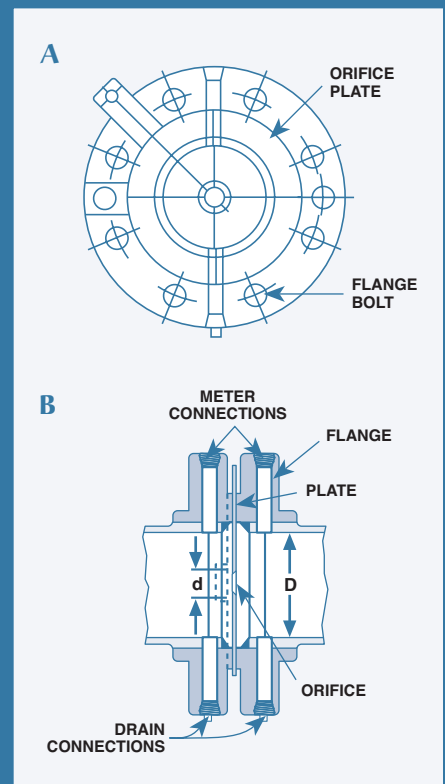
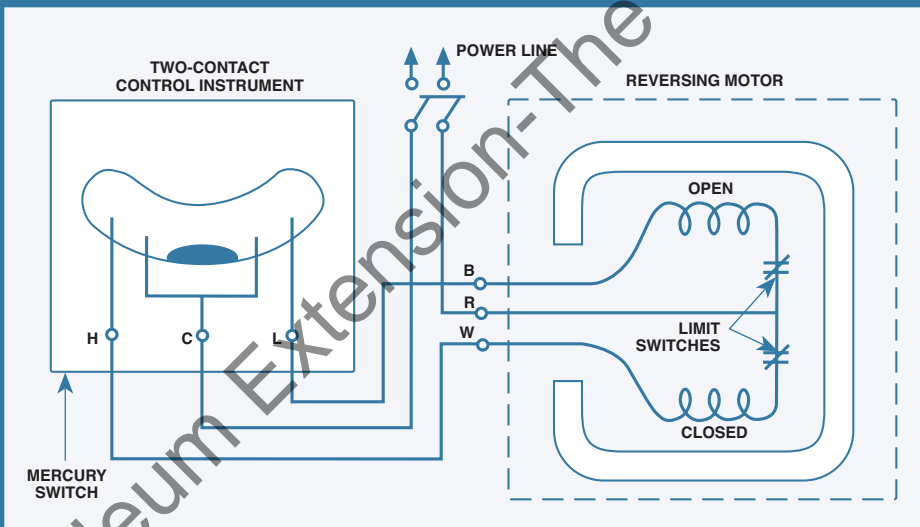
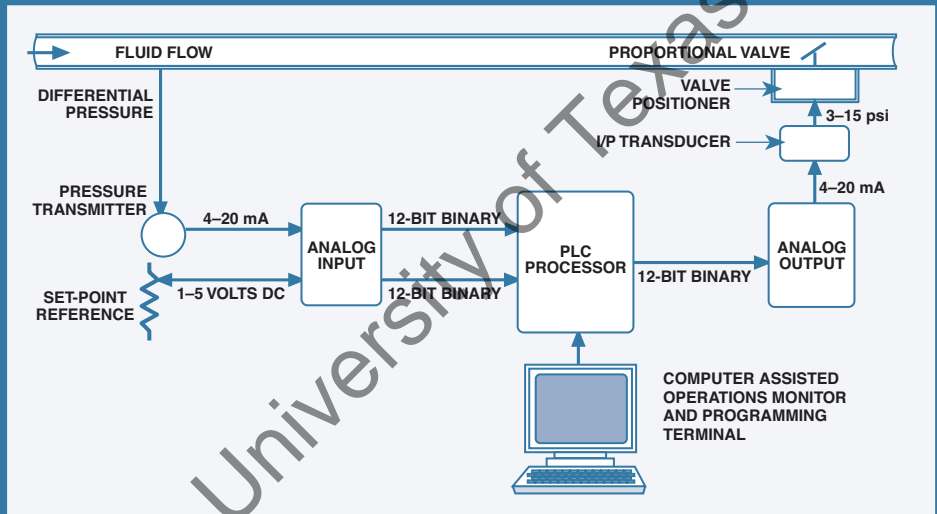
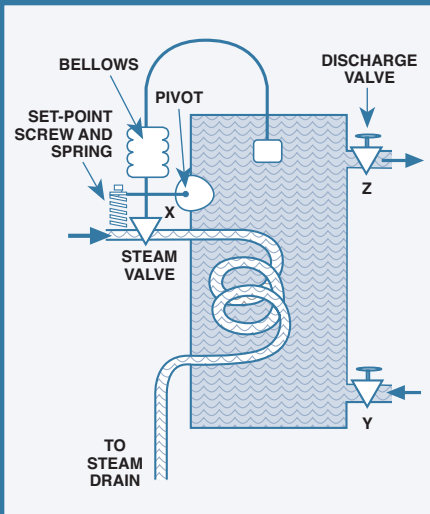


