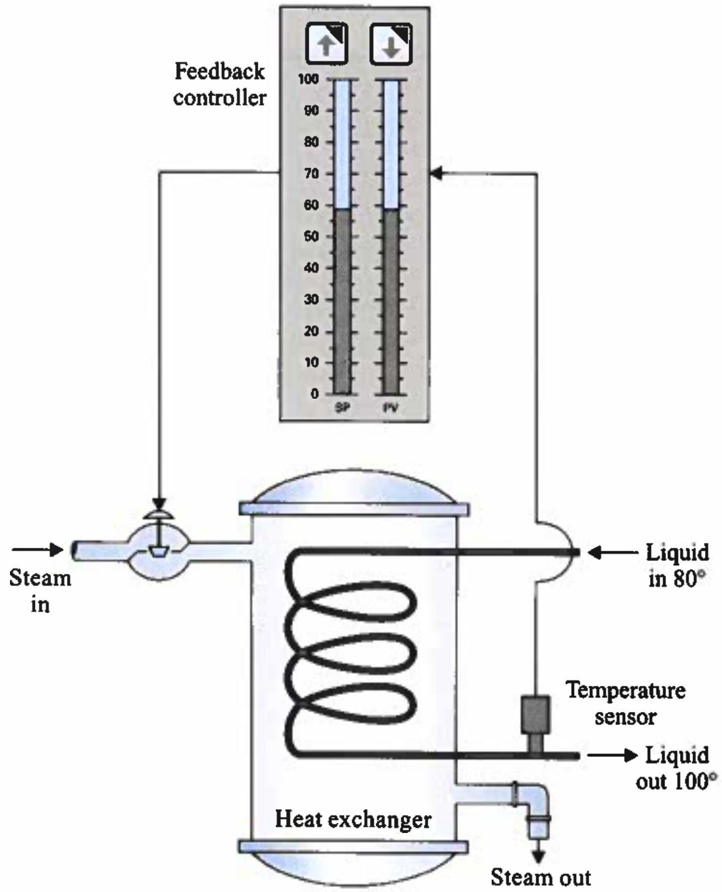


FIGURE 11-23 Feedback control system

incoming liquid, and the other measures its flow rate. Based on inputs from the two sensors, the feed-forward controller calculates how much steam is required to maintain the controlled variable at setpoint.

The feed-forward control system does not operate perfectly. There are usually unmeasurable disturbances not compensated for by feed-forward control, such as a worn steam valve, sensors out of tolerance, or inexact mathematical calculations programmed into the controller. If any variances occur resulting from these problems, the controlled variable, such as the desired temperature of 100 degrees being discharged from the exchanger, will be affected.

To detect a deviation of the controlled variable from the setpoint due to an unmeasurable disturbance, feedback control is added to the system, as shown in Figure 11-25. The controller performs both the feed-forward and feedback operations. A temperature sensor is connected to the outflow line to form the feedback loop. The controller compares the feedback signal with the setpoint and causes the valve to alter the flow of steam if an error develops.

In summary, feedback systems determine a correction that needs to be made after the controlled variable deviates from setpoint; feed-forward systems detect a disturbance before the controlled variable can deviate from setpoint. Feed-forward control is used when no variation from setpoint can be tolerated in a process or when a system is very slow in responding to corrective action. Due to the inaccuracy of feed-forward control in some situations, it is seldom used by itself.

Ratio Control

A wide range of industries use a mixing operation to blend two or more ingredients together to form an end product. To ensure that a quality product is produced, the quantity of each ingredient must be very precise. One method used for mixing applications is to proportionally control the flow of one ingredient based on the amount of flow of another ingredient. This procedure is called **ratio control.** With ratio control, the flow of one material is uncontrolled.

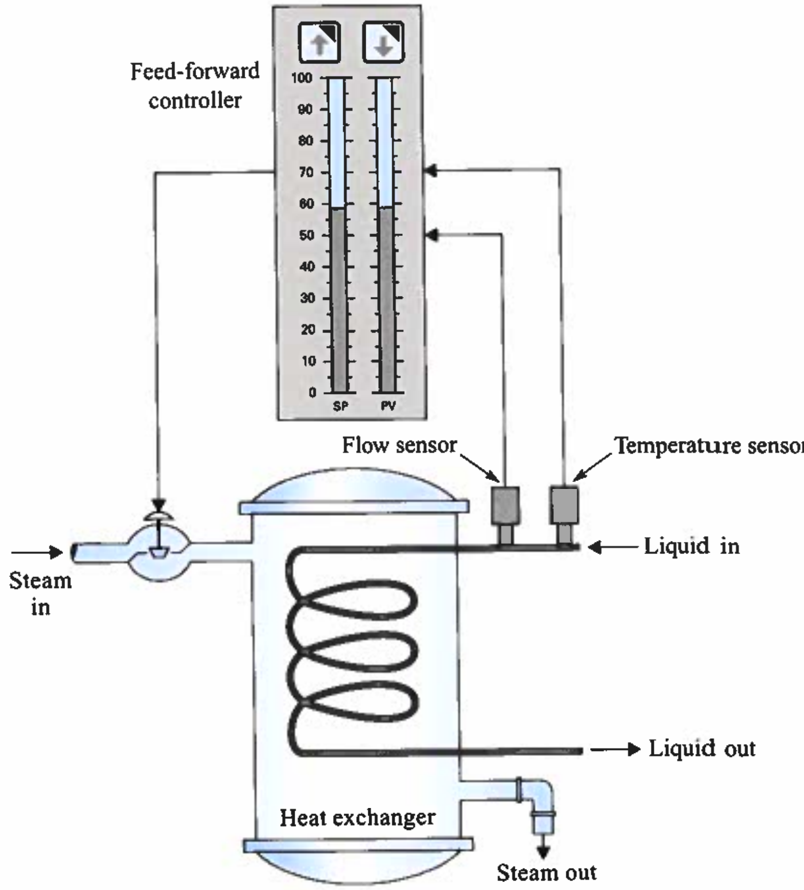


FIGURE 11-24 Feed-forward control system

This flow rate is commonly designated *wild flow.* The rate of the wild flow ingredients is measured and used as a reference to set the flow rate of the other material. This flow rate is referred to as *controlled flow.*

A ratio control system is shown in Figure 11-26. One sensor is used to measure the flow rate of the wild flow, and another sensor is used to measure the flow rate of the controlled flow. The flow rate of each line is measured by reading the differential pressure across an orifice plate, which is nonlinear. A square root extractor transducer is connected between the each D/P flow sensor and the controller. Its function is to convert the nonlinear output of the pressure sensor to a linear signal that is proportional to the flow rate for each liquid. By using the flow signals from each line, the controller varies a valve position that adjusts the controlled flow and maintains it in proper ratio to the wild flow.

The ratio control flow method is used for continuous blending applications, or can be integrated to provide a specified volume for a batch process. An example of how ratio control is used in a continuous process in which two materials are used is in a sewage treatment plant. When a sudden downpour of rain occurs, a rush of water flows through the facility. The flow rate of the untreated water is measured as the wild flow. A ratio controller is used to add a controlled percentage of chlorine to purify the water as it passes through the system. If two or more ingredients are combined in a process, such as when lead, dyes, and other additives are mixed with gasoline to form a specific blend, more than one ratio controller is used. An example of a batch process which uses ratio control is soft drink production, where syrup and water are mixed in a tank.

Adaptive Control

Most of the other control systems previously discussed in this chapter produce a control signal that is proportional to the size of the signal error. Figure 11-27(a) uses a graph to show that the relationship between the process measurement signal and the resulting signal

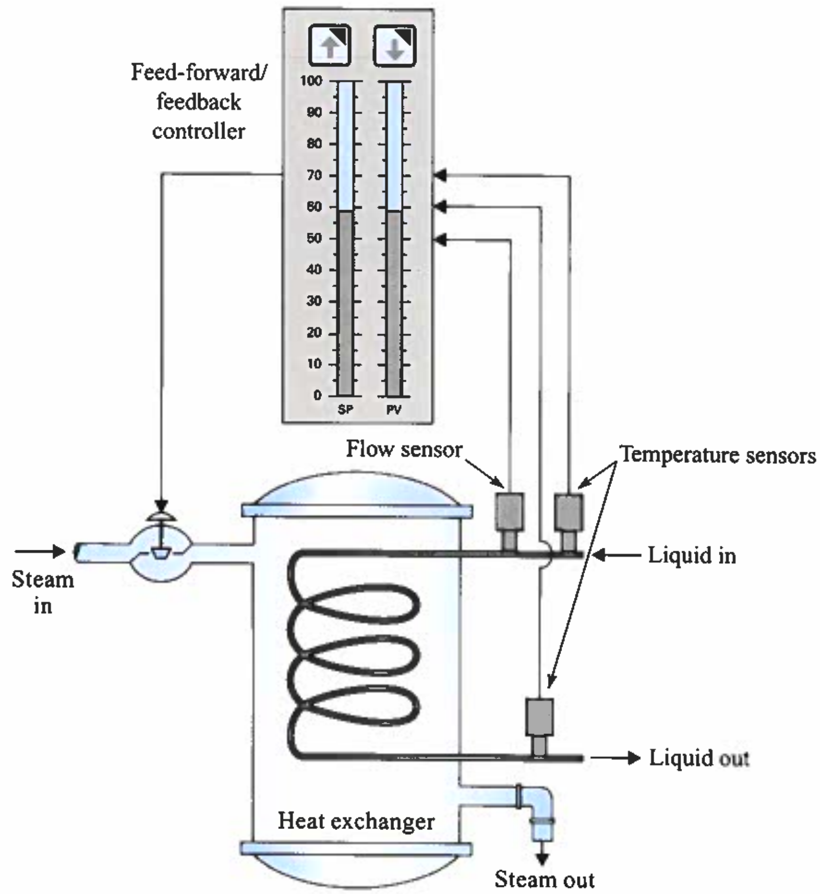


FIGURE 11-25 Feed-forward/feedback control system

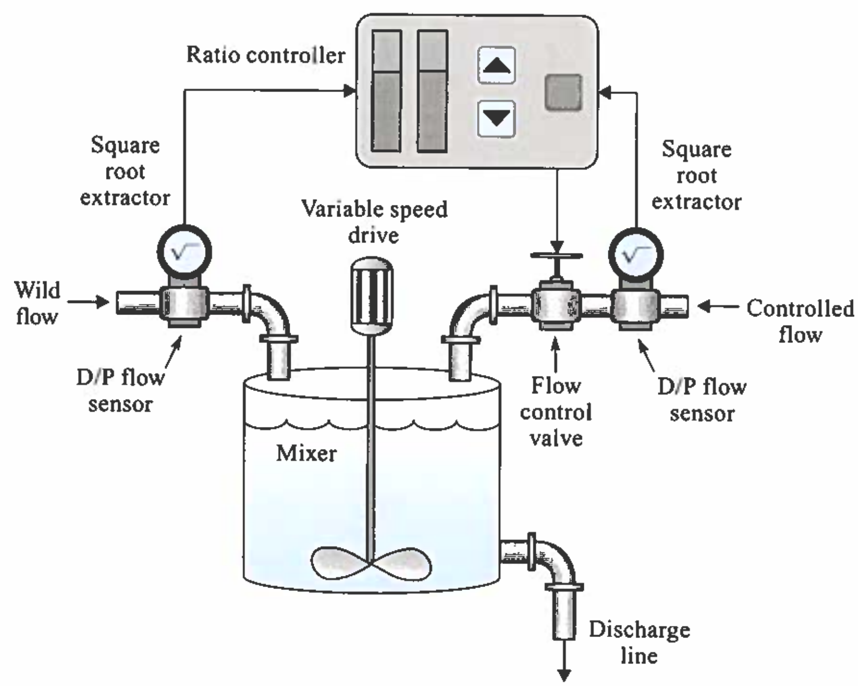


FIGURE 11-26 Ratio control mixing process

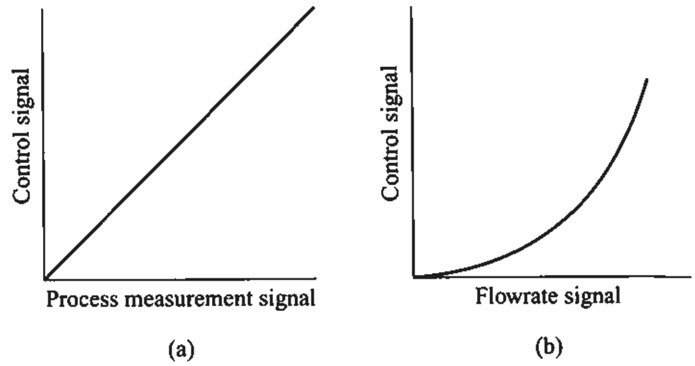


FIGURE 11-27 Relationship between measurement and control signals: (a) linear, (b) nonlinear

produced by the controller is linear. A relationship between the measurement and an output control signal that is not proportional, is graphically represented by the diagram in Figure 11-27(b). The reason for the resulting nonlinear signal is due to the characteristic of the measurement device that reads the condition of a process variable. For example, the two pressures that develop on each side of the orifice plate of a differential flowmeter are not proportional to the flow rate, as shown in Table 11-2.

One way to compensate for the nonlinear characteristics of the differential pressure sensor is to use an instrument called a square root extractor. This specialized transducer converts the nonlinear output of the sensor into a linear signal used by the controller.

In addition to a differential pressure sensor that is nonlinear, some processes also have this characteristic. An example is an analytical control system which controls the *pH* of a solution. To accommodate a nonlinear process, a controller which has **adaptive control** capabilities is used. An adaptive controller uses a combination of software programming and microelectronics to compensate for nonlinear situations.

TABLE 11-2 Comparing an Actual Linear Flow Rate to the Nonlinear Output of a Flowmeter

Actual Flow Rate	*Differential Flowmeter Reading*
100%	100%
50%	70.7%
25%	50%
0%	0%

Problems

1. The automatic operation performed by an industrial manufacturing machine is referred to as ________.
2. Timing functions used to control an operation by industrial manufacturing machines are performed by ________.
   a. ladder logic hardware
   b. a sequential drum controller
   c. a programmable controller
   d. computers
   e. all of the above
3. T/F Open-loop systems do not provide automatic control of a machine operation.
4. Which of the following industrial operations is referred to as a process? ____
   a. Fluid flow rate through a pipe
   b. Ingredients filling a vat at a required level
   c. Heat applied to a vessel to cause a chemical reaction
   d. A vacuum pressure applied to a confined tank
   e. All of the above
5. T/F The output signal of a sensor is referred to as the controlled variable.
6. List three influences that cause a controlled variable to change.

7. Dynamic response pertains to ____.
   a. the reaction time of instruments in a control loop
   b. the inertia of the controlled variable
   c. dead time
   d. all of the above
8. T/F Dead time is influenced by the mass of the material from which the controlled variable is made.
9. T/F The pure lag of a controlled variable is determined by the quantity and the type of material from which it is made.
10. One time constant is defined as ____ percent at which the controlled variable changes after it is exposed to an energy change.
    a. 1 c. 63.2
    b. 36.2 d. 100
11. The dynamic response of a control loop can be improved by ____.
    a. selecting a controller with proper operation features that respond to the process
    b. properly tuning a controller
    c. both a and b
12. T/F The amount at which the final control element turns on in an On-Off system is proportional to the error signal.
13. What are two household applications that purposely have a deadband to turn a device on and off?
14. T/F The output of the proportional controller moves the final control element to a definite position for each value of the controlled variable.
15. The average voltage of a time proportioning controller ____ if the ON time decreases compared to the OFF time.
    a. increases c. stays the same
    b. decreases
16. When the input to a proportional controller changes by 5 percent, the ____ will change by ____ percent if there is a gain of 5.
    a. 1 e. controller output signal
    b. 5 f. final control element
    c. 10 g. controlled variable
    d. 25 h. all of the above
17. The proportional ____ setting effects how fast the controlled variable changes in response to a step change or load change.
    a. gain c. both a and b
    b. band
18. A controller with a proportional band of 50 will produce a proportional gain of ____.
19. When the controlled variable is above the proportional band, the proportional action will cause the final control element to be ____.
    a. fully off c. fully on
    b. partially on
20. A controller has more sensitivity if its proportional band is ____.
    a. narrower b. wider
21. What condition might occur if a controller is too sensitive? ____
    a. A sluggish response to a load change might occur.
    b. Excessive cycling will occur.
    c. There will be no signal change applied to the final control element.
22. A controller with what kind of control mode eliminates offset automatically? ____
    a. On-Off c. Integral
    b. Proportional d. Derivative
23. T/F The magnitude of the integral output is proportional to the time duration of a deviation between setpoint and the controlled variable.
24. The ____ adjustment is made on a controller for integral.
    a. reset c. PB
    b. rate
25. If the reset rate adjustment on a controller is increased, the integral time will ____.
    a. increase c. stay the same
    b. decrease
26. A reset rate of 10 repeats per minute equals an integral time of ________ minutes per repeat.
27. What kind of controller action is related to the rate at which an error develops? ____
    a. On-Off c. Integral
    b. Proportional d. Derivative
28. While the deviation between the setpoint and measured variable is increasing, the derivative action will ____ the control effort to compensate.
    a. increase b. decrease
29. While the deviation between the setpoint and measured variable is decreasing, the derivative action will exhibit a ____ action.
    a. braking b. boosting
30. The magnitude of the derivative output is directly proportional to the ____.
    a. time duration of the deviation between setpoint and the measured variable
    b. rate at which the error signal changes
    c. both a and b
31. T/F The derivative mode is recommended in applications where the controlled variable lags behind the change of the final control element.
32. When tuning a cascade control system with two loops, which loop should be tuned first? ____
    a. The primary loop b. The secondary loop
33. Which of the following terms describes a control strategy in which the output of one controller is used to manipulate the setpoint of another controller. ____
    a. Ratio c. Feed-forward
    b. Cascade d. Adaptive
34. The ____ controller in a cascade system receives a feedback signal that represents the condition of the controlled variable.
    a. primary b. secondary
35. In a cascade system, the ____ loop is considered the primary loop.
    a. inner b. outer
36. Which of the following statements are true about feed-forward control? (More than one answer is possible.) ________
    a. It should be implemented with feedback control.
    b. It can compensate for unmeasurable disturbances.

c. Its output causes the manipulated variable to be changed.
d. It improves the speed at which corrections are made to a disturbance.