# BASIC INSTRUMENTATION

## FOURTH EDITION



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Petroleum Extension-The University of Texas at Austin

# Contents

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Preface	xiii
Acknowledgments	xv
Chapter 1. Introduction	1
The Need for Measurement and Control	1
Methods of Measurement	2
Types of Control	4
Methods or Modes of Control	9
Summary	14
Review Exercise	14
Chapter 2. The Units of Measurement	15
Comparison of Systems of Units	15
Système International (SI) d'Unités	16
Measuring Length	16
Measuring Time	18
Measuring Temperature	18
Measuring Mass, Weight, and Force	19
Measuring Work and Energy	22
Measuring Dimensions of Various Quantities	24
Summary	27
Review Exercise	28
Chapter 3. Final Control Elements	29
Valves	29
Sizing and Piping Arrangements	39
Actuators	39
Controlled-Volume Pumps	48
Variable-Volume Pumps	50
Other Final Control Elements	50
Summary	50
Review Exercise	50
Chapter 4. Pneumatic Automatic Controls	51
Pneumatic Controls	51
Commercial Pneumatic Controllers	61
Volume Booster Relays	64
Valve Positioners	65
Summary	69
Review Exercise	69
Chapter 5. Electronic Automatic Controls	71
Analog Circuits and Equipment	71

Modes of Control and Control Loops	73	
System Stability and Loop Tuning	78	
Programmable Logic Controllers (PLC) Control Systems		79
Specialized Flow Computers	81	
Distributed Control Systems	81	
Human-Machine-Interface (HMI)	83	
Summary	84	
Review Exercise	84	
Chapter 6. Pressure Measurement and Control		85
Units of Pressure Measurement	85	
Mechanical Pressure Elements	87	
Electronic Pressure Measurement	92	
Vacuum Measurements	95	
Pressure Control	97	
Summary	104	
Review Exercise	105	
Chapter 7. Temperature Measurement and Control		107
Defining Temperature Measurement	108	
Mechanical Temperature Sensors	109	
Electronic Temperature Measurement	112	
Wheatstone Bridges	117	
Electronic Temperature Transmitters	117	
Temperature Control	121	
Summary	124	
Review Exercise	124	
Chapter 8. Liquid-Level Measurement and Control		125
Defining Level Measurement	125	
Mechanical Level Sensors	125	
Electrical Level Measuring Devices	134	
Level Control	138	
Summary	140	
Review Exercise	141	
Chapter 9. Flow Measurement	143	
Defining Flow Measurement	143	
Mechanical Flow Sensors and Meters	144	
Electronic Flow Sensors and Meters	150	
Summary	156	
Review Exercise	156	
Chapter 10. Flow Control	157	
Mechanical Flow Control Elements	157	
Electronic Flow Controllers	159	
Integral Flow Controllers	162	
Summary	170	
Review Exercise	170	

Chapter 11. Gravity, Viscosity, Humidity, and pH	171
Measuring Specific Gravity and Density	171
Measuring Viscosity	177
Measuring Humidity and Dew Point	180
Measuring pH	185
Summary	187
Review Exercise	187
Chapter 12. Programmable Logic Controllers	189
PLC Operating Concepts	189
PLC Brands	195
PLC Applications and Loop Tuning	203
Summary	205
Review Exercise	205
Appendix A. Numbering Systems and Codes	207
Appendix B. Temperature Sensor Reference Tables	213
Glossary	297

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# Units of Measurement

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Throughout the world, two systems of measurement dominate: the English system and the metric system. Today, the United States is almost the only country that employs the English system.