37. Mark each true statement about feed-forward control.
____ Feed-forward control is another name for feedback control.
____ Feed-forward control is based on observing changes in the controlled variable and then adjusting the manipulated variable to compensate.
____ Feed-forward control helps to prevent changes in the controlled variable before they occur.

38. T/F When two or more ingredients are blended in a mixing operation, the flow of each one is controlled by a ratio control system.

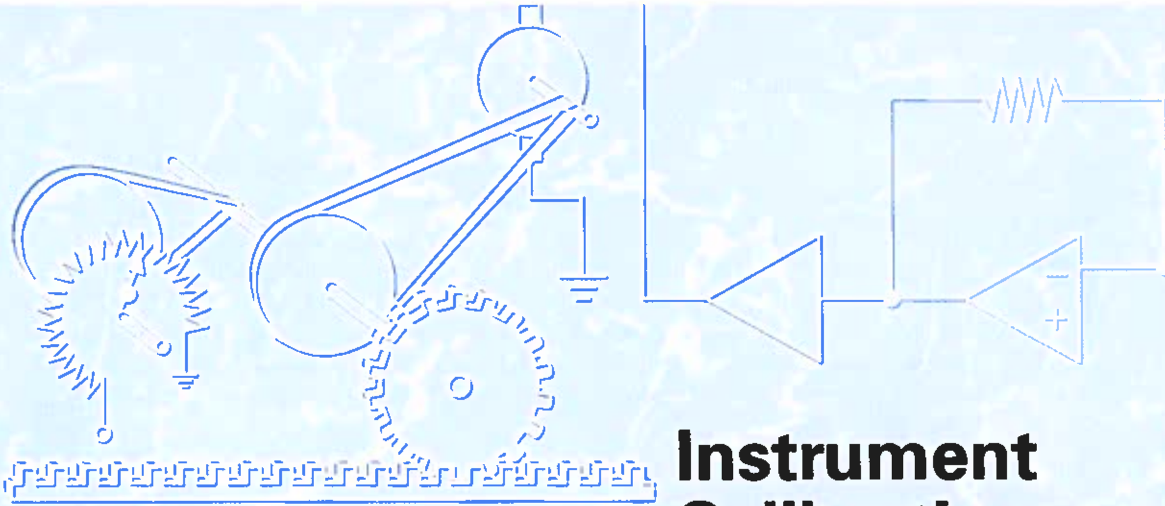
39. A strategy in which the flow rate of one fluid stream is maintained at some proportion to the flow rate of another fluid stream is ____.
a. cascade control
b. feedback control
c. ratio control
d. adaptive control

40. T/F The wild flow ingredient in ratio control is measured.

41. In ratio control, the reference flow rate is referred to as ____ flow.
a. wild
b. controlled

42. An adaptive controller uses a combination of software programming and microelectronics to compensate for ____ measurements.
a. linear
b. nonlinear

43. Which of the following process measurements produce a nonlinear signal? (More than one answer is possible.)
____
a. Differential pressure flowmeter
b. Ultrasonic level meter
c. pH of a solution
d. None of the above



CHAPTER 12

Instrument Calibration and Controller Tuning

OBJECTIVES

At the conclusion of this chapter, you should be able to:

- List the circumstances that require calibration procedures.
- Properly assemble the instruments required to perform the calibration procedure.
- Explain three-step and five-step calibration procedures.
- Properly assemble the instruments required to perform the calibration procedure.
- Recognize zero shift and span errors so that they can be properly corrected.
- Describe process identification.
- Use the following methods to tune a controller:

Trial-and-Error	Autotuning
Ziegler-Nichols Reaction Curve	Ziegler-Nichols Continuous Cycling

- Define the following terms associated with controller tuning:

Bump Test	Proportional Gain (PG)	Effective Delay
Unstable	Proportional Band (PB)	Process Reaction Rate
Ultimate Period	Ultimate Proportional Gain Value	Unit Reaction Rate
Ultimate Proportional Value		

- List and describe three process models that result from a step change.

INTRODUCTION

To ensure the proper operation of a closed-loop feedback system, there are several requirements that must be met.

Proper Design. During the design and engineering phase, the proper instruments throughout the system must be selected to perform the required operation. For example, the appropriate sensor must be selected to accurately monitor the variable that is being controlled; if a flow control valve is used as the actuator, it must be properly sized.

Instrument Calibration. The instruments throughout the loop must accurately produce output signals that represent the value of the measured variable. Due to wearing or aging of components, the signals that are produced by various instruments may be altered and create undesirable results. Many of these instruments are designed so that adjustments can be made to compensate for the deterioration of their internal components. The process of making these adjustments, called **calibration,** is typically performed by instrumentation technicians.

Controller Tuning. When a disturbance happens, a load demand varies, or a setpoint change is made, it is important that the system responds quickly and accurately. This action is primarily dependant on the controller, or the "brain" of the closed-loop. A proper response is dependant on how well the controller is tuned, which requires the proper settings of the proportional, integral, and derivative control modes. An engineer is typically responsible for tuning the controller, although properly trained technicians may also be given this responsibility.

After the closed-loop feedback system installation is refined and verified through a process called "start-up," its instruments are rarely changed unless they need to be replaced due to repair. However, it is necessary to constantly monitor the instruments by calibrating them to ensure their accuracy, and to periodically re-tune the controller so that there is a quick and accurate response to any changes in the process variable, or the setpoint.

This chapter presents information on instrument calibration and controller tuning, typically performed by instrumentation technicians and engineers.

12-1 Instrument Calibration

The proper operation of any process depends on the accurate operation of each instrument in a closed-loop configuration. One of the instruments commonly used in a closed-loop system is a **transmitter.** Its function is to convert a signal from a sensor that monitors the condition of the process variable to a standard analog signal that is used by the controller as its feedback input. The two most common analog standard signals are electrical and air pressure. For electrical systems, the signals are transmitted by wires, and in an air pressure system, the signals are carried by pipes or flexible tubing.

The most common electrical signal is current, which ranges from 4 to 20 mA. The most common air signal is a pneumatic signal that ranges from 3 to 15 psi. The lowest value of each signal range often represents the minimum condition of the process variable. For example, the lowest level of liquid in a tank is represented by a 4 mA current signal, and a 3 psi pneumatic signal. The maximum level in a tank is represented by a 20 mA current signal, or a 15 psi pneumatic signal.

Transmitters commonly have a feature that provides a way in which they can be adjusted to ensure that the output signals they produce accurately represent the input they receive. The procedure of making these adjustments is called **calibration.** The adjustments are made so that the transmitter's output will vary through the full range in proportion to the full range that the variable being measured changes. Calibration is performed to establish the *zero* and *span* settings for the transmitter. The zero setting adjustment causes the transmitter to produce its lowest output signal when the variable is at its minimum condition. The span setting causes the transmitter to produce its largest output signal when the variable is at its maximum condition.

If the transmitter interfaces with electronic signals, it commonly has a small screw that can be turned to adjust a variable resistor located in the electronic circuitry of the instrument. If the transmitter is mechanical, a nut on a bolt may be turned and repositioned to change the leverage or range of movement, to control something like air pressure or flow. Smart transmitters, which are the newest version of this instrument, are programmable and use keypads to make the necessary adjustments.

12-2 Reasons for Performing Calibrations

There are various reasons why transmitters require calibrations. As previously explained, the value of internal electronic components change and mechanical parts wear. For this reason, transmitters require a scheduled calibration procedure on a routine basis to ensure they are operating properly and to make adjustments if they are not.

Calibration procedures are performed for other reasons, such as:

Before New Instrument Installation. Although they are factory calibrated, the operation of new instruments may be altered due to rough handling in the shipping department, or during transit.

After Extended Shutdown. Calibration settings can be adversely affected over a period of time due to a change in environmental conditions or prolonged exposure to process materials (especially if they are corrosive).

After Repair. Instruments must be calibrated to verify their accuracy.

The Product Fails to Meet Specifications. If the product being manufactured is out of tolerance, it may be the result of a transmitter not operating properly.

It is common practice to attach calibration stickers to each instrument to provide a record of the last calibration.

12-3 Calibration Preparation

Before a calibration procedure is performed, several steps must be followed first:

Step 1: Determine the full range of the variable being measured. For example, the full range of a level process being controlled is 10 inches to 90 inches.

Step 2: Establish what type of sensor is used to measure the process variable. This information is required because it is necessary to know what kind of signal is applied to the transmitter. For example, it may be pneumatic pressure, a variable voltage, or a variable resistance.

Step 3: Once the required signal is established, it is applied to the transmitter under test to simulate the process variable that is measured during manufacturing. This simulation signal may come from the actual sensor that measures the process, or from a source that is independent from the actual sensor. When the signal is from the actual sensor of the system, the variable being controlled is changed manually to cause the sensor to produce a signal. Examples of a source that simulates the sensors output is an adjustable air supply that represents a pneumatic pressure, or a calibrator that provides a variable voltage to simulate a thermocouple output.

To apply the simulator signal to the transmitter, input connections are made, as shown in Figure 12-1. In this illustration, a temperature calibrator is used to simulate a variable resistance of a three wire resistance temperature detector (RTD).

Step 4: Connect a power supply to the transmitter, as shown in Figure 12-1. All transmitters require a power source. As the transmitter produces an output signal, it uses power from the source to which it is connected. For example, if its output is pneumatic, the transmitter must be connected to an air supply.

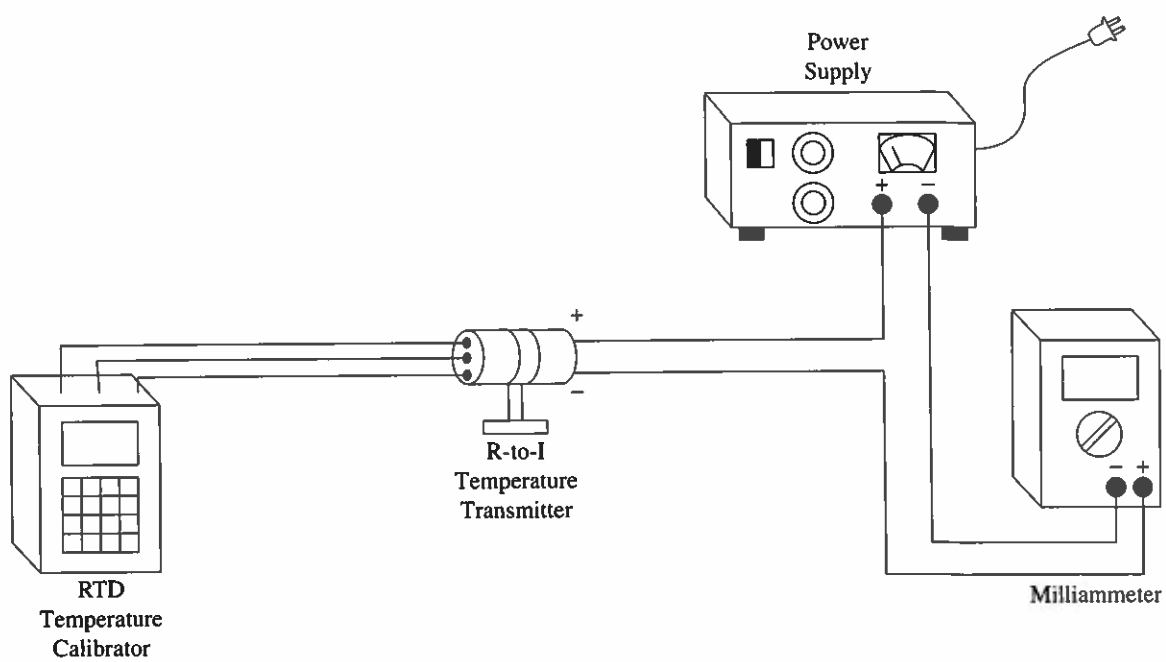


FIGURE 12-1 Calibration Circuit

Step 5: Connect a test instrument to the transmitter's output. As the signal that simulates the measured variable is applied to its input, the transmitter must produce a corresponding output. To ensure accuracy, a precision test instrument is used to measure the output signal.

Any precision test instrument used during calibration to either monitor the simulated signal at the transmitter's input, and the corresponding signal produced at the output, are called *secondary standard* devices. Ideally, the secondary standard should be at least ten times more accurate than the transmitter being tested.

The connection points for calibration of either electronic or pneumatic transmitters are similar in that both types of instruments require a simulated input, a power supply, and a method to measure the output value.

Calibration equipment connections must not introduce errors during the test procedure. To avoid this possibility, the connections, whether they are pneumatic or electronic, must be securely tightened.

12-4 Standard Calibration Procedure

Using the example of a level process that varies between 10 inches and 90 inches, the following steps are recommended to perform a standard calibration procedure. In this process shown in Figure 12-2, a float cable is attached to a rotary potentiometer.

The potentiometer is the level sensor that produces a variable voltage from 0 to 10 volts as the feedback signal. The float device is especially designed to measure water, so the amount of buoyancy is known. Therefore, to compensate for how much of it sinks, a mark exists on the side of the float to indicate the level as it rides on the surface.

The transmitter for this system converts a variable voltage at its input to a corresponding 4 mA to 20 mA output value.

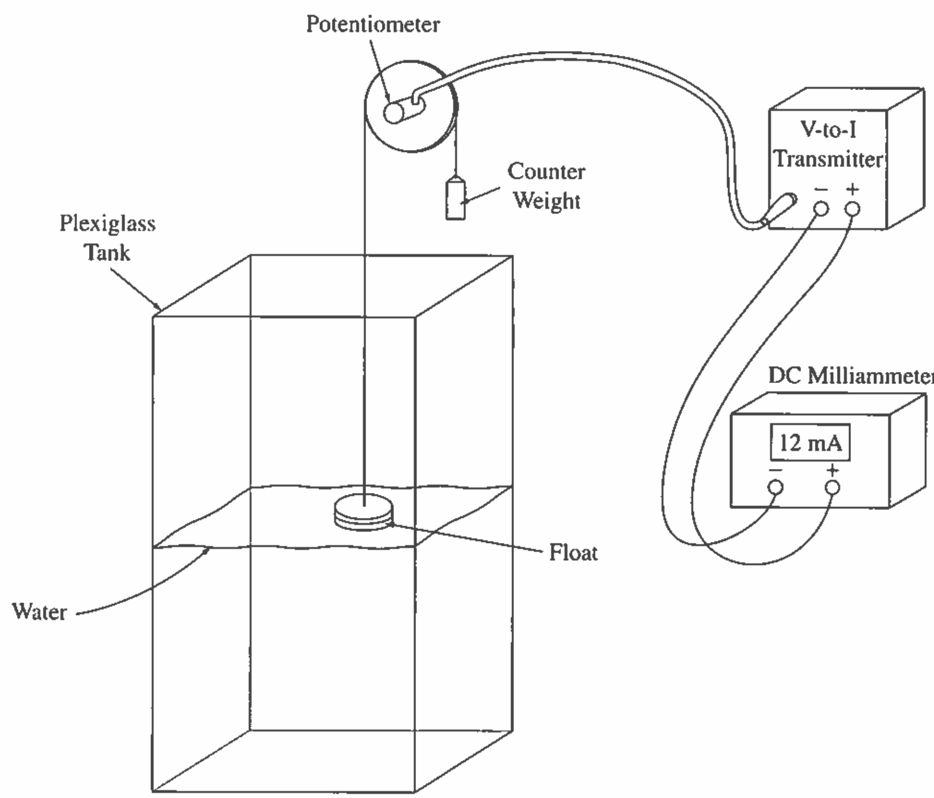


FIGURE 12-2 Calibrating a water level process

Step 1: Empty the water from the plexiglass tank.

Step 2: Manually move the float so that the indicator mark is at the minimum level of 10 inches. Assume that the potentiometer produces 1 volt at this position.

Step 3: Observe the output of the transmitter. If it is not 4 mA, make a zero adjustment to the screw pot or keypad until it is.

Step 4: Move the float so that the indicator mark is at the maximum level of 90 inches. Assume that the potentiometer produces 9 volts at this position.

Step 5: Observe the output of the transmitter. If it is not 20 mA, make a span adjustment on the screw pot or keypad until it is.

Step 6: Span adjustments may affect zero adjustments, and vice versa. Therefore, it is recommended that this calibration procedure is performed more than once.

Step 7: Verify the adjustments by measuring the 0 percent output at 4 mA when 10 inches are detected, a 50 percent output of 12 mA when 50 inches are detected, and a 100 percent output of 20 mA when a 90 inch level is detected.

This procedure in which measurements at 0, 50, and 100 percent of the transmitter's input are made, is called a three-point calibration check.

12-5 Five-Point Calibration Procedure

The disadvantage of using the three-point calibration check is that it does not effectively show a linearity error condition. In a linearity error situation, the readings are in the form of an S-shaped calibration curve, rather than being in a uniform straight line throughout the range of the measurements, as shown in Figure 12-3. By adding two more steps to the procedure, a linearity problem can be detected.

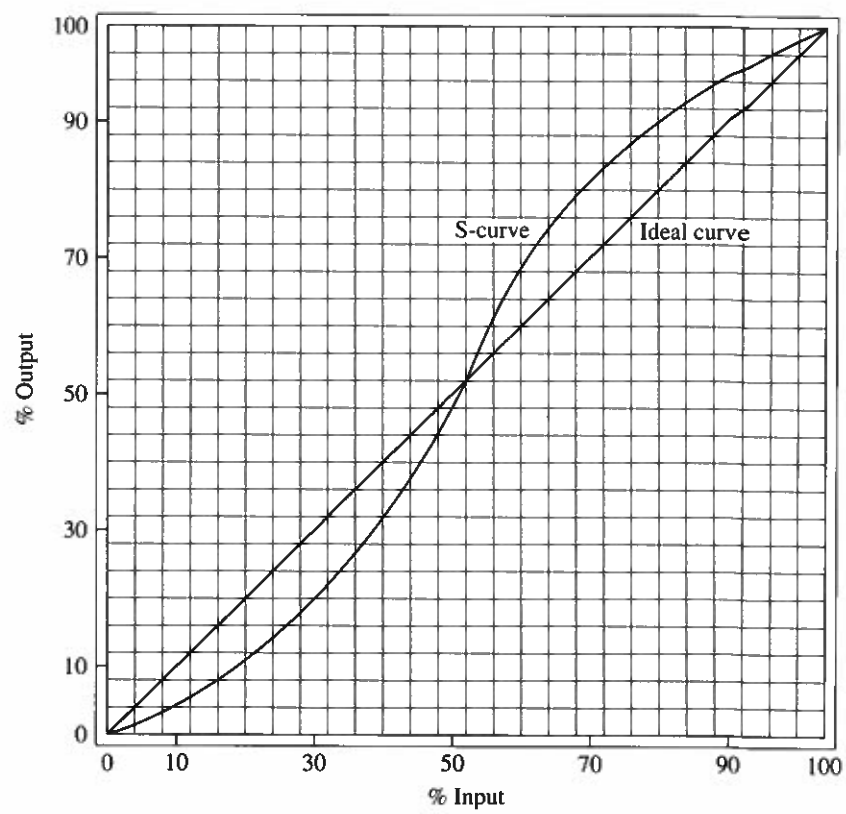


FIGURE 12-3 S-shaped calibration curve

Calibration Check

Although there are no firm rules on the procedure for a five-point calibration check, the following general guidelines are recommended. A P-to-I transmitter with an input that ranges from 0 to 25 psi, and an output of 4 to 20 mA, will be used as an example.

- The five input test points should be distributed over most of the instruments entire range.
- Unless otherwise specified, the values of 10 percent and 90 percent are chosen to represent the low and high ends of an instrument's range. Zero percent should be avoided because some procedures require that each test point be approached from a lower value. Also, 100 percent should not be used because some procedures require the test points be approached from a higher level. To meet this requirement, the instrument's range would have to be exceeded.
- Test point values of 10, 30, 50, 70, and 90 percent of the instruments input range are recommended. Once the test points have been established, it is necessary to calculate the input and output values that correspond to each percentage of the range.

Calculating the Input Values

The pressure applied to a P-to-I transmitter's input is 0 to 25 psi. Therefore, the range of the applied pressure is 25 psi. To determine the input pressure value that corresponds to 10 percent, multiply 10 percent times the range (25) and add the product to the lower range limit of 0 psi. The 10 percent value is 2.5 psi. The remaining four test points are calculated using the same procedure for each test point percentage value.

Calculating the Output Values

The corresponding output test point values of the transmitter are calculated by using a similar procedure. For example, the range produced at the transmitter's output is 4 to 20 mA, or 16 mA. To determine the output current value that corresponds to 30 percent, multiply .30 times 16 and add the product to the lower range limit of 4.0. The 30 percent value is $(.30 \times 16) + 4.0 = 8.8$ mA. The remaining four test points are calculated the same way.

- A series of readings at each established test point should be taken on both upscale and downscale traverses. Upscale readings are approached from the low end, which means the check for each value is approached from a lower value. If the test point is exceeded, it is necessary to reduce the value below the desired check point to repeat the measurement. The same rules apply to downscale readings, which require that each check point be approached from the high end. Each series of readings are called a *calibration cycle*.
- A minimum of five calibration cycles should be made to ensure the measurements are valid.
- As each simulated value is applied to the input, record the corresponding test point measurements of the transmitter's output on an appropriate document called a data sheet.

Analysis of Calibration Data

- After recording the data on a calibration check form, it is recommended that the measured output values recorded on the data sheet are plotted on a graph to visually analyze the results.
- The graph in Figure 12-4 shows that both the upscale and downscale values recorded at 10 percent were consistently lower than the ideal value. It also shows that the 90 percent measurements are very close to the ideal values.

It may appear that the only correction that is required is for the zero adjustment to be made higher. However, the 10 percent error should also cause the 90 percent reading to be low. Therefore, it can be concluded that the instrument's span setting will also need to be changed.

Transmitter Zero and Span Adjustments

- Instructions from the manufacturers who make transmitters are frequently available to explain how the calibration adjustments should be made. The zero adjustment is usually made first.

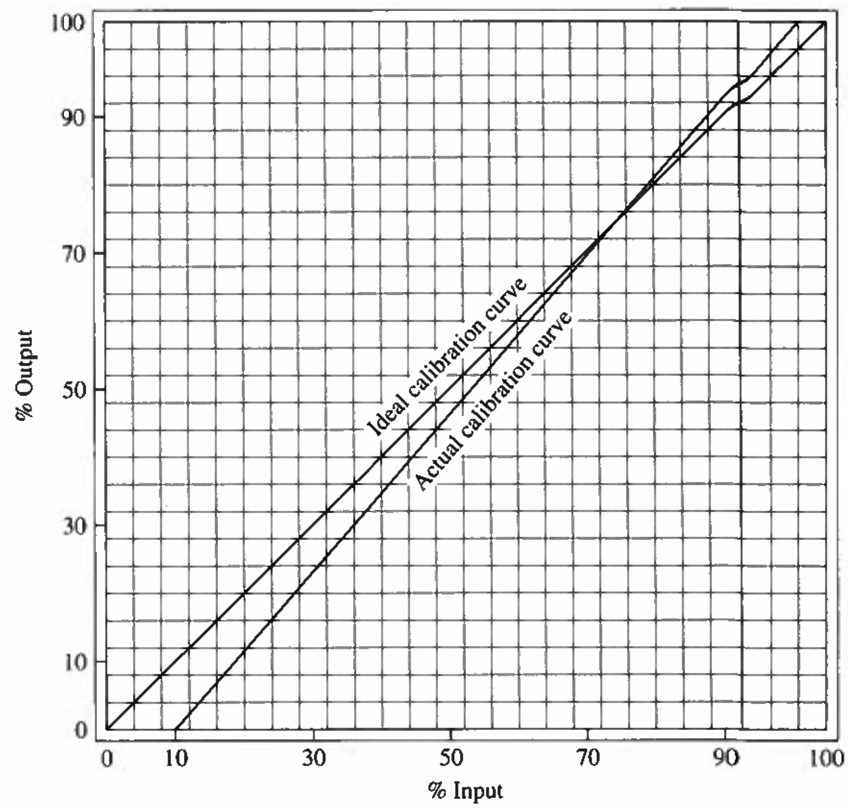


FIGURE 12-4 Combined zero shift and span error

- After applying a simulated 10 percent value of 2.5 psi to the transmitter's input, make a zero adjustment until the transmitter's output reads 5.6 mA. This adjustment provides an accurate starting point for the span adjustment.
- Apply a simulated 90 percent value of 22.5 psi to the transmitter's input and make a span adjustment until the transmitter's output reads 18.4 mA.

Verification of Adjustments

- Repeat the calibration check because zero and span adjustments may affect each other. If necessary, readjust the zero setting first, and then the span setting. Continue rechecking until no further adjustments are needed.
- Complete at least one calibration cycle to verify the adjustments eliminated the zero and span errors.

Another example of the need for a five-point calibration check is illustrated in Figure 12-5. Test points plotted on a graph are shown. It reveals that a zero shift does not occur, so the zero point is correct. However, the curve reveals that span error does exist because it is too high.

After the span adjustment is made, recheck the 10 percent value and change the zero adjustments if necessary. After the zero and span adjustments are properly made, run at least one calibration cycle to verify the results of the adjustments.

Documentation is usually provided by the manufacturer of transmitters on how to properly test and calibrate their product. The instructions usually include the following information.

- Diagrams that show the proper connection of the calibration equipment.
- Adjustment points for zero, span, and linearity.
- Requirements for input and output secondary standard devices.
- Recommended test conditions under which the calibration process is made.

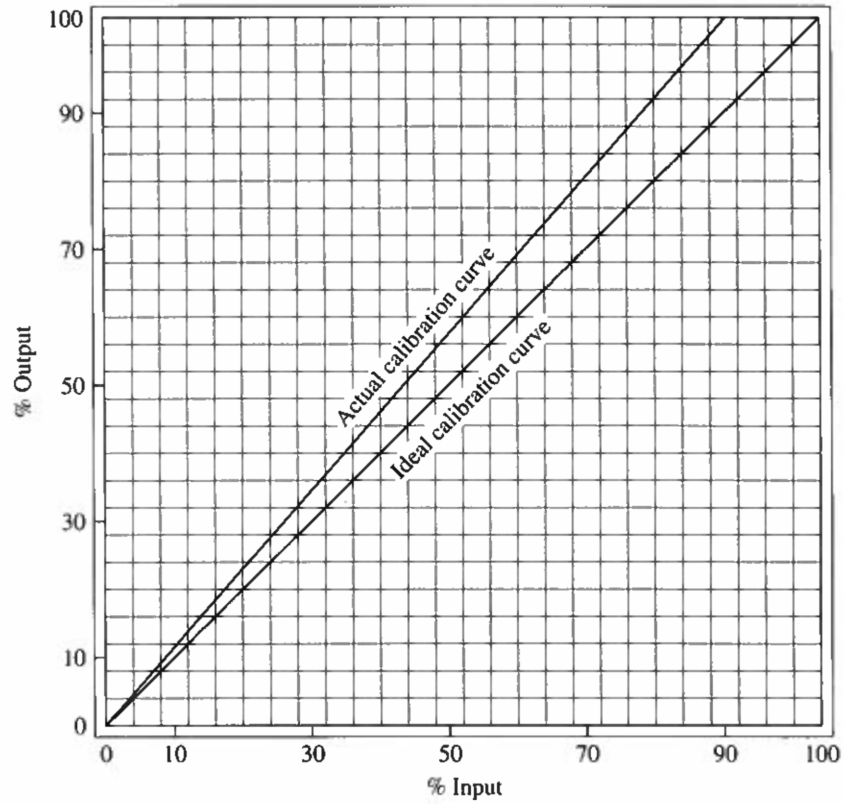


FIGURE 12-5 Span error

12-6 Tuning the Controller

In addition to selecting a controller with the proper control modes for a particular application, as described in Sections 11-4 to 11-6, it is also possible to minimize the dynamic response in a process system by fine-tuning the controller. *Fine-tuning* is a procedure in which the proper adjustments are made to the *gain* setting for proportional, the *reset* setting for integral, and the *rate* setting for derivative. When the optimal balance of mode adjustments is achieved, the system will minimize the size of the initial deviation and return the controlled variable to setpoint as quickly as possible if a disturbance or load change occurs. When a system reacts quickly, it is referred to as being *responsive*. When it reacts slowly, it is referred to as being *sluggish*.

Before a controller can be properly tuned, several preliminary steps should be performed:

Step 1: Study the diagram of the control loop to become familiar with its function and its components.

Step 2: Obtain the proper clearance for tuning activities. The tuning procedure often involves making a setpoint change that is 5 to 10 percent of its span. Since this change can alter the normal operation of the process, make sure that it will not have an adverse effect on the product or the equipment. The operator of the equipment is often the best person from which to obtain information about the system and to make recommendations before tuning begins.

Step 3: Confirm that each component in the loop is operating correctly. This procedure involves:

- Verifying that energy sources are adequately supplied to the final control element by observing the condition of the controlled variable.
- Performing a calibration procedure to determine that the sensor, transmitter, controller, and the final control element are functioning properly.

The first step in the tuning procedure is to analyze the particular system being tuned by observing the way in which the controlled variable responds to an actuator change. Some types of processes respond differently from others, especially the speed at which they change. For example, the flow rate of a fluid changes immediately after the valve position through which it passes is altered. Conversely, it takes much longer for the temperature of a liquid in a large tank to change after a heating element is varied. The information about the response of the process is referred to as *process identification.* It is obtained by using a two-pen chart recorder. One pen records the measured variable signal (which indicates the condition of the controlled variable), and the other pen records the controller's output signal (applied to the actuator). The lines they produce graphically show how the controlled variable responds to actuator changes.

The information on the recorder's graph is used to determine the proper settings that enable the controller to produce an appropriate output signal for the specific process it is regulating. For example, a properly tuned controller that regulates a flow process will require different mode settings than a controller that regulates a temperature process. The proper settings cause the controller to produce an output response signal that changes at an appropriate speed to match the dynamic response of the controlled variable. If the controller output is too slow, the system will be sluggish. If the controller output is too fast, overshoot or oscillations may occur.

There are two methods of process identification. One involves a closed-loop test where the process is forced into a sustained oscillating condition. The other method entails doing an open-loop step change of the actuator and then observing how the process responds. The data shown on the graph is either used in formulas to calculate proper controller settings, or to provide the necessary response information to the person conducting a nonmathematical tuning procedure.

Modern software programs are available which simulate the chart recorder operation on a computer monitor. These programs also enable the operator to make the controller mode settings by using a mouse and a computer screen.