The English system uses the pound as the unit of weight, the foot as the unit of length, and the gallon as the unit of capacity. In the English system, for example, 1 foot equals 12 inches, 1 yard equals 36 inches, and 1 mile equals 5,280 feet or 1,760 yards.

The metric system uses the gram as the unit of weight, the metre as the unit of length, and the litre as the unit of capacity. In the metric system, for example, 1 metre equals 10 decimetres, 100 centimetres, or 1,000 millimetres. A kilometre equals 1,000 metres. The metric system, unlike the English system, uses a base of 10; thus, it is easy to convert from one unit to another. To convert from one unit to another in the English system, you must memorize or look up the values.

In the late 1970s, the Eleventh General Conference on Weights and Measures described and adopted the *Système International (SI) d'Unités*. Conference participants based the SI system on the metric system and designed it as an international standard of measurement.

*Basic Instrumentation* gives both English and SI units. And because the SI system employs the British spelling of many of the terms, the book follows those spelling rules as well. The unit of length, for example, is *metre*, not *meter*. (Note, however, that the unit of weight is *gram*, not *gramme*.)

To aid U.S. readers in making and understanding the conversion to the SI system, we include the following table.

## English-Units-to-SI-Units Conversion Factors

Quantity or Property	English Units	Multiply English Units By	To Obtain These SI Units
Length, depth, or height	inches (in.)	25.4	millimetres (mm)
		2.54	centimetres (cm)
	feet (ft)	0.3048	metres (m)
	yards (yd)	0.9144	metres (m)
	miles (mi)	1609.344	metres (m)
		1.61	kilometres (km)
Hole and pipe diameters, bit size	inches (in.)	25.4	millimetres (mm)
Drilling rate	feet per hour (ft/h)	0.3048	metres per hour (m/h)
Weight on bit	pounds (lb)	0.445	decanewtons (dN)
Nozzle size	32nds of an inch	0.8	millimetres (mm)
Volume	barrels (bbl)	0.159	cubic metres (m <sup>3</sup> )
		159	litres (L)
	gallons per stroke (gal/stroke)	0.00379	cubic metres per stroke (m <sup>3</sup> /stroke)
	ounces (oz)	29.57	millilitres (mL)
	cubic inches (in. <sup>3</sup> )	16.387	cubic centimetres (cm <sup>3</sup> )
	cubic feet (ft <sup>3</sup> )	28.3169	litres (L)
		0.0283	cubic metres (m <sup>3</sup> )
	quarts (qt)	0.9464	litres (L)
	gallons (gal)	3.7854	litres (L)
	gallons (gal)	0.00379	cubic metres (m <sup>3</sup> )
pounds per barrel (lb/bbl)	2.895	kilograms per cubic metre (kg/m <sup>3</sup> )	
barrels per ton (bbl/tn)	0.175	cubic metres per tonne (m <sup>3</sup> /t)	
Pump output and flow rate	gallons per minute (gpm)	0.00379	cubic metres per minute (m <sup>3</sup> /min)
	gallons per hour (gph)	0.00379	cubic metres per hour (m <sup>3</sup> /h)
	barrels per stroke (bbl/stroke)	0.159	cubic metres per stroke (m <sup>3</sup> /stroke)
	barrels per minute (bbl/min)	0.159	cubic metres per minute (m <sup>3</sup> /min)
Pressure	pounds per square inch (psi)	6.895	kilopascals (kPa)
		0.006895	megapascals (MPa)
Temperature	degrees Fahrenheit (°F)	$\frac{^{\circ}\text{F} - 32}{1.8}$	degrees Celsius (°C)
Thermal gradient	1°F per 60 feet	—	1°C per 33 metres
Mass (weight)	ounces (oz)	28.35	grams (g)
	pounds (lb)	453.59	grams (g)
		0.4536	kilograms (kg)
	tons (tn)	0.9072	tonnes (t)
	pounds per foot (lb/ft)	1.488	kilograms per metre (kg/m)
Mud weight	pounds per gallon (ppg)	119.82	kilograms per cubic metre (kg/m <sup>3</sup> )
	pounds per cubic foot (lb/ft <sup>3</sup> )	16.0	kilograms per cubic metre (kg/m <sup>3</sup> )
Pressure gradient	pounds per square inch per foot (psi/ft)	22.621	kilopascals per metre (kPa/m)
Funnel viscosity	seconds per quart (s/qt)	1.057	seconds per litre (s/L)
Yield point	pounds per 100 square feet (lb/100 ft <sup>2</sup> )	0.48	pascals (Pa)
Gel strength	pounds per 100 square feet (lb/100 ft <sup>2</sup> )	0.48	pascals (Pa)
Filter cake thickness	32nds of an inch	0.8	millimetres (mm)
Power	horsepower (hp)	0.7	kilowatts (kW)
Area	square inches (in. <sup>2</sup> )	6.45	square centimetres (cm <sup>2</sup> )
	square feet (ft <sup>2</sup> )	0.0929	square metres (m <sup>2</sup> )
	square yards (yd <sup>2</sup> )	0.8361	square metres (m <sup>2</sup> )
	square miles (mi <sup>2</sup> )	2.59	square kilometres (km <sup>2</sup> )
	acre (ac)	0.40	hectare (ha)
Drilling line wear	ton-miles (tn•mi)	14.317	megajoules (MJ)
		1.459	tonne-kilometres (t•km)
Torque	foot-pounds (ft•lb)	1.3558	newton metres (N•m)