There are many different methods used to tune a process control loop. Some methods are mathematically based, some rely on the experience of the technician, and some can be performed automatically by the controller. Four common methods of tuning are covered in this section: *Trial-and-Error, Ziegler-Nichols Continuous Cycling, Ziegler-Nichols Reaction Curve,* and *Autotuning.*

Trial-and-Error Tuning Method

The **trial-and-error method** of controller tuning does not use mathematical formulas. Instead, it involves using a chart recorder to observe the response of the controlled variable to a setpoint change or a load upset. Based on an interpretation of the observed response, adjustments are made to one or more of the controller mode settings. This method can give acceptable results in many situations. To perform this tuning procedure, the following steps are recommended:

- Place the controller in the manual mode.
- Turn the derivative mode off.
- Turn the integral mode off.
- Adjust the proportional mode to the minimum gain (or maximum PB) setting.
- Place the controller in the auto mode.
- Increase the proportional mode by increasing the gain from zero until a cycling action begins. Read the gain setting and readjust the setting to one-half that value. This should stop the cycling, but also provide a reasonably fast response. If proportional band (PB) is used instead of gain, begin with 100 percent and reduce the setting until oscillations begin. Read the PB setting and increase the adjustment to twice that value. If the value is 35 percent for example, then double the setting to 70 percent.
- Produce a step change (setpoint change, also known as a *bump test*) of 5 to 10 percent of the span and observe the system response on the chart recorder. If the system is too sluggish, as shown in Figure 12-6(a), increase the gain. If the system cycles continuously, as shown in Figure 12-6(b), reduce the gain. (Whenever a control loop produces excessive oscillations around the setpoint, it is referred to as being *unstable.*) Continue making

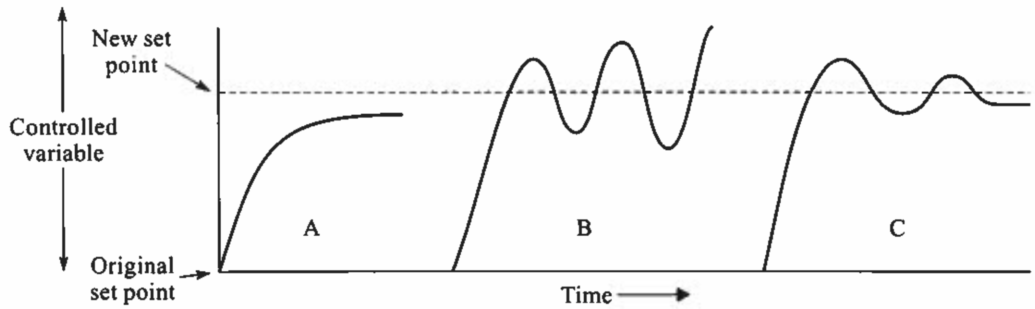


FIGURE 12-6 Response curves

proportional gain adjustments before repeating each bump test until the controlled variable cycles once or twice before stabilizing, as shown in Figure 12-6(c).

- If the process stabilizes with a constant difference between the setpoint and controlled variable, add integral until the offset is eliminated. It may be necessary to change the proportional setting each time the integral adjustment is made.
- When the proportional and integral adjustments are at their optimal settings, switch on and add derivative action to speed up the process response time.

The trial-and-error method can be very time consuming because the settings of one mode affect the actions of the other modes. Therefore, after a change of one setting, it is usually necessary to readjust the settings of the other two modes. Time, patience, and the experience of the person performing the tuning procedure are often required before the optimal balance is found to achieve the desired output response of the controller.

Ziegler-Nichols Tuning Methods

In the early 1940s, two engineers who worked for Taylor Instrument Company, John Ziegler and Nathaniel Nichols, developed two formal procedures for tuning control loops. Their methods have proven to be effective in many applications and are still widely used throughout industry. The two tuning procedures are referred to as the **continuous cycling method** and the **reaction curve method.** Both methods provide a way to calculate controller settings mathematically. There are two major differences between them. The continuous cycling method performs a closed-loop response test with the controller on automatic. The reaction curve method performs an open-loop process identification procedure with the controller in the manual setting.

Ziegler-Nichols Continuous Cycling Method

In the continuous cycling method, the objective is to analyze the process response by forcing the controlled variable to oscillate in even, continuous cycles. This action is achieved by adjusting the proportional setting to a value that causes the cycling to take place. The time duration of one cycle, shown in Figure 12-7, is called an **ultimate period** (P_u). It is read from a

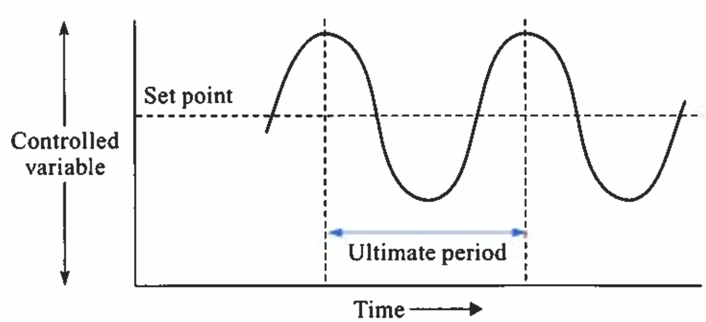


FIGURE 12-7 Determining the ultimate period

chart recorder and recorded because it represents the response of the process to a change of the actuator. The proportional setting that causes the sustained cycling is also recorded. This setting is called the **ultimate proportional value.** The ultimate period and the ultimate proportional value are used in mathematical formulas to calculate controller settings.

Process Identification Procedure for the Continuous Cycling Method

The process identification procedure for the continuous cycling method is performed as a closed-loop test with the controller in the auto-mode. The objective is to obtain the ultimate period and the ultimate proportional value. The steps involved are listed two ways, one for a controller with proportional gain (PG) settings (see Table 12-1), and the other for a controller that has proportional band (PB) settings (see Table 12-2).

Once the process identification information is obtained from Figure 12-7, the next step is to use this data in calculations that determine the proper proportional-integral-derivative (PID) controller settings. Proportional calculations will be shown two ways: for a controller with a

TABLE 12-1 Process Identification Procedure for PG Settings

Step 1	Place the controller in the manual mode.
Step 2	Adjust the set point to the value most often used.
Step 3	Turn the integral and the derivative mode adjustments to a setting that will produce a minimal effect on the controller.
Step 4	Set the proportional gain to its lowest value, which is zero.
Step 5	Switch the controller from manual to automatic mode and introduce a small setpoint step change of 5 to 10 percent of the span. Return the set point to its original value as soon as the waveform is recorded.
Step 6	Watch the response of the process on the chart recorder. At the low setting of proportional gain, the process response curve will likely dampen out quickly as the oscillations stop and the process becomes stable, but with some offset, as shown in Figure 12-8. Return the set point to its original value.
Step 7	Slightly increase the proportional gain setting and make another step change. Continue repeating this procedure until the process cycles and produces the waveform on the chart recorder that is shown in Figure 12-7. Return the set point to its original value each time before repeating.
Step 8	Determine and record the time duration of one cycle that is displayed on the horizontal axis of the chart recorder shown in Figure 12-7. One cycle is referred to as an *ultimate period.* If the process is fast, such as flow, the ultimate period is typically read in seconds. If the process is slow, such as temperature, the ultimate period is typically read in minutes.
Step 9	Record the proportional gain setting that causes the sustained oscillations. This value is called the *ultimate proportional gain,* or G_u. The G_u value is used to mathematically find the appropriate setting for tuning the proportional mode.

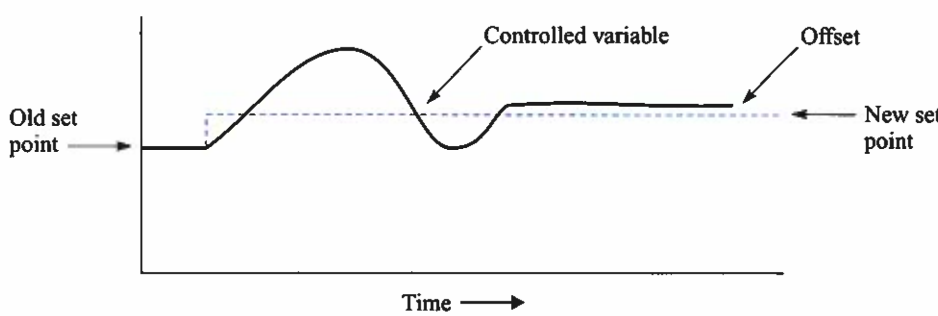


FIGURE 12-8 Response curve when the PG is too low or the PB is too high

TABLE 12-2 Process Identification Procedure for PB Settings

Step 1	Place the controller in the manual mode.
Step 2	Adjust the set point to the value most often used.
Step 3	Turn the integral and the derivative mode adjustments to a setting that will produce a minimal effect on the controller.
Step 4	Set the proportional band at its highest value.
Step 5	Switch the controller from manual to automatic mode and introduce a small setpoint step change of 5 to 10 percent of the span. Return the set point to its original value as soon as the waveform is recorded.
Step 6	Watch the response of the process on the chart recorder. At a high proportional band setting gain, the process response curve will likely dampen out quickly as the oscillations stop and the process becomes stable, but with some offset, as shown in Figure 12-8. Return the set point to its original value.
Step 7	Slightly decrease the proportional band setting and make another step change. Continue repeating this procedure until the process cycles and produces the waveform on the chart recorder that is shown in Figure 12-7. Return the set point to its original value each time before repeating.
Step 8	Determine and record the time duration of one cycle that is displayed on the horizontal axis of the chart recorder shown in Figure 12-7. One cycle is referred to as an *ultimate period.* If the process is fast, such as flow, the ultimate period is typically read in seconds. If the process is slow, such as temperature, the ultimate period is typically read in minutes.
Step 9	Record the proportional band setting that causes the sustained oscillations. This value is called the *ultimate proportional band,* or PB_u. The PB_u value is used to mathematically find the appropriate setting for tuning the proportional mode.

gain setting, and for a controller that uses PB settings. Integral calculations will be shown two ways: for a controller with a reset time (RT) setting, and for a controller that uses reset rate (RR) settings.

Calculations for a Proportional-Only Controller

The following calculations are made to obtain the proper proportional setting.

Proportional Gain Calculate the proper setting for proportional gain by using the following Ziegler-Nichols formula:

$$K_c = G_u \times 0.5$$

where,

K_c = Proper Proportional Gain Setting and

G_u = Ultimate Proportional Gain Value

Proportional Band Calculate the proper setting for proportional band using the following formula:

$$PB = PB_u \times 2$$

where,

PB = Proper Proportional Band Setting and

PB_u = Ultimate Proportional Band Value

Verifying the Calculated Settings

The calculated value indicates the adjustment at which the proportional setting should be made. To verify that the correct value is used, introduce a step change that is 5 to 10 percent

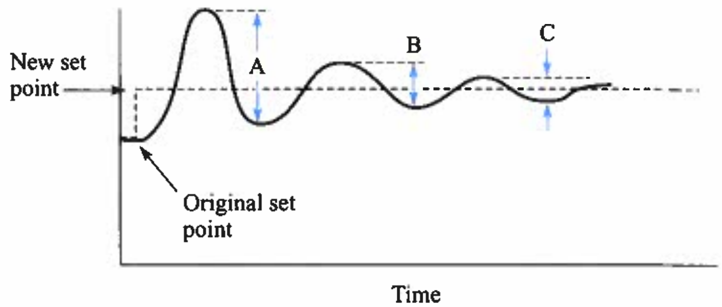


FIGURE 12-9 ¼ decay ratio

of the span and observe the waveform on the chart recorder. The reaction curve should show a decay ratio of ¼, as illustrated in Figure 12-9. The decay ratio indicates the size of any given peak is ¼ the size of the previous peak. The ¼ decay ratio is used by the Ziegler-Nichols tuning methods as a guideline for good control because it represents a compromise between the size of the initial deviation from the setpoint and a quick return to the setpoint.

If the curve dampens out too quickly, the proportional gain should be increased slightly or the proportional band should be decreased slightly. If the curve has too much oscillation, the proportional gain should be decreased slightly or the proportional band increased slightly. When the oscillations stop, it is likely that a slight offset will be observed on the waveform.

Calculations for a Proportional-Integral Controller

The proportional-integral controller is also commonly referred to as a two-mode controller. To determine the proper settings from mathematical calculations for a two-mode controller, the *Ultimate Period* (P_u) and *Ultimate Proportional Gain Value* (G_u) or *Ultimate Proportional Band Value* (PB_u) are used in the formula.

Determining the Proportional Setting Since the proportional and integral actions of a two-mode controller interact, the settings for proportional gain (or proportional band) will be slightly different from the setting on a proportional-only controller. Therefore, the formulas to determine the proportional setting for the proportional-only and the two-mode controller are also different.

Proportional Gain

$$K_c = 0.45 \times G_u$$

where,

K_c = Proper Proportional Gain Setting and
G_u = Ultimate Proportional Gain Value

Proportional Band

$$PB = 2.2 \times PB_u$$

where,

PB = Proper Proportional Band Setting and
PB_u = Ultimate Proportional Band Value

Determining the Integral Setting The calculation to determine the proper integral setting is listed two ways, one for a controller with an RT adjustment, and the other for a controller that has an RR adjustment.

Reset Time

$$T_i = \frac{P_u}{1.2}$$

where,

T_i = Proper Reset Time and
P_u = Ultimate Period

Reset Rate

$$T_r = \frac{1.2}{P_u}$$

where,

T_r = Proper Reset Rate and
P_u = Ultimate Period

Verifying the Calculated Settings

The calculated values indicate the adjustment at which the proportional and integral settings should be made. To verify that the correct values are used, introduce a 5 to 10 percent step change and observe the waveform on the chart recorder. The reaction curve should show a 1/4 decay ratio without offset. Slight readjustments of the proportional setting may be necessary to fine-tune the controller to produce the 1/4 decay ratio.

Calculations for a Proportional-Integral-Derivative Controller

The proportional-integral-derivative (PID) controller is also referred to as a three-mode controller. To determine the proper settings from mathematical calculations for a three-mode controller, the ultimate period and ultimate proportional gain (or ultimate proportional band) are used in the formula.

Determining the Proportional Setting Since the proportional, integral, and derivative actions of a three-mode controller interact, the proportional and integral settings will be slightly different from the settings on a two-mode controller. Therefore, the formulas used to determine the values of a three-mode controller are different from the formulas used for a two-mode controller.

Proportional Gain

$$K_c = 0.6 \times G_u$$

where,

K_c = Proper Proportional Gain Setting and
G_u = Ultimate Proportional Gain Value

Proportional Band

$$PB = 1.7 \times PB_u$$

where,

PB = Proper Proportional Band Setting and
PB_u = Ultimate Proportional Band Value

Determining the Integral Setting

Reset Time

$$T_i = \frac{P_u}{2}$$

where,

T_i = Proper Reset Time and
P_u = Ultimate Period

Reset Rate

$$T_r = \frac{2}{P_u}$$

where,

T_r = Proper Reset Rate and
P_u = Ultimate Period

Determining the Derivative Setting The following calculation is made to obtain the proper setting for derivative time (DT):

Derivative Time

$$T_d = \frac{P_u}{8}$$

where,

T_d = Proper Derivative Time and
P_u = Ultimate Period

Verifying the Calculated Settings

The calculated values indicate the adjustments at which the proportional, integral, and derivative settings should be made. The proportional adjustment should be made first, the integral adjustment second, and the derivative adjustment last. To verify that the correct values are used, introduce a 5 to 10 percent step change and observe the waveform on a chart recorder. The reaction curve in Figure 12-10 shows no offset and a 1/4 decay ratio with a shorter time duration and less amplitude during each peak of the oscillations than when a proportional-only test is performed. If the process overshoots too much when it reaches the new setpoint, the derivative time should be increased slightly. If the process is too slow in returning to the setpoint, the derivative time should be decreased slightly.

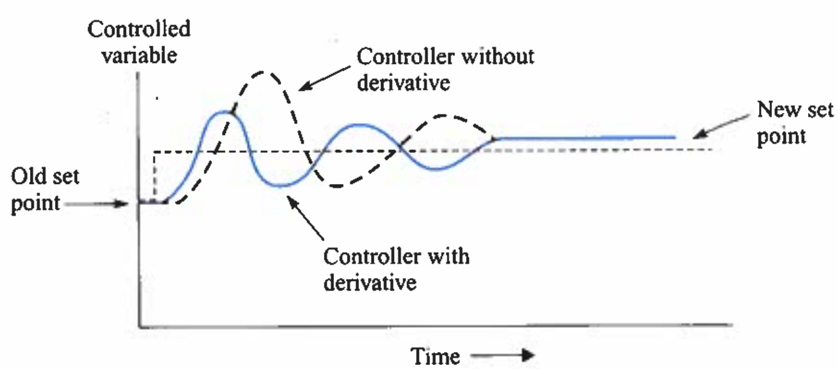


FIGURE 12-10 Reaction curve observation to determine proper control mode settings

For convenience, the Ziegler-Nichols formulas are summarized in Table 12-3.

TABLE 12-3 Ziegler-Nichols Continuous Cycling Formulas

Controller Mode	Proportional Gain K_c	Proportional Band PB	Reset Time T_i (Minutes per Repeat)	Reset Rate T_r (Repeats per Minute)	Derivative Time T_d
P	0.5 G_u	2 PB_u	N/A	N/A	N/A
PI	0.45 G_u	2.2 PB_u	P_u/1.2	1.2/P_u	N/A
PID	0.6 G_u	1.7 PB_u	0.5 P_u	2/P_u	P_u/8

EXAMPLE 12-1

Continuous Cycling Method

The example shows a slow acting temperature process. The process identification steps determine that the ultimate proportional gain value (G_u) is 2 when the process oscillates, as shown in Figure 12-11. The ultimate period (P_u) of the waveform is 10 minutes.

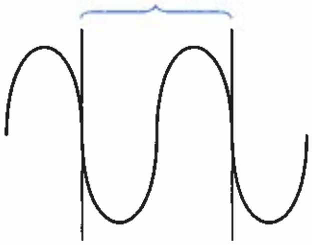


FIGURE 12-11 Determining the ultimate period

$$G_u = 2$$

Using the continuous cycling method with a PID controller that has a proportional gain, reset time, and derivative time adjustments, determine the proper settings for each mode.

Solution

Proportional-Only Control

$$K_c = 0.5 \times G_u = 0.5 \times 2 = 1$$

Proportional-Integral

$$K_c = 0.45 \times G_u = 0.45 \times 2 = 0.9$$

$$T_i = \frac{P_u}{1.2} = \frac{10 \text{ min.}}{1.2} = 8.3 \text{ minutes per repeat}$$

Proportional-Integral-Derivative

$$K_c = 0.6 \times G_u = 0.6 \times 2 = 1.2$$

$$T_i = \frac{P_u}{2} = \frac{10 \text{ min.}}{2} = 5 \text{ minutes per repeat}$$

$$T_d = \frac{P_u}{8} = \frac{10 \text{ min.}}{8} = 1.25 \text{ minutes}$$

Ziegler-Nichols Reaction Curve Tuning Method

The main drawback of the continuous cycle tuning method is that the process is made to oscillate. This condition can be undesirable in some situations. Each time the cycle peaks, the process may go outside an acceptable tolerance range from the setpoint and cause, for example, a food product to be ruined. Cycling should also be avoided if it creates a safety hazard, such as too much pressure in a boiler or an excessive temperature in a nuclear power plant.

To avoid an oscillating condition, another version of Ziegler-Nichols tuning called the *Reaction Curve Tuning Method* is used. This method involves doing a step change to the controller output and then observing the rate at which the process reacts on a chart recorder. The graph in Figure 12-12 shows the actuator output that represents the step change and the signal from a sensor which illustrates the reaction curve of the process.

The graph provides three different values that are used in mathematical calculations to determine the proper controller settings:

1. The **effective delay** (D), which is the time that expires from when the step change is made until the process variable begins to react. This delay is caused by the process lag, dead time, or both.
2. The **process reaction rate,** which is defined as how much the process changes per unit of time. This value is obtained by calculating the slope of the process reaction curve. A curve with a steep slope indicates a faster reaction rate than a curve with a gradual slope.
3. The **unit reaction rate,** which is a measure of how much the process reacts for each percent of actuator change. To determine this value, the size of the step change must be taken from the graph. The size is read as a percentage of the actuator's span. The step change information is used because its size affects how quickly the process reacts.

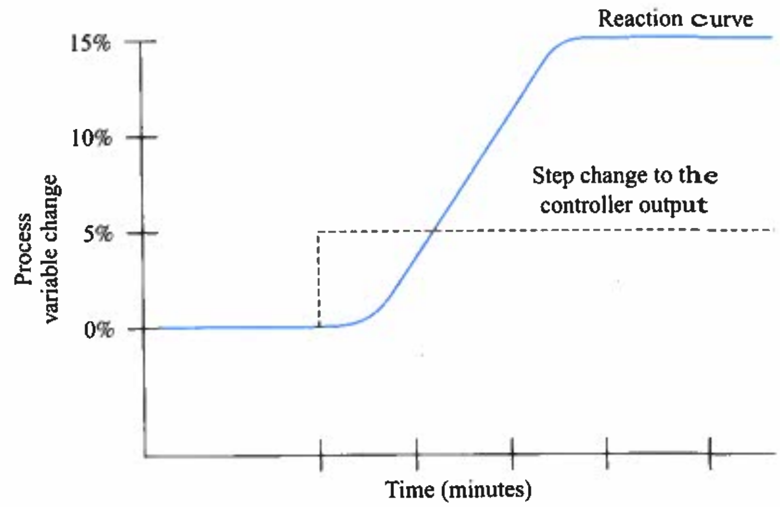


FIGURE 12-12 A process reaction curve produced by a step change

The reaction curve tuning method performs an open-loop step change with the controller in the manual mode to obtain process identification information.

Process Identification Procedure for the Reaction Curve Method

Before making calculations to determine proper controller settings, perform the following steps:

Step 1: Put the controller in the manual mode.

Step 2: Produce a step change by changing the controller output 5 to 10 percent and observe the rate at which the process responds on the chart recorder.

Step 3: Find the maximum slope of the reaction curve and draw a tangent line at this point, as shown in Figure 12-13(a).

Step 4: Calculate the slope of the tangent by drawing two lines on the graph. Line A is a horizontal line that begins at the starting point on the tangent, as shown in

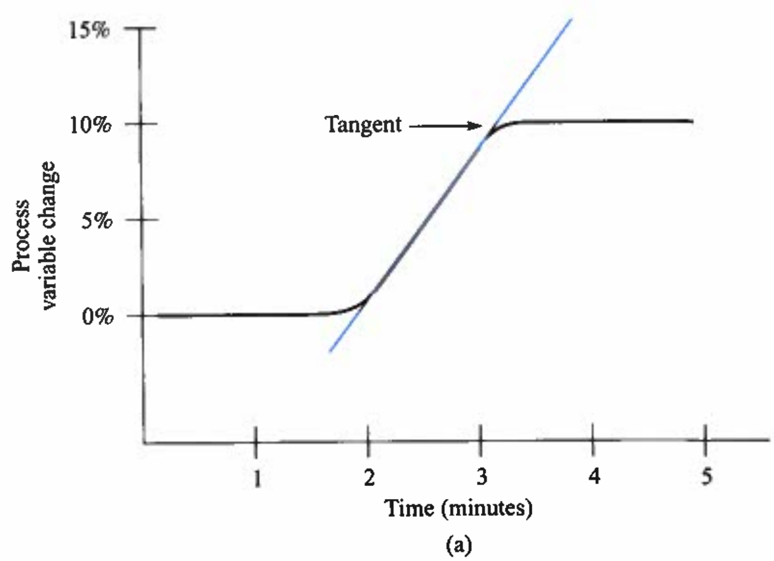


FIGURE 12-13 Reaction curve tuning method

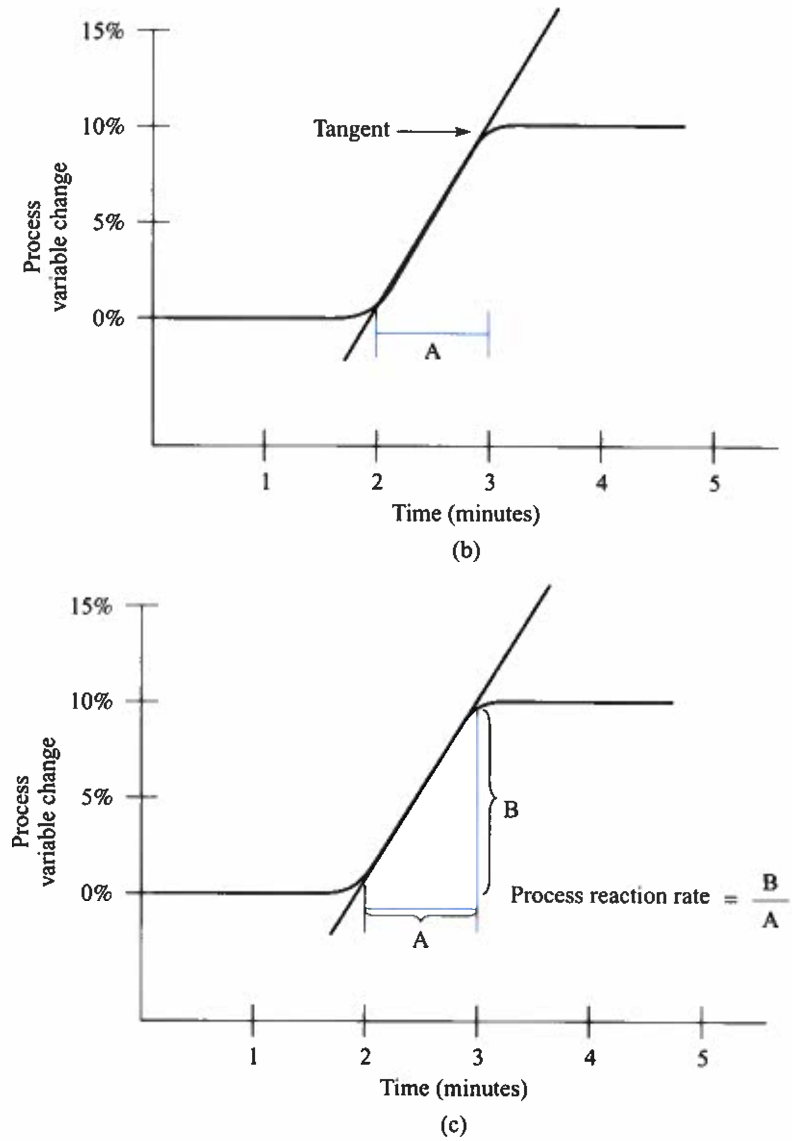


FIGURE 12-13 *(continued)*

Figure 12-13(b). Line B is drawn vertically in an upward direction from line A to the end of the tangent, as shown in Figure 12-13(c).

Step 5: Determine the process reaction rate, which is indicated by the slope of the tangent, by using the formula,

$$R = \frac{B}{A}$$

where,

R = Process reaction rate
A = Time in minutes
B = Percentage of the process variable change

Figure 12-14 shows the value of B is 10 percent and the value of A is 1 minute. Therefore,

$$R = \frac{10\%}{1} = 10\%$$

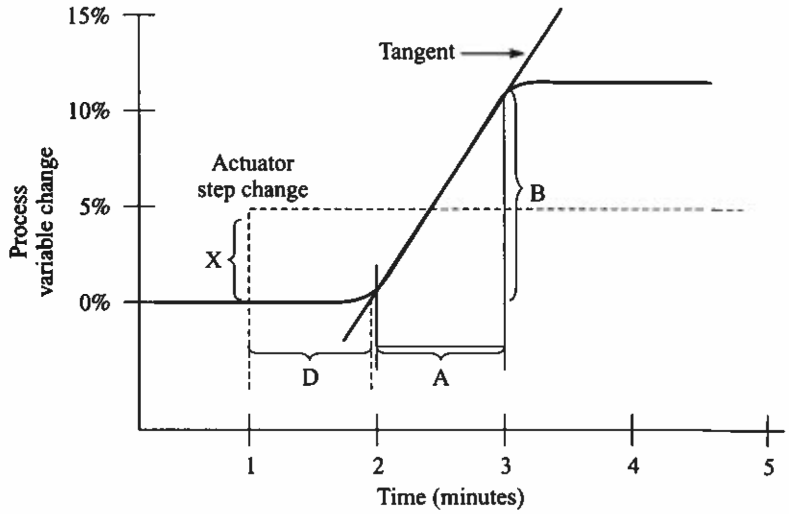


FIGURE 12-14 Values on a graph that are used to calculate controller settings

Step 6: Calculate the unit reaction rate (R_1). Divide the reaction rate (R) by the percentage of the actuator change (X).

$$R_1 = \frac{R}{X}$$

Figure 12-14 shows the actuator changes 5 percent. The reaction rate is determined by Step 5, Therefore,

$$R_1 = \frac{10\%}{5\%} = 2$$

Step 7: Determine the effective delay (D). This delay is shown on the graph as the time from which the step change is made to where the tangent line crosses the line of initial controlled variable status.

Figure 12-14 shows that D = 0.9 minute.

Calculating the Proper P, PI, and PID Controller Settings

Using the unit reaction rate and effective delay values by the formulas listed in Table 12-4, the proper settings for a P, PI, and PID controller can be determined. The proper settings are verified by doing a step change and observing a 1/4 decay ratio reaction curve on a chart recorder.

TABLE 12-4 Ziegler-Nichols Reaction Curve Formulas

Controller Mode	Proportional Gain K_c	Proportional Band PB	Reset Time T_i (Minutes per Repeat)	Reset Rate T_r (Repeats per Minute)	Derivative Time T_d
P	$K_c = 1/R_1D$	$PB = 100R_1D$	N/A	N/A	N/A
PI	$K_c = 0.9/R_1D$	$PB = 110R_1D$	3.33D	0.3/D	N/A
PID	$K_c = 1.2/R_1D$	$PB = 83R_1D$	2D	0.5/D	0.5D

EXAMPLE 12-2

Reaction Curve Method

The values on the graph in Figure 12-15 are:

- Effective Delay (D) is 1.5 minutes
- Step Change is 10% of the actuator span
- Process Reaction is 27% each minute

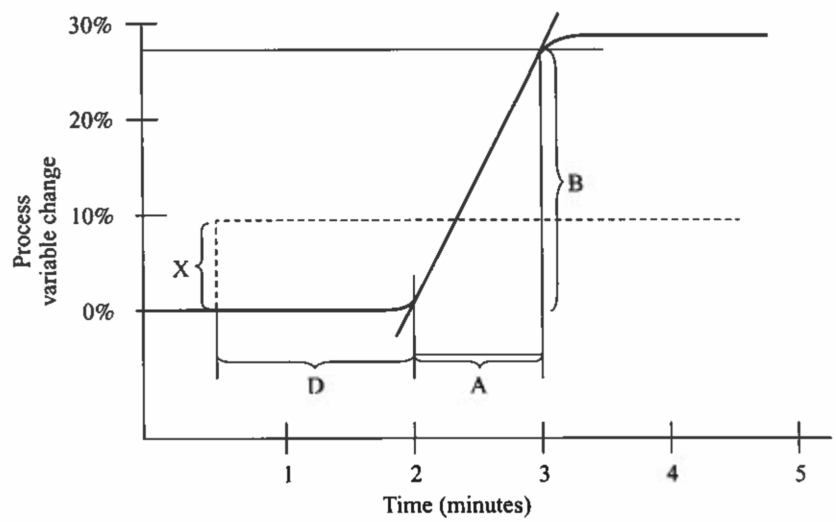


FIGURE 12-15 Reaction curve for Example 12-2

Use Table 12-4 to determine the proper settings for a PID controller with proportional band, reset time, and derivative time adjustments.

Solution

Step 1: Determine the slope of the tangent to find the process reaction rate.

$$R = \frac{B}{A} = \frac{27\%}{1\,\text{min.}} = 27\%$$

Step 2: Determine the unit reaction rate (R_1).

$$R_1 = \frac{R}{X} = \frac{27\%}{10\%} = 2.7$$

Calculate the proportional band setting.

$$PB = 83R_1D = 83 \times 2.7 \times 1.5 = 336.15$$

Calculate the integral setting.

$$T_i = 2 \times D = 2 \times 1.5 = 3 \text{ minutes per repeat}$$

Calculate the derivative setting.

$$T_d = 0.5D = 0.5 \times 1.5 = .75 \text{ minutes}$$

Controller Autotuning

Modern microprocessor-based controllers are designed to calculate the appropriate mode settings automatically. When the autotuning function is activated, it causes the process to cycle. By measuring the time duration of a cycle, it either adjusts the settings automatically for each mode or displays the recommended values for the operator to enter.