# 1

## Introduction

---

In broad terms, an *instrument* is a mechanical or electronic device that measures the present value of a quantity under observation. A *control* is a device that regulates and guides a process quantity against a previously selected standard or reference. A third term, *instrumentation*, suggests the measurement and control of a process.

This book uses many terms to describe the process of instrumentation. It is important to understand these terms so that you can understand the text. The terms are regularly used in the process industry and are commonly understood by those who work in it.

Instrumentation generally includes any arrangement of instruments used to measure, indicate, record, or control variable quantities that exist in a process. *Variable quantities* include such items as pressure, temperature, flow, and level. They are also referred to as *process variables*. A system of instrumentation may include transmitters, resistance temperature detectors, thermometers, pressure gauges, transducers, and control valves.

### THE NEED FOR MEASUREMENT AND CONTROL

Early humans used crude devices, such as simple clubs, which were instruments of survival. Many centuries passed before people developed instruments that improved the environment and were not just for survival. They devised ways to observe the stars; measure distances, angles, and times; and to monitor natural phenomena more accurately.

Improvement in measurements also improved and adjusted human activity to an advantage. By obtaining measurement data, people could exert control over their basic needs and environment. In early Roman times, piping and aqueducts distributed water to homes and businesses in Rome from

a central water supply. Customers were charged according to the size of the pipe or the channel that delivered the water. One consequence of developing such projects led humans to observe that they could improve products, conserve time, and produce better product quality through instrumentation.

Early process industries in Europe and Asia included brewing and winemaking, which used measurement and control to insure success. Measurement may have been as simple as visual observation of the fermenting process, and control as simple as locating the product in a cool cellar. Instruments as we know them today were crude and almost nonexistent.

In modern industrial processing, such as chemical manufacturing, the quality of the product may depend on the proper proportioning of ingredients by weight or volume, maintaining a constant pressure in a reaction vessel for a prescribed time, and adjusting the acidity (or pH) of the final product by adding a corrective agent. The economic gains achieved through proper measurement and control of processes are of primary importance in the instrumentation field.

Not only is instrumentation applied in manufacturing to increase savings in material and labor, but also it is used to improve the overall quality of the product. Even in the average modern home, instrumentation is applied in our heating and air conditioning systems, sprinkler irrigation, and security systems. This instrumentation provides us with basic needs and allows us to do a better job in a variety of environments.

One major benefit of instrumentation is to reduce the labor required to monitor and operate process equipment. However, officials of a Middle Eastern country contracted with an automation firm for the design of a modern refinery. When the plans were completed and submitted for approval,



# 2

## The Units of Measurement

---

Instrumentation involves measuring relatively few quantities—for example, length, mass, time, and temperature. Such quantities are fundamental quantities because we cannot divide them into other quantities. By comparison, speed is not a fundamental quantity. We can measure it, of course, but also we can divide it into length and time.

All quantities have dimensions. Some dimensions are easy to see, such as length. Others, however, may be a little harder to make out. For example, mass and time also have dimensions, but we cannot physically measure them with a ruler or a yardstick. Instead, we have to apply a measuring tool, such as a clock or a scale, which, when set to a standard (is calibrated), makes the measurement and indicates it to us. Also, some quantities feature several dimensions. For example, as mentioned earlier, speed has dimensions of length and time; and force has dimensions of length, time, and mass.

A unit is a standard measure of a quantity. Laws establish some units of measurement while we adopt others by common usage. We use units to measure quantities of any size, and we always express the measurements in terms of the chosen unit.

### COMPARISON OF SYSTEMS OF UNITS

Over the centuries, countries and regions initiated their own system of measurements. However, they rarely shared it with other countries. Moreover, many of these measurement systems were so crude and ill conceived that it was virtually impossible to convert one system to another.

As communication, transportation, and commerce expanded, measurement units evolved, merged, and became standardized. Today, the world is well on its way to adopting a single set of measurement standards common to all nations.

In instrumentation, it is important to use common units so they can be shared between companies, organizations, and countries. In most cases, measurements and readings are either in the English system of units (also called the conventional system) or in the *Système International (SI) d'Unités* (International System of Units), which is based on the metric system.

### Conventional System of Measurement Units

The United States uses the *English, or conventional, system of measurement* for most of its trade and commercial dealings. People in the U.S. have used this system for a long time and are therefore comfortable with it. Unfortunately, it is ambiguous and it is difficult to convert from one unit to another that measures the same quantity. For example, the unit of mass in the conventional system is the pound, which in the U.S., surprisingly enough, is defined in terms of the kilogram, which is an SI unit. The pound is divided into ounces, drams, grains, and other units, each of which relates to the pound. To convert from one unit of weight to another, users have to remember such facts as 16 ounces make up a pound and that a ton weighs 2,000 pounds. The yard is the standard length in the system, and it is divided into feet and inches. To convert from one unit of length to another, users have to remember that 36 inches or 3 feet make up a yard. Also, 5,280 feet or 1,760 yards make up a statute mile. Interestingly, the yard, like the pound, is also defined in terms of the metric (SI) system.

Besides the difficulty of converting from one English unit to another, other shortcomings exist.

# 3

## Final Control Elements

In fluid flow processes, the final control element regulates the rate of flow. Most final control elements are valves; indeed, the two terms are almost synonymous. However, the petroleum industry also uses controlled-volume pumps, variable-speed pumping drives, and other devices as final control elements.

A final control element usually consists of a valve, an actuator, and piping. An actuator provides the force that operates the valve, which controls the rate of flow of a controlled variable through the valve. Mechanical, pneumatic, electrical, hydraulic, or a combination of these means operate the actuator.

A controlled-volume pump delivers a definite and predetermined volume of liquid with each stroke, or cycle. The petroleum industry widely uses controlled-volume pumps to force chemicals into lines and vessels.

In large-volume pumping systems, the final control element often includes variable-speed drives, which power variable-volume pumps. Many pipeline systems use variable-volume, variable-speed pumps to provide variable flow on a continuous basis, depending on demand. A signal from an electronic control, programmable logic controller, or similar electrical device operates the pumps. The magnitude of the signal determines the speed of the variable-speed drive, which, in turn, controls the volume rate of the pump.