Problems

1. What is the purpose of instrument calibration?
2. During the ____ check, test points should be approached from below.
   a. upscale
   b. down scale
   c. either a or b
3. It is unlikely a ____ error can be detected using the three-point calibration check.
   a. span
   b. linearity
   c. zero shift
   d. all of the above
4. After an instrument adjustment is made, another ____ should be performed to verify the procedure.
   a. inspection
   b. calibration cycle
   c. adjustment
5. The simulation of an input signal applied to a transmitter can be obtained from ____.
   a. a process calibrator
   b. from the actual sensor being manually adjusted
   c. either a or b
6. The lowest condition of a process variable is usually represented by ____ mA produced at the transmitters output.
   a. 0
   b. 4
   c. 12
   d. 20
7. If zero shift and span errors are detected during a series of calibration cycles, the ____ is usually corrected first.
   a. span error
   b. zero shift
8. The ____ adjustment is made to the transmitter so that it accurately represents the highest value of a process.
   a. zero
   b. span
9. When the process being measured is at 90 percent of its range, the signal produced by a transmitter that has a 4–20 mA output is ____ mA.
   a. 4
   b. 14.4
   c. 18.4
   d. 20
10. T/F The first step in performing mathematically-based tuning methods is to obtain *process identification* information from a chart recorder graph.
11. The term *ultimate gain* (or *ultimate proportional band*) refers to the controller adjustment that ____.
    a. causes the process to continuously cycle
    b. is the proportional setting when the controller is tuned
12. Determine the proper settings for a two-mode controller using the Ziegler-Nichols continuous cycling method and Table 12-3.
    Given: Ultimate Proportional Band = 3
    Ultimate Period = 2 minutes
    Proportional Setting ________
    Integral Setting (Reset Rate) ________
13. If a process reaction curve produced when the controller is tuned does not display a proper ¼ decay ratio because it dampens out too quickly, the proportional gain is set too ____.
    a. low
    b. high
14. The process identification information for the Ziegler-Nichols reaction curve method is observed on a chart recorder with the controller in the ____ mode, and the ¼ decay ratio is observed when the controller is in the ____ mode.
    a. manual
    b. automatic
15. T/F The *process reaction rate* value is obtained from the slope of the *process reaction curve*.
16. Using Table 12-4, determine the proper proportional, integral, and derivative controller settings by using the Ziegler-Nichols reaction curve method, which provides the following process identification information on a graph:
    Effective Delay (D): 0.5 minutes
    Step Change (X): 8%
    Slope of the Reaction Curve: 12%
    Process Reaction Rate = ________
    Unit Reaction Rate = ________
    Proportional Gain Setting = ________
    Integral Setting (Reset Time) = ________
    Derivative Time Setting = ________

Answers to Odd-Numbered Problems

Section 1

CHAPTER 1

1. motion, process or open-loop, closed-loop
3. negative
5. *Motion Control* — *Process Control*
   Hall-effect speed sensor — Float
7. c. feedback loop
9. feedback signal
11. error, error
13. b. manipulated;
    a. controlled
15. d. control signal
17. d. All of the above.
19. True
21. True
23. b. feed-forward

CHAPTER 2

1. $R_F/R_{IN} = 5\text{ K}/1\text{ K} = 5$
3. +2.4 volts
5. squarewave
7. a. < b. = c. >
9. It determines if one binary number is greater than, less than, or equal to the other binary number.
11. reverse
13. $2^5 = 32,\ 32 - 1 = 31$ $\quad 15\text{ V}/31 = .4838\text{ V}$
15. $2^5 = 32,\ 32 - 1 = 31$ $\quad 10\text{ V}/31 = .3225\text{ V}$
17. 2.56
19. high
21. $$f = \frac{1.44}{(R_A + 2R_B)C}\ \frac{1.44}{120\text{ k}\Omega \times 10\text{ ufd}} = 1.2\text{ Hz}$$

Section 2

CHAPTER 3

1. Controller section
3. Process disturbances
   The controller cannot adjust the output to match the process demand.
5. $$\%\text{ Differential Gap} = \frac{\text{Differential Gap}}{\text{Total Control Range}} = \frac{8}{80} = .1 \times 100 = 10\%$$
7. $$PB = \frac{30}{60} = .5 \times 100 = 50\%$$
9. True
11. offset
13. True
15. 25
17. b. reset
19. c. both A and B
21. False
23. subtracts from
25. c. both A and B
27. Proportional: Inverting opting
    Integral: Integrator
    Derivative: Differentiator
29. a. on
31. c. 15 V

Section 3

CHAPTER 4

1. e. All of the above
3. b. decreased
5. Less
7. b. liquid(s), a. gas(es)
9. b. decrease
11. 6.28 (S.G.) × 0.433 = 2.72 for 1 ft.
    1 ft. (Pressure) 51.3 ÷ 2.72 = 18.86 ft.
13. b. decreases
15. a. compression
17. Atmospheric Pressure: Gauge
    Absolute zero (Vacuum): Absolute
19. 29.92
21. 3 × .491 = 1.473 psig
23. higher
25. Pins 2 and 4
27. Compressed air
29. Gravity

CHAPTER 5

1. thermal energy
3. a. conductance
5. Blast Furnace: Glass, steel, cement
   Fossil Fuel Furnace: Heat treating metals
   Arc Furnace: Heat treating
   Resistance Furnace: Burn-in chamber for ICs
   Induction Furnace: Melting iron in a foundry
7. b. absorbing heat from the contents
9. 5 × 10 = 50
11. C = 5/9 (74 − 32)
    = .555 (42)
    = 23.33 degrees C
13. Ceramic Kiln
15. decreased
17. cold

19. directly
21. $a = \frac{R_{100} - R_0}{100\,(R_0)} = \frac{69.25 - 50}{100\,(50)} = \frac{19.25}{5000} = .00385$
23. Over-current protection; motor starters
25. negative
27. Surge suppression
29. By a drilled hole because only emitted energy is radiated from the hole.
31. Several thermocouples connected in series.
33. Ratio pyrometer

CHAPTER 6

1. Cubic feet, gallons, liters
3. $F = \frac{WS}{L} = \frac{100\text{ lb} \times 100\text{ ft/min}}{5\text{ feet}} = 2000\text{ lb/min}$
5. Volume = 156.6 ft^3/min
   Mass = 9772 lb/min
7. decrease, decrease
9. R = 1693
11. $Q = K\sqrt{16} = 1.22\sqrt{16} = 1.22 \times 4 = 4.9$
13. is
15. is
17. 5 to 20
19. Pressure
21. c. both A and B
23. flow straightener

CHAPTER 7

1. Feet, meters
3. To determine if there is enough material to complete a job. Determine inventory. To prevent a container from underfilling.
5. a direct
7. b. a noninvasive
9. a. an invasive
11. decreases
13. At the bottom
15. c. both solids and liquids
17. b. noninvasive
19. b. decreases
21. $\text{Level} = \frac{40\text{ psi}}{0.43} = 93\text{ feet}$
23. $62.3 \times 3.2\text{ ft}^3 = 199.36$ lbs

CHAPTER 8

1. negative logarithm hydrogen
3. c. 7
5. b. positive
7. False
9. b. changing the dimensions of the plates
11. b. Carbon monoxide
13. False
15. b. dry
17. hygroscopic
19. b. relative humidity
21. False

CHAPTER 9

1. d. All of the above.
3. c. both A and B
5. c. both A and B
7. a. adding
9. b. kept constant
11. b. precision
13. b. transmitter
15. c. 15 psi
17. b. linearize a signal
19. True
21. c. control valve
23. d. Ball
25. b. air-to-open
27. $F = PA$
    $= 12\text{ psi} \times \pi \times r^2$
    $= 12 \times 3.14 \times 4$
    $= 150.7$

CHAPTER 10

1. e. None of the above
3. c. mounted at an auxiliary location
5. field
7. a. 1^{st}
9. a. Installed in the field
11. c. both a and b
13. c. both a and b
15. True
17. c. loop number
19. a. open
21. c. actuator
23. b. valve in a temperature loop
25. d. all of the above

CHAPTER 11

1. process; control
3. False
5. False
7. d. all of the above
9. True
11. c. both A and B
13. Furnace, refrigerator
15. b. decreases
17. c. both A and B
19. a. fully off
21. b. Excessive cycling will occur.
23. True
25. b. decrease
27. d. Derivative
29. a. braking
31. True
33. b. Cascade
35. b. outer
37. _X_ Feedforward control helps to prevent changes in the controlled variable before they occur.
39. c. ratio control

41. a. wild

43. a. Differential pressure flowmeter

    c. pH of a solution

CHAPTER 12

1. To ensure that the output accurately represents the signal applied to the input.

3. b. linearity

5. c. either a or b

7. b. zero shift

9. c. 18.4

11. a. causes the process to continuously cycle

13. a. low

15. True

Glossary

A

absolute humidity the mass of water vapor present in a particular volume of atmosphere.

absolute pressure 1. a pressure scale that uses absolute zero, which is the complete absence of pressure, as a reference. 2. the gas pressure above a perfect vacuum.

actuator an element of a control system that converts electrical, hydraulic, or pneumatic energy into work.

adaptive control a control technique that uses a combination of software programming and microelectronics to compensate for nonlinear situations.

alarm an instrument that produces a warning signal when an undesirable process condition develops.

amplitude proportional a method in which the output of the controller is proportional to the size of the error signal.

analog-to-digital converter (ADC, A/D) a device that converts an analog voltage applied to its input into a proportional digital output.

analytical measurement and control a procedure that monitors and regulates the composition of a chemical.

aqueous solution water that is mixed with another ingredient.

astable multivibrator a circuit that generates a continuous squarewave output.

B

batch process a sequence of timed operations executed on a product being manufactured.

C

calibration a procedure of making adjustments to a transmitter so that its output varies through its full range in proportion to the full range that the variable being measured changes.

capacitive probe sensor a sensor that uses a capacitive probe to detect the level of contents inside a tank.

cascade control a method that controls a process by monitoring both the controlled and the manipulated variable.

chemical reaction the process of combining two or more materials or reactants to form a product.

closed-loop a method of control in which feedback is used by a system to produce a controlled process dictated by a command signal.

combustion also known as burning, a chemical reaction that occurs when heat, gases, and fuel are combined.

comparator a device that produces various output signals by comparing the signals applied to its inputs.

compression 1. the process of storing additional gas into a confined container. 2. reducing the size of the confined container that holds a fixed quantity of gas.

conduction the process by which heat is transferred by a solid.

conductive probe sensor a sensor that uses a conductive probe to detect the level of a conductive liquid.

conductivity a process used to determine the purity of a liquid by measuring the amount of current that is able to flow through it.

continuous cycling method a controller tuning method in which a closed-loop response test is made with the controller on automatic.

continuous level measurement a method of locating the interface point within a range of all possible levels at all times.

continuous process one or more operations performed simultaneously as a product is produced during a manufacturing process.

controlled variable the actual process that is being controlled by an open- or closed-loop system, such as temperature or pressure.

controller an element that is considered the "brain" of a closed-loop system. An instrument in a closed-loop system that performs the decision-making function.

convection the transfer of heat through fluids such as liquids and gases.

Coriolis meter a U-shaped tube instrument that measures flow by determining at how much of an angle it is twisted as fluid passes through.

custody transfer measuring flow to determine how-much of a product is passed from the supplier to the customer.

D

damping the prevention of overshoot of the load past the end point in a motion control system or the desired state in a process control system.

deadband *See differential gap.*

dead time the elapsed time between the instant a deviation of the controlled variable occurs and the corrective action begins.

density 1. the weight of a certain volume of liquid. 2. the weight per unit volume of a fluid.

derivative control a control scheme whereby the controller produces an output that is proportional to the rate that the error signal changes. This function is also called rate control.

derivative mode *See derivative control.*

dew point the temperature at which the air (or gas) becomes saturated.

difference operational amplifier an amplifier that produces an output signal that is the algebraic difference between two input voltages.

differential gap the range above and below the setpoint reached by the controlled variable before the controller element turns an actuator on or off.

differential pressure 1. a difference in pressure between two measured points. 2. the difference in gas pressure between any two points in a system.

differential pressure flowmeter an instrument that measures flow rate by comparing two different pressures developed across a restrictor.

differential pressure level detector a device that detects the level of a material inside a confined container by measuring the difference between hydrostatic pressure and the pressure above the material.

differentiator an amplifier circuit that produces an output proportional to the rate of change of the input signal. It performs the derivative function.

digital-to-analog converter (DAC, D/A) a device that translates digital data into an analog voltage.

displacement the amount of material replaced by a sensor probe as it measures level.

dissociation compounds that break up into charged particles, called ions, when they are combined with water.

disturbance a factor that upsets the manufacturing process, causing a change in the controlled variable.

duty cycle the ratio of time a squarewave signal is high to the total time period of one cycle.

dynamic 1. the state in which the controlled variable is moving or changing. 2. the characteristic of an instrument while it is changing.

dynamic response the time a closed-loop system takes to perform a corrective action.

E

effective delay the time that expires from when a change is made until the process begins to react.

effluent a treated solution that flows out of the tank in a pH batch process system.

electromagnetic flow detector a transducer that converts volumetric flow rate of a conductance substance into voltage.

endothermic processes that require a source of heat while forming a product.

error detector (comparator) 1. the element of a closed-loop control system that produces an error signal by comparing the setpoint to the feedback signal. 2. a device that produces various output signals by comparing the signals applied to its inputs.

error signal the difference between the desired response and the actual response.

exothermic a process where heat is generated during the reaction phase.

F

feedback signal the signal or data fed to the comparator of a closed-loop system from an actuator or processor to indicate the response to the command signal.

feed-forward the process of providing information to the controller element device, which indicates that a change is going to occur.

feed-forward control *See feed-forward.*

final control element also referred to as an actuator, a device that directly influences the process variable.

float a spherical element that rides on the surface of the material it is measuring to determine its level.

flow the transfer of material from one location to another.

flow rate the measurement of flow that is determined by how fast a material is moving past a given point.

fluid a liquid or gas commonly used in a process control system.

G

gauge pressure 1. a pressure scale that uses atmospheric pressure as the reference point. 2. the gas pressure above or below atmospheric pressure.

gain the ratio of change in output to the change in input.

H

head a term commonly used to describe the height of a liquid above the measurement point.

humidity the amount of moisture present in air.

hydrocarbon fuel a material that will burn when combined with fuel and heat.

hydrostatic pressure exerted equally in all directions at points within a confined fluid.

hydrostatic head level detector a sensor that determines level by measuring the weight of the contents in the container.

hydrostatic pressure the resultant pressure obtained from multiplying the height times the density of a liquid.

hygroscopic the ability of a material to absorb moisture.

hysteresis the characteristic evidenced when a target causes a sensor to turn on at one distance and off at another distance. *Also see process lag time.*

I

indicator an instrument used to display information about a process.

industrial controls the automated equipment that monitors and controls the operation of a manufacturing process.

inferred a procedure whereby some other variable is measured and then translated into the reading that is required.

inferred measurement a condition wherein one type of measurement is taken to find the value of another type of measurement.

influent an untreated solution that enters the tank through an inlet port in a pH batch process system.

instrumentation a term commonly used to describe process control; it refers to the instruments that control and monitor the condition of the process.

integral control a control scheme whereby the controller produces an output that is proportional to the length of time an input signal has been applied. This function is also called reset control.

integrator an amplifier circuit that continuously increases gain over a period of time. It performs the integral function.

interface 1. the boundary between two media, such as water and air. 2. the connecting together of two different circuits.

L

level the height at which a material fills a container.

linear variable differential transformer (LVDT) a type of linear-motion position sensor that uses transformer action to produce a signal that is proportional to distance.

load 1. the type of device or equipment to which the sensor output signal is applied. 2. the demand on an actuator by the device to which power is delivered.

lobed impeller flowmeter a rotating device with lobed impellers that measures volumetric flow rate of fluid that passes through it by multiplying displacement times the RPM.

loop gain the ratio of output speed to the following error.

M

magnitude comparator a logic circuit that compares two binary numbers and produces an output signal that indicates either which one is greater or if they are equal.

manipulated variable the fuel or energy that is physically altered by the actuator to change the condition of the controlled variable.

manufacturing process the operation performed by an actuator to control a physical variable, such as motion or a process.

mass flow measurement a method used to measure flow by reading the actual weight of a fluid during a given period of time.

mass flow rate the measurement of flow that is determined by the weight of materials that move during a specific time period.

measured variable the condition of the controlled variable, usually detected by a sensor.

measurement device an element in a closed-loop control system that detects a controlled variable and produces an output signal, which represents its status. Other terms used are detector, transducer, and sensor.

mixing/blending an operation that involves combining two or more ingredients together.

monostable multivibrator a circuit that produces a temporary logic level voltage after an activating signal is applied to its input. Also known as a one-shot.

motion control an industrial control system that controls the physical motion or position of an object.

N

negative temperature coefficient the characteristic of a sensor in which its resistance decreases when the ambient temperature to which it is exposed increases.

O

offset the error that remains between the setpoint and the desired output condition after the controller element has caused a transient response. *See steady-state error.*

on-off control the most basic type of control system in which the actuator is either fully on or fully off.

open-loop a method of control where there is no feedback to initiate self-correcting action for the error of the desired operational conditions.

operational amplifier an integrated circuit that performs several types of linear circuit operations.

overdamped a system that is sluggish and responds to a changed command signal by causing the controlled variable to reach its end position or desired state very slowly and without overshoot.

P

paddle wheel detector a paddle that detects when the material it is measuring reaches a specified level by stopping it from turning as contact is made.

pH control the analytical process in which acid and alkaline levels are controlled.

PID a controller that uses proportional, integral, and derivative control in one unit.

pipe size the diameter of a pipe that carries fluid.

piping and instrumentation diagram (P&ID) a standard drawing format used in all types of process control fields.

point level measurement a measuring method that detects if the interface is at a predetermined level.

polymerization process in which a large number of molecules are combined to form a product.

positive temperature coefficient (PTC) the characteristic of a sensor in which its resistance increases when the ambient temperature to which it is exposed increases.

precision the degree of consistency with which a sensor responds to the same repeated input value.

pressure the force exerted over a surface area.

process control an industrial control system that regulates one or more variables during the manufacturing of a product.

process lag time the response lag time of a control system to a setpoint change or a disturbance.

process reaction rate a measure of how much the process changes per unit of time after a step change is made.

process stream the flow of either a gas or liquid in analytical process control applications.

proportional band the range at which a controller produces an output signal proportional to the error signal applied to its input.

proportional control a control scheme whereby the controller produces a signal that is proportional to the error signal.

proportional gain the ratio of change in output to the change in input.

pure lag the opposition of a controlled variable being changed due to the material from which it is made.

pyrometer an instrument that measures temperature by detecting the amount of thermal energy radiated from the surface of the measured body.