### VALVES

Valves have many parts (fig. 3.1). However, their function and use is straightforward and easy to understand. Important valve parts include the body, the plug, the guides, and the seats.

Also, keep in mind that this manual does not cover the extensive considerations involved

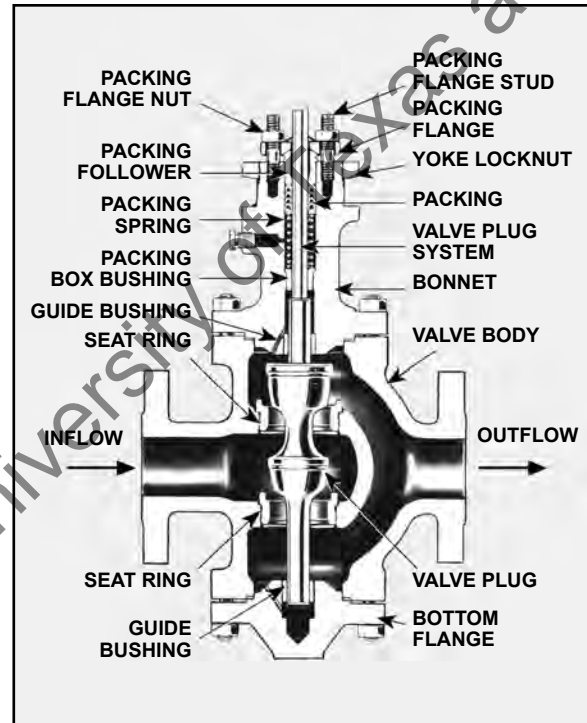


Figure 3.1. Double-ported valve (Courtesy Fisher Controls)

in the process of selecting valves for special applications. Valve selection is one of the many jobs engineers who design control systems do. But, readers should understand and appreciate the fact that control valve selection is based on the valve's having met many critical specifications to fulfill the exacting requirements of a particular control system.

### Valve Bodies

Most control applications employ globe valve bodies. However, certain applications may use other types of body. The term globe comes from the round shape of the body.

# 4

## Pneumatic Automatic Controls

Automatic control of processes has evolved from simple control systems to the complex systems in today's plants and facilities. Electronic controls, sensors, and measuring devices are significant developments that have advanced automation. We now can set adjustments with dials and digital switches. We can push a start button and watch a system perform its function completely and automatically without the intervention of an operator. Microprocessors have not only put personal computers within reach of almost everyone, but also they have taken instrumentation processes to a new level.

This chapter reviews pneumatic concepts that many facilities still employ. Although many facilities use electronic automatic controls, learning about pneumatic controls leads to a better understanding of electronic controls. Because electronic controls form a significant part of process instrumentation and automatic control, they are covered in chapter 5.

### PNEUMATIC CONTROLS

Automatic regulators and controls perform self-correcting functions—that is, once operators correctly set the automatic controls, they do not have to do anything further to control the system. Examples of automatic regulators include automobile speed controls, air conditioner thermostats, and oven temperature regulators—devices we use daily. We set them and forget them, as the saying goes. The system does the rest.

Regulating functions use devices that are hydraulically, pneumatically, or electrically controlled. This chapter covers pneumatic controls.

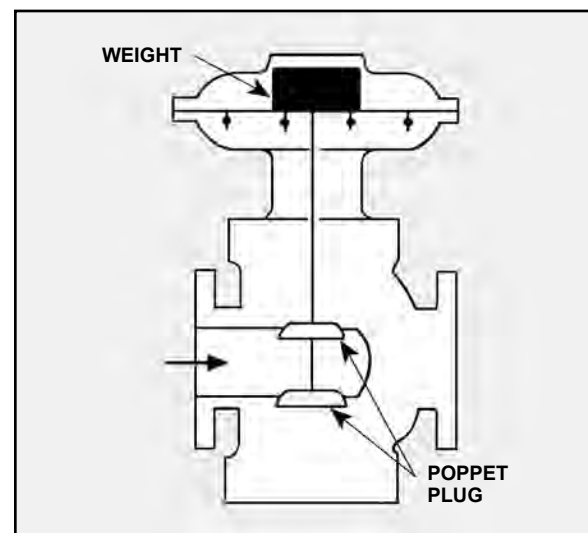
### Pressure Regulators

Pneumatic devices depend on pressure from an air supply. For a pneumatic device to perform properly,

the supply air pressure must be held steady at the required value. In short, the air pressure must be regulated. Thus, it is important to understand how a pressure regulator adjusts and holds pressure at a constant value. Let's say we have a source of air pressure delivering 100 psi (700 kPa). This pressure is too high for most control devices. So, a device is needed to reduce this pressure to an acceptable level. Moreover, once the device reduces the pressure, it must also regulate it—that is, maintain the reduced pressure at a constant value.

### Weight-Loaded Regulators

A weight-loaded regulator (fig. 4.1) is a self-contained device that reduces and regulates pressure at its output. It is a double-ported valve with a poppet-type plug that a diaphragm actuates. The diaphragm also supports a weight, which is sized for the particular regulator. A flexible diaphragm isolates the weight



**Figure 4.1** A self-contained force-loaded pressure regulator

## Electronic Automatic Controls

Electronic devices can duplicate all pneumatic control effects and they can do it with less maintenance, greater flexibility, and easier adjustment. In addition, electronic controls provide virtually immediate response, transmit control signals over long distances, and are easily modified when using devices incorporating microprocessors.

This chapter assumes that readers have a basic knowledge of electricity and of such electrical components as resistors, capacitors, potentiometers, rheostats, and switches. This chapter also explains the fundamental differences and similarities between analog and digital equipment.

### ANALOG CIRCUITS AND EQUIPMENT

The word *analog* refers to a signal that is continuous and has an infinite number of points between its beginning and ending values. For example, an analog pressure signal of 3 to 15 psi (20 to 100 kPa) varies between 3 and 15 psi (20 and 100 kPa), but it has an infinite number of points, or values, in between. Similarly, an electrical analog signal of 4 to 20 milliamperes (mA) varies between 4 and 20 mA and has an infinite number of values in between.

Essentially, analog signals are an analogy, or a representation, of a process. For example, an electronic pressure transmitter can sense a pressure range of 0 to 200 psi (0 to 1,500 kPa) and produce an electrical signal of 4 to 20 mA that corresponds to this range of pressure. Zero psi corresponds to 4 mA and 200 psi (1,500 kPa) corresponds to 20 mA. A pressure between these two limits produces a corresponding electrical signal output—for example, 100 psi (750 kPa) produces a signal of 12 mA.

A signal range of 4 to 20 mA is a standard value in process systems. Other less frequently used signals

from process transmitters include values such as 0 to 5 volts direct current (VDC), 1 to 5 VDC, or 10 to 50 mA. Typically, most electronic process transmitters produce a 4-to-20 mA signal that is converted to 1 to 5 V when the signal loop is terminated to a programmable logic controller (PLC), recorder, metering device, or other indicator. A simple but accurate 250- $\Omega$  resistor converts current to voltage in accordance with Ohm's law. Ohm's law is stated mathematically as—

$$V = I \times R \quad (\text{Eq. 5.1})$$

where

$V$  = voltage drop across resistor, volts (V)

$I$  = current in signal loop, amperes (A)

$R$  = resistance of signal terminating resistor, ohms ( $\Omega$ ).

Thus, if  $I$  is 0.004 A (4 mA), and  $R$  is 250  $\Omega$ , then—

$$V = 0.004 \times 250$$

$$V = 1.$$

Electronic signals in the form of current in mA are preferred over voltage for several reasons. For one thing, if a long length of wire is used from the transmitter terminals to the signal interface point, which may be a PLC, a recorder, or the like, resistance in the wire reduces the signal's voltage. Voltage can, however, represent a process input accurately if the signal is near the transmitter's signal terminals. In any case, if a signal reduction occurs, it represents a measurement error and is undesirable. On the other hand, if a 4 to 20 mA current signal range is used, resistance in the wire does not affect its mA value even if the wire is miles in length. When the current signal reaches the measuring point, an electronic device then converts it to an accurate voltage of 1 to 5 V.