R

radiation the transfer of thermal energy through a vacuum.

rate a control scheme whereby the controller produces an output that is proportional to the rate that the error signal changes. This function is also called derivative control.

rate time an adjustment made to a controller for the derivative mode.

ratio control a method of controlling one variable based on the measured condition of another variable.

reaction curve method a controller tuning method in which a closed-loop response test is made with the controller in the manual setting.

reagent the corrective ingredient of an acid or a base that is added to bring the pH to the desired level.

recorder a data acquisition instrument that stores information about a process.

relative humidity the actual amount of water vapor present as compared to the maximum amount of water vapor the air can hold at a given temperature.

repeatability the range in which the output position of the servosystem will come to rest whenever a given input command signal is repeated.

reset a control scheme whereby the controller produces an output that is proportional to the length of time an input signal has been applied. This function is also known as integral control.

resistance temperature detector (RTD) a thermal sensing device made of two metals that increases in resistance when the temperature to which it is exposed increases.

resolution 1. the number of equal divisions into which a digital-to-analog converter divides the reference voltage.

response time the amount of time a sensor takes to respond to a change in the measured variable.

Reynolds number (R number) a numerical scheme that assigns values to express fluidity of a moving fluid. It represents the ratio of the liquid's inertial force to its drag (viscous) forces.

rodgauge a dipstick inserted into the material being measured to determine level.

rotameter a flow measurement device that is based on the proportionality of the rise of a float in a tapered tube, arranged vertically, placed in the flow system.

rotary vane flowmeter a rotary device with spring-loaded vanes that measures volumetric flow rates of the fluid that passes through it by multiplying displacement times the RPM.

rotor flow detector an instrument that uses the rate at which a paddle turns to determine flow rate.

S

Schmitt trigger a device that converts sine waves or arbitrary waveforms into crisp square-shaped signals.

sensitivity the ratio of a sensor's output change to a change of its input quantity that represents a measurement.

separation an operation that involves removing an ingredient from a mixture.

servomechanism a closed-loop motion device that automatically controls velocity and position.

setpoint the input applied to the elements of a control system that represents the desired value of the controlled variable.

sight glass a transparent tube connected to the side of a vessel to measure level.

signal processors special devices that change or modify signals applied to their inputs.

specific gravity the relative weight of any liquid when compared to water at a 60 degrees Fahrenheit temperature.

stable a closed-loop system that is under control and does not oscillate around setpoint.

static 1. a state in which the controlled variable does not move or change appreciably within an arbitrary time interval. 2. the condition of an instrument, which has stabilized after changing.

static head the force developed at the bottom of a tank that results from the weight of fluid placed above it.

steady-state error the error that remains between the setpoint and the desired output condition after a transient response by the controller element is completed. Also known as offset.

step change an abrupt setpoint change.

T

thermal energy molecular movement that creates heat.

thermal flowmeter a detector that measures the flow rate of liquids by using the principle of thermal conductivity.

thermistor a temperature sensor that exhibits a large change in resistance when subjected to a small change in temperature.

thermocouple a temperature sensing device made of dissimilar metals that converts heat into a voltage.

thermowell a protective device that encloses a temperature sensor.

time lag the time duration from when a change is received at the input of an instrument to when it produces an output response.

time-of-flight flowmeter a liquid-measuring device that uses ultrasonic waves to determine flow rate.

time proportioning a method in which the output of the controller is continually switched fully on and fully off.

transducer an instrument that converts one type of signal into another.

transient response the response time of the actuator to sudden changes of speed or position signals.

transmitter an instrument that converts a signal from a sensor into a standardized signal in process systems.

trial-and-error method a method of tuning a controller by interpreting a step response on a chart recorder to determine proper control mode settings.

turbine flowmeter a rotating device with turbine blades that measure the velocity or total volume of fluid flow.

U

ultimate period the time duration of one cycle.

ultimate proportional value the proportional controller setting that causes a sustained cycling to occur.

ultrasonic flowmeter a liquid measuring device that operates on the principle of sound propagation to measure flow rate.

ultrasonic level sensor a sensor that uses sound waves to detect the height of the contents in a container.

unit reaction rate a measure of how much the process reacts for each percent of actuator change.

unstable a closed-loop system that is out of control and oscillates around setpoint.

V

vacuum the absence of a gas inside a container. Any reduction of pressure compared to atmospheric pressure is called a partial vacuum.

variable capacitor pressure detector a sensor that has a bellows that changes the position of a capacitor plate when air pressure causes it to expand or contract.

velocity the speed at which an object or a material moves.

velocity flowmeter an instrument that directly measures fluid flow to determine volumetric flow rate.

viscosity 1. the ability of a liquid to flow and take the shape of a container. 2. the ease with which a liquid flows.

volumetric flow rate the measurement of flow, which is determined by the volume of material that flows during a given time period.

vortex flowmeter an instrument that measures the pressure of vortices that form downstream from a blunt object to determine flow.

W

weight detector a device that uses an inferred method of determining level by measuring the weight of a material within a container.

A

Absolute humidity, 163–164
Absolute pressure
gauge, 78–79, 82
manometer, 83f
measurement scale, 78f
Absorption bands, 162f, 163f
Accuracy, 179–180, 180f
Acetone, 174f
Actuators, 9
symbols of, 207, 207f
time-proportioning control controlling, 65–66
valve, 195–197, 196f
Adaptive control, 239–241
ADC. *See* Analog-to-digital converters
ADC0804, 38f
Adiabatic expansion, 167
Advanced control techniques, 234–241
Air flow applications, 79
Air moisture content, 164f
Alarms, 190
Aluminum oxide sensor, 164–165, 165f
American National Standards Institute (ANSI), 110
Amplification, 55
Amplifiers
difference operational, 21–22, 22f, 22t, 24f, 59, 63
differentiator operational, 23, 62f
integrator operational, 22, 23, 23f, 61f
inverting summing, 20f, 20t
noninverting, 21
operational, 17–22, 18f, 19t, 23, 23f, 24f, 34f
proportional operational, 57
summing, 20
symbols of, 18f
Amplitude proportional method, 223–228
Analog output voltage, 32, 33f
Analog sensors, 146
Analog-to-digital converters (ADC), 34–38
ADC0804 as, 38f
SAR with, 35f
Analog-to-digital transducer, 186
Analytical control, 176
Analytical measurement and control, 149–152
Angle valves, 206
ANSI. *See* American National Standards Institute
Anticipatory (predictive) control, 64
Arc furnaces, 95–96, 96f
Archimedes principle, 140
Astable multivibrators, 39, 40–42
Atmospheric pressure, 75–76
elevations influencing, 76f
gauge pressure scale using, 77–78
vacuum systems and, 89–90
Atomic structure, 28f
Augers, 137
Automated systems, 69–70
Automation, 178–179
Automobile, 11–12
Autotuning controller, 265

B

Ball valve, 193f, 206
Barometer, 81f
Batch mixer, 221f
Batch processing, 4–5, 172–174
cookie machine using, 5f
quantity control in, 173
raw materials in, 176
types of, 174
Batch reactor, 172f
Batch systems, 154–155
Bellows gauge, 85, 85f
Bimetallic thermometers, 102, 102f
Binary weighted digital-to-analog converters, 31f
Blending process, 174
Block diagram
of closed-loop systems, 8f, 178f
of open-loop systems, 10f
Bottle filling, 90f
Bourbon tube gauge, 83–84, 83f
Bouyancy method, 139
Bridge network, 104f
Broadband pyrometer energy detector, 113
Bubble level detector, 141f
Bubbler, 141
Bump test, 253
Butterfly valve, 193, 206

C

Calibration, 183, 245
circuit, 247f
data analysis, 250
five point, 249–252
of instruments, 246
preparation, 247–248
procedures, 248–249
reasons for, 246–247
S-shaped curve in, 249f
verification, 251
of water level process, 248f
Capacitive probes, 144–145, 145f
Capacitor, 44
Capacity, 194
Carbon monoxide/dioxide absorption bands, 162f
Cascade control system, 235–237, 236f
Case study
of on-off controller, 221–222
of proportional control, 227–228
of proportional-integral control, 231
of proportional-integral-derivative control, 233–234
Celsius scale, 98–99
Central heating system, 11
Characteristic curves, 194f
Chart recorder, 222f
Chemical reaction process, 174
Circuits, 45f, 247f
Closed-loop control systems, 214–216
Closed-loop feedback system, 245–246
Closed-loop flow process system (symbols), 203f

Closed-loop systems, 6, 7–8
in automobiles, 11–12
block diagram of, 8f, 178f
controller's in, 49
difference operational amplifier used in, 21–22
dynamic response in, 13
elements of, 8–10
feedback device in, 7f
feedback signal in, 10
feedback system with, 12
integrators/differentiators in, 23
negative feedback in, 11
pressure used in, 74
proportional control mode in, 59
temperature control system using, 12f
voltages in, 27
Closed-loop temperature process control system, 215f
Closed water systems, 158–159
Cold junction compensating network, 108f
Cold junction compensators, 110
Combustible gases, 160–161
Combustion, 160
analyzers/control, 160–163
controlling, 162–163
furnace, 95
gases ignited in, 161–162
Common dimensional ranges, 186t
Comparator, 18f, 19t
Comparator devices, 26–27
Comparison readings, 78f
Compression, 76–77, 77f
Computer command, 58f
Computer display, 188
Conductive probes, 144, 144f
Conductivity, 94f, 156–157
electrode probe, 157–158, 157f
inductive probe, 158, 159f
values, 159t
Continuous control, 223–234
Continuous cycling method, 255–256, 260
Continuous level measurement, 138
Continuous processes, 5, 175–177
heat exchange in, 177f, 227f
quantity control in, 175
temperature in, 175
Continuous systems, 155, 156f
Controlled flow, 239
Controlled variable, 8, 215, 229, 231
derivative mode with, 64
factors changing, 12–13
pure lag of, 217–218, 217f
Controller, 9, 186–189
amplification, 55
autotuning, 265
in closed-loop system, 49
on-off, 50–53
proportional-only calculations of, 256
representation of, 50f
selecting, 219
setting values for, 263–264, 263f
time proportional signals by, 223f
tuning of, 252–265
Control loop, 178
for heat exchange system, 208f
single-variable, 216–218
Control signals, 241f
Control systems, 87–92, 136–137
Control valve, 191–199, 214
Convection, 94, 95f
Converters, 35f, 38f
analog-to-digital, 34–38
binary weighted digital-to-analog, 31f
digital-to-analog, 31–34
integrated circuit of, 36
op amp in, 34f
Conveyer belt system, 120–121, 121f, 137
Cookie machine, 5f
Cooling systems, 96–97
Coriolis meters, 129, 129f
Crayons, 101
Crystalline solid indicators, 101f
Current (I), 184
Current signals, 183
Custody transfer, 119

D

DAC0808, 34
DACs. *See* Digital-to-analog converters
Dampers, 206
Data acquisition, 191
Data analysis, 250
DCS. *See* Distributed control systems
Deadband, 51
Dead space, 182
Dead time, 13, 218, 218f
Decision-making function, 49
Deionizer, 159
Density, 75
Derivative mode, 231–234
controlled variable lagging in, 64
error signal in, 61–62
Derivative time, 259
Dew point, 164, 167–168
Diaphragm gauge, 84–85
Difference operational amplifiers, 21–22, 22f, 22t, 24f, 59, 63
Differential gap, 51, 52f, 53f
Differential pressure flowmeter, 124–126, 124f
Differential pressure method, 142
Differential pressure scale, 79, 82
Differential pressure transducer, 142
Differential temperature, 99–100, 100f
Differentiator operational amplifier, 23, 62f
Digital input, 33f
Digital magnitude comparator, 26
Digital-to-analog converters (DACs), 31–34
analog output voltage of, 32
binary weighted, 31f
integrated circuit of, 34, 36
op amp in, 34f
Digital-to-analog transducer, 186
Directional control valve, 88
Displacement level sensor, 140–141, 140f, 141f
Displacement method, 140–141
Distributed control systems (DCS), 188–189
Disturbances, 10–13, 65
Diverting valves, 193
Divider networks, 39–40
Double-acting cylinder, 88
Double-seated valve, 192
Dry bulb, 165
Duty cycles, 41
square waves in, 65
time-proportioning circuit and, 67f
waveforms showing, 42f, 66f
Dynamic response, 13, 216

E

E. *See* Voltages
Effective delay, 260
8-bit strings, 28f
Electrical furnaces, 95
Electrolytes, 157
Electromagnetic flow detectors, 129–130, 130f
Electronic capacitance detector, 166, 166f
Electronic pressure sensors, 85–87
Electronic sensors
flowmeter, 129–133

for fluid levels, 144–148
for temperature measurement, 103–115
Elevations, 76f
Endothermic process, 173
Energy, 112f
England, industrial revolution, 3–4
Error signal, 9, 61–62
Example 5-1 solution, 109f
Exothermic process, 173

F

Fahrenheit scale, 98
Feedback
device, 7f
information, 139–148
loop, 236
loop interface instruments, 182–186
negative, 11, 11f
signal, 9, 10
system, 12
Feedback control, 10–12, 238f, 240f
development of, 11
feed-forward control loop with, 14f
Feed-forward control, 13–15, 14f, 237–238, 239f, 240f
Field of view, 115f
Filled-bulb thermometers, 102, 102f
Final control element, 191, 214
Fine-tuning, 252
555 Astable multivibrator, 40–42
555 IC astable timer, 39f
555 IC package, 39f
555 Monostable multivibrator, 42–44, 43f
Five point calibration, 249–252
Float-type level indicator, 139, 139f
Flow, 117
actuator, 207f
nozzle, 125
restrictors, 125f
solid, measurement, 120–121
straightener, 133f
velocity, 120
Flow control
measuring, 119–120
soft drink system concept of, 118f
system concepts of, 118–119
Flowmeters, 241t
electronic sensors in, 129–133
placement of, 133
selecting, 133–134
Fluid, 73–74
Fluid flow
currents in, 123f
measurement, 121–128
Reynolds number used in, 122–123
Fluid flowmeters
classifications of, 123
differential pressure in, 124f
Fluid levels
electronic sensors measuring, 144–148
measurements of, 138–144
Force balance positioner, 198, 198f
Fossil fuel, 160
Functional identifiers, 202, 204t
Functional symbols, 202f
Function table, 27f
Furnaces, 95–96

G

Gain, 55, 252
level control and, 224f, 225f
steady-state error and, 57f
Gas(es)
combustion ignited by, 161–162
container, 76–77
properties of, 76–77
rotameter measuring, 126f
temperature and, 76
Gauge pressure, 81
manometer, 82f
measurement scales, 78f
scale, 77–78
Glass
characteristics, 154f
thermometers, 102, 102f
Globe valves, 206
Graph recorder, paperless, 188

H

Head, 74
Head pressure, 81
Heat
blending process, 177f
conduction principle, 94f
convection principle, 95f
radiation principle, 95f
sensitive indicators, 101
treating, 95
Heat exchange, 177f, 227f
Heat exchange system, 99–100, 176f, 177f, 208f
Heating system, 54f
Height (liquid), 74
Home heating system, 50
Humidity, 163–169
as air moisture content, 164f
controlling, 168–169
hygrometric detector measuring, 165
measuring, 163–164
Humidity measurement applications, 168–169
Hydraulic systems, 87–88, 88f
Hydrocarbon (fossil) fuel, 160
Hydrocarbon gases, 161–162
Hydrogen ion, 151, 152
Hydrostatic pressure, 75, 75f
method, 142
Hygrometric detector, 165
Hygroscopic materials, 163
Hysteresis, 24, 181, 220
as lagging influence, 52
loop, 181f
in Schmitt trigger, 25f

I

I. *See* Current
IC. *See* Integrated circuit
I/E transducer, 185, 185f
Inches of water column, 79
Indicating devices, 100–101
Indicators, 189–190, 189–190f, 228f
Induction furnaces, 96
Industrial applications, 74
Industrial controls, 3–4, 4–8
Industrial furnaces, 95
Industrial revolution, 3–4
Inferred measurements, 80, 119
Influent, 154
Information block, 208–210, 209f
Infrared gas analyzer, 161–162
Input values, calculating, 250
Instrument(s)
calibration, 246
functional symbols of, 202f
loop interface feedback, 182–186
monitoring, 189–191
pressure measuring, 80
process connected to, 205f
process control diagram of, 201–202
response time of, 216
Instrumentation
in automated systems, 69–70
automation using, 178–179
piping, diagrams, 201
Integral control mode (reset), 59
Integral function, 229
Integral mode, 229–231
Integrated circuit (IC), 34, 36

Integrator operational amplifier, 22, 23f
  in closed-loop system, 23
  operation of, 61f
Interface, 137
Invasive devices, 137
Inverting op amps, 19–20, 19f, 20f
Inverting summing amplifiers, 20f, 20t
I/P transducer application, 184f
Irrigation system reservoir, 7f

J

Junction types, 108f

K

KCl. *See* Potassium chloride

L

Labels, 101
Lag (hysteresis), 52
Level, 135–136, 175
  control, 224f, 225f
  control system, 136–137
  determination system, 136f
  float-type indicator of, 139, 139f
  measurement methods, 138–148
  sensors, 140f, 147–148
Linear flow rate, 241t
Linearity, 180–181
Linear voltage differential transformer (LVDT), 121, 122f
Line symbols, 205–206
Liquid(s)
  column gauges, 80–81
  crystal indicator, 101
  heated vapor from, 75f
  measuring, 138–148
  properties of, 74–76
  rotameter measuring, 126f
  temperature influencing, 75
  thermometers filled with, 102
Load changes, 65
Lobed impeller flowmeters, 127–128, 127f
Loop identifier, 203
LVDT. *See* Linear voltage differential transformer

M

Magnetic float, 140f
Magnitude comparator
  of 8-bit strings, 28f
  diagram of, 26f
  digital, 26
  function table for, 27f
Manipulated variable, 9
Manipulation devices, 191–199
Manometer, 81
  absolute pressure, 83f
  gauge pressure, 82f
Manual chilled mirror, 167
Manufacturing process, 10
Mass flow
  measurement, 128–129
  rate, 120
Material list, 209, 210f
Material transfer, 117
Measured variable, 8
Measurement devices, 8–9
  feedback information from, 139–148
  with sensors, 179–182
Measurements, 69–70
  conductivity, 157–158
  control signals relationship with, 241f
  by electronic sensors, 103–115, 144–148
  fluid flow, 119–120, 121–128
  fluid level, 138–148
  humidity, 163–164
  of mass flow, 128–129
  methods of, 137–138
  of pressure, 75, 77–80
  sampling systems for, 169
  solid flow, 120–121
  of temperature, 97–100, 103–104
Mechanical gauges, 83–85, 84f
Mechanical machines, 76
Mechanical motion, 70
Mechanical position, 70
Metal combinations, 110
Metal heat treating, 95
Mixing/blending process, 174
Mixing valves, 193f
Monitoring instruments, 189–191
Monostable multivibrators, 38–39, 42–44, 43f
Motion controls, 4
Motors (AC/DC), 199

N

Negative feedback, 11, 11f
Negative temperature coefficient, 103
Noise, 24
Nonelectrical pressure sensors, 80–85
Noninvasive devices, 137
Noninverting amplifiers, 21, 21t
Nonlinear output
  linear flow rate compared to, 241t
  of sensors, 181f

O

Offset example, 229f
  1/4 decay ratio, 257f
On-off controller, 50–53, 51f, 219–222, 219f, 220f, 222f
Op amps. *See* Operational amplifiers
Open-loop control, 214
Open-loop systems, 5–7
  block diagram of, 10f
  elements of, 8–10
  irrigation system reservoir using, 7f
Operational amplifiers (Op amps), 17–22
  comparator, 18f
  in DACs, 34f
  difference, 24f
  differentiator, 23
  integrator, 22, 23f
  inverting, 19–20
  operation comparator of, 19t
  symbol of, 18f
  voltage comparator in, 18–19
  voltage gain determined in, 20
Optical chilled mirror hygrometer, 167–168, 167f
Optical pyrometer energy detector, 113f, 114
Optocoupler
  photodiodes in, 29f
  photo SCR in, 30f
  photo triac in, 30f
Optoelectronic interface devices, 27–31, 28f
Optoelectronic packaging, 30–31, 30f
Output
  actuators, 23
  buffer, 40
  calculating values of, 250
  signal, 186t
Overcurrent protection, 105f

P

P. *See* Pneumatic
Paddle wheel detector, 142
Paints, 101
Panel-mounted controllers, 187, 187f
PB. *See* Proportional band
PC. *See* Personal computers

PD. *See* Positive displacement methods
Pellets, 101
Personal computers (PC), 187
PG. *See* Proportional gain
pH
activity, 151t
continuous systems of, 155, 156f
controlling, 154
control system, 155f, 156f
hydrogen ion relationship with, 152
measurements, 152–154
reference electrode, 153f
sensing electrode, 152, 152f
sensor, electronic, 154f
temperature influencing, 152t
value, 151f
Photocoupler, 29f
Photodiodes, 29, 29f
Photoelectronic devices, 28f
Photo SCR, 29–30, 30f
Phototransistors, 29, 29f
Photo triac, 30, 30f
PID. *See* Proportional integral derivative circuits
P&ID diagram, 203f, 205
P&IDs. *See* Piping/instrumentation diagrams
Pipe flow principles, 122
Pipeline elbows, currents, 133f
Pipe system, 216f
Piping/instrumentation diagrams (P&IDs), 201
P/I transducer application, 185f
PLC. *See* Programmable logic controllers
Pneumatic (P), 184
Pneumatic activated diaphragm symbol, 207f
Pneumatic controllers, 186–187
Pneumatic signals, 183
Pneumatic systems, 89, 89f
Point level measurements, 138
Polarization, 158
Polymerization process, 174
Positioners, 197–198
Positive displacement methods (PD), 127, 128
Potassium chloride (KCl), 153
Pounds per square inch differential (PSID), 79
Precision, 180, 181f
Pressure, 73–74, 175
control systems, 87–92
higher/negative, 81
laws, 74
measurement instruments, 80
measurement scales, 77–80, 82
scale comparisons, 80f
temperature influencing, 75
Pressure flowmeter, differential, 124–126, 124f
Pressure sensors
electronic, 85–87
nonelectrical, 80–85
Primary feedback loop, 236
Probe assemblies, 111
Process
analyzer, 150
behavior, 215, 216f
identification, 253
instrument connected to, 205f
reaction rate, 260
stream, 149, 156
Process control, 4
final control element in, 191
instruments in, 201–202
in pulp paper operation, 6f
variable regulation in, 69
Process identification procedure
for continuous cycling method, 255–256
for proportional band, 256t
for proportional gain, 255t
for reaction curve method, 261–263
Product composition, 176
Programmable logic controllers (PLC), 188
Proportional band (PB), 55, 56, 225–226, 255f, 256–258, 256t
Proportional control, 53–59
case study of, 227–228
in heating system, 54f
indicators in, 228f
Proportional control mode, 59
Proportional gain (PG), 55, 56, 224–225, 255f, 255t, 256–258
Proportional-integral action, 229f
Proportional-integral control, 59–61
case study of, 231
system diagram of, 60f
Proportional-integral controller, 231f, 257–258
Proportional integral derivative circuits (PID), 62, 65
Proportional-integral-derivative control, 61–65, 233–234, 234f, 258–259
Proportional-integral-derivative mode control system, 63f
Proportional integral derivative mode summary, 234t
Proportional-integral-derivative robotic control system, 64f
Proportional mode control system, 58f, 59f, 223
Proportional-only controller, 256
Proportional op amp, 57
Proportional-plus-derivative action, 232f
Protective housing, 111f
PSID. *See* Pounds per square inch differential
Psychrometric chart, 166f
Psychrometric detector, 165
Pulp paper operation, 6f
Pulse Width Modulation (PWM), 65
Pure lag, 13, 217–218, 217f
Purge method, 141–142
PMW. *See* Pulse Width Modulation
Pyrometer energy detector
broadband, 113
energy transmitted with, 112f
field of view of, 115f
optical, 113f, 114
ratio, 114, 114f
simplified, 113f

Q

Quantity control, 173, 175

R

Radiation, 94, 95f
Radiation thermometry, 112–113
Rate time, derivative, 233
Ratio control, 238–239, 240f
Ratio pyrometer energy detector, 114, 114f
Raw materials, 175, 176
Reaction curve, 259f, 264f
method, 261–264
step change, 261–262f
tuning method, 261–262f
Reaction curve method, 261–263
Reaction cycle, 173
Reaction rate, 260
Reactor, 172
Reagent, 154, 155
Recorders, 190–191
Reference electrode, 153
Reference point, 70
Refrigeration systems, 96–97, 97f
Relative humidity (RH), 164, 165
Reservoir system, 11
Reset action, 230f
Reset rate (RR), 258

Reset time (RT), 258
Resistance furnaces, 96
Resistance temperature detectors (RTD), 105–106, 105f, 106f
Response curves, 254f, 255f
Response time, 13, 179, 180f, 216
Revision, 209, 210f
Reynolds number, fluid flow, 122–123
Reynolds, Osborne, 122
RH. *See* Relative humidity
Rod gauge, 138
Rotameter, 126–127, 126f
Rotary actuator, 89f
Rotary motion valves, 193
Rotary-vane flowmeter, 127, 127f
Rotational suppression method, 142
Rotor flow detectors, 129, 129f
RR. *See* Reset rate
R-S flip-flop, 40
RT. *See* Reset time
RTD. *See* Resistance temperature detectors

S

Sampling measurement systems, 169, 169f
SAR. *See* Successive-approximation register
Schmitt trigger, 24–25, 25f
SCR, photo, 29–30
Sea level readings, 81f
Seebeck, Thomas, 106
Semiconductor production, 159
Semiconductor strain gauges, 85, 86f
Sensitivity, 181–182, 182f, 226–227
Sensors
  comparisons of, 111t
  level, 140f, 147–148
  in measurement devices, 179–182
  nonlinear output of, 181f
  poor sensitivity of, 182f
  sensitivity of, 181–182
Separation process, 174
Servomechanisms (servos), 4, 70, 197f
Set point, 9, 10, 13, 229
  as reference point, 70
  steady-state error and, 57
  temperature oscillation from, 51f
Setting values, 263–264, 263f
S.G. *See* Specific gravity
Short cycling, 51
Sight glass, 138–139
Signal conversion, 58f
Signal processors, 22–25
Signals, 183
Single loop, 207–208
Single loop controller, 235f
Single-seated valve, 192f
Single-stage one-cylinder compressor, 77f
Single-stage one-cylinder vacuum pump, 77f
Single-variable control loop, 216–218
Sliding-stem globe valves, 192
Soft drink system, 118f
Solenoid, 197, 197f
Solid flow measurement, 120–121
Span adjustment, 250–251
Span error, 252f
Specific gravity (S.G.), 75
Split-beam optical gas analyzer, 161f
Square root extractor, 125, 185–186
Square waves, 24, 38, 65
S-shaped calibration curve, 249f
Stable system, 56
Start winding, 106f
Static inertia, 13
Static mixer, 155, 156f
Static pressure systems, 90–91
Static pressure tanks, 137
Steady-state error, 56–58, 57f
Steam
  boiler, 91f
  pressure systems, 91–92
  valves, 222f
Step change, 215
Strain gauges
  semiconductor, 85, 86f
  transverse voltage, 85–87, 86f
Strip chart recorder, 191
Successive-approximation register (SAR), 34
  A/D converter with, 35f
  timing diagram of, 37f
Summing amplifiers, 20, 20f, 20t
Surge suppression, 104
Symbols
  actuator, 207, 207f
  Closed-loop flow process system, 203f
  functional, 202f
  of instruments, 202f
  line, 205–206
  of operational amplifiers, 18f
  of pneumatic activated diaphragm, 207f
  of valves, 206, 206f, 207f
System comparisons, 53f
System concepts, 118–119
System diagram, 60f

T

Tag numbers, 202–204
Tank storage, 220f
Tank system, 217f
TCD. *See* Thermo-conductivity detector
Temperature
  compensation, 104
  in continuous processes, 175
  crystalline solids indicators of, 101f
  differential, 99–100, 100f
  electronic sensors measuring, 103–115
  fundamentals of, 94
  gas and, 76
  indicating devices for, 100–101
  liquid-pressure caused by, 75
  measurements, 97–100, 103–104
  measuring bridge network, 104f
  measuring differential, 100f
  measuring voltage divider, 103f
  negative coefficient of, 103
  oscillation, 51f
  pH value influenced by, 152t
  pressure influenced by, 75
  resistance detectors of, 105–106
  scales, 98–99
  sensor comparisons, 111t
Temperature control system
  closed—loop system used in, 12f
  using feed-forward control, 14
Thermal conductivity, gases, 161t
Thermal control systems, 94
Thermal energy, 94, 95
Thermal energy sources, 95–97
Thermal flowmeters, 130, 131f
Thermal lag, 179
Thermistor, 55, 103, 104f
Thermo-conductivity detector (TCD), 160, 160f
Thermocouples, 106–111, 107f
  cold junction compensating network with, 108f
  junction types in, 108f
  metal combinations in, 110
  millivolts produced in, 110f

protective housing of, 111f
selection considerations of, 111
Thermodynamic transfers, 94
Thermometers, types of, 102, 102f
Thermometry, radiation, 112–113
Thermostat
differential gap of, 52f
negative feedback signal in, 11f
Thermowell, 111f, 179
Three-way valve, 206
Time duration, 13
Time lag, 216
Time-of-flight flowmeter, 132–133, 133f
Time proportional signals, 223f
Time proportioning, 223
Time-proportioning circuit, 66–67, 67f
Time-proportioning control, 65–66
Timing devices, 38–44
Timing diagram, 37f
Title block, 208, 209f
Transducer, 142, 184, 185f, 186
Transfer systems, 137
Transistor, 40
Transmission signals, 182t
Transmitters, 182, 246, 250–251
Transverse voltage strain gauges, 85–87, 86f
Trial-and-error tuning method, 253–254
Triggering signal, 42, 43
Tuning methods
for controller, 252–265
trial-and-error, 253–254
Ziegler-Nichols, 254
Ziegler-Nichols continuous cycling method, 254–255
Ziegler-Nichols reaction curve, 260–261
Turbine flowmeters, 128, 128f

U

Ultimate period, 254, 254f, 260f
Ultrasonic flowmeters, 131–132, 132f
Ultrasonic sensors, 145–147, 145f, 147f
Unit reaction rate, 260
Unmeasurable disturbances, 15
Unstable system, 56

V

Vacuum, 81
pressure measurement s cale, 80f
pressure scale, 80
Vacuum pump, single-state one-cylinder, 77f
Vacuum systems
atmospheric pressure and, 89–90
bottle filling using, 90f
Valves
actuator, 195–197, 196f
body of, 191
capacity of, 194
characteristic curves of, 194f
characteristics, 194–195
positioners in, 197–198
sliding-stem global, 192
symbols of, 206, 206f, 207f
Vapor, 75f
Variable capacitor pressure detector, 87, 87f
Variable regulation, 69
Velocity meters, 128
Venturi tube, 126
Viscosity, 74
Visual measurements, 138
Voltages (E), 185
in closed-loop systems, 27
comparator, 18–19, 40
divider networks, 39–40
gain, 20
signals, 183
temperature measuring divider for, 103f
of thermocouples, 110f
Volumetric low rate, 119
Vortex flowmeters, 130–131, 131f

W

Wafer-type butterfly valve, 193f
Water, 174f
Water column, inches of, 79
Water level process, 248f
Waveforms, 42f, 66f
Wavelengths, 163f
Weight, 75, 75f
Weight method, 143–144
Wet bulb, 165
Wild flow, 239

Z

Zero adjustments, 250–251
Ziegler-Nichols continuous cycling formulas, 259t
Ziegler-Nichols continuous cycling method, 254–255
Ziegler-Nichols reaction curve formulas, 263t
Ziegler-Nichols reaction curve tuning method, 260–261
Ziegler-Nichols tuning method, 254

Instrumentation and Process Control

Terry L. M. Bartelt

This book provides comprehensive coverage of components, circuits, instruments, and control techniques used in today's process control technology field. It is ideal for students and technicians who will be installing, troubleshooting, repairing, tuning, and calibrating devices in a process control facility. Following an overview of an industrial control loop, each element of the loop is explored in detail.

FEATURES:

- Uses a practical and minimal-math approach to industrial control techniques, such as on-off, PID, ratio, cascade, feedforward, adaptive, and time proportioning.
- A chapter on Instrumentation Symbology provides information about drawings used in process control, such as symbols, tag numbers, functional identifiers, line symbols, and title blocks.
- A chapter on Instrumentation Calibration and Controller Tuning describes how to perform calibration procedures on instruments, and how to properly tune controllers.
- Follows a systems approach to understanding industrial process control systems. The text introduces block diagrams of an industrial control system and then expands on the function of measurement devices, instruments, and control techniques.

ABOUT THE AUTHOR:

Terry Bartelt is an instructor at Fox Valley Technical College. He has more than 25 years of experience in his field and was a National Science Foundation Recipient for Process Control. In addition, his Electromechanical Technology program was recognized as one of the top ten programs in the country and was recognized with the Secretary of Education Award.