Voltage transmitters are also sensitive to interference from external current and voltage sources. Because a voltage transmitter's output impedance is low, power circuits can induce voltages in the trans-

# 6

## Pressure Measurement and Control

Over the past 20 years, technology in pressure measurement has advanced considerably, progressing from mechanical techniques to electronic methods. Although temperature measurement rivals pressure measurement in automatic control, pressure measurement is also vital. Pressure measurement can serve as an indicator and can control other process variables in the system. The measurement and control of pressure occurs in tanks, pipes, vessels, and other components in a process system. Pressure is also used in measuring such variables as temperature, level, and rate of flow.

In this chapter, pressure is discussed in its use to control process variables, as well as to provide a reference in checking other measurement methods. Mechanical methods of pressure measuring are covered first; electronic methods follow.

### UNITS OF PRESSURE MEASUREMENT

When the word measure is used, it is typically meant in a broad sense because, in some instances, pressure is not literally measured. For example, pressure may actuate a measuring means that is not an indicator. A Bourdon tube may be attached directly to the flapper of a pneumatic controller and the controlled pressure applied to flex the tube. In this case, the Bourdon tube is the primary element and it measures the controlled variable although no graduated scale is present.

Another example is an electronic pressure transmitter where the pressure actuates a capacitor whose change results in a control signal from the transmitter. In this case, the primary element is the capacitor and it measures the controlled variable.

### Pressure Scales

Pressure is defined as force per unit area. As pointed out earlier, in the U.S., pressure is usually stated in pounds per square inch, or psi. The SI system uses kilopascals (kPa), which are derived from newtons per metre (N/m). In the atmosphere, a uniform pressure of about 14.7 psi (101.4 kPa) exists all around us, although we are usually not aware of it. Some pressure measurements ignore atmospheric pressure and begin the pressure measurement at zero. We refer to measurements that ignore atmospheric pressure as *gauge pressure*. In the conventional measurement system, it is often abbreviated as psig, which stands for pounds per square inch gauge. Most pressure gauges indicate gauge pressure, which is the pressure above ambient atmospheric pressure. Pressure below atmospheric pressure is referred to as *vacuum pressure*.

If we change our reference pressure from atmospheric to that of space where no pressure exists, *absolute pressure* is obtained. In the conventional measurement system, absolute pressure is abbreviated as psia, which stands for pounds per square inch absolute. Using mechanical methods on earth, it is almost, but not quite, possible to attain a pure vacuum, which is the vacuum of space, or the complete absence of pressure. Gauges on an absolute scale indicate about 14.7 psi for atmospheric pressure, while a gauge pressure scale indicates zero for atmospheric pressure. Gauge pressure measurements are often referred to as *GP* while absolute pressure measurement is referred to as *AP*.

Another form of pressure measurement is *differential pressure*. Differential pressure is the difference between a low pressure and a high pressure at some point in a system. Gauges that measure pressure differences are differential-pressure, or *dP*, gauges.

## Temperature Measurement and Control

Modern technology has vastly improved temperature measurement and control. While many mechanical, pneumatic, and hydraulic techniques for temperature measurement are still in use, electronic measuring devices have made significant inroads. Indeed, electronic measurement is now considered the standard method of temperature measurement and control.

Temperature is the most important variable encountered in automatic control, yet its quantitative value cannot be readily determined by direct means. Regardless of how it is determined, temperature has a profound effect on almost every process. (Its effect on personal comfort alone shows that it can bring about some spectacular events.) Temperature frequently acts with other variables to produce inter-related effects. Well known physical laws establish

dependency between temperature and pressure and between temperature and volume. Also important, but not as obvious as temperature-pressure and temperature-volume relationships, is the relation between humidity and temperature. Humidity is a measure of air's ability to contain moisture at different temperature levels.

Inferential temperature measurement takes many forms, including the expansion and contraction of metals (bimetallic thermometers), changes in volume and pressure of liquids and gases (filled-system thermometers), change in electrical properties (resistance and thermocouples), and radiation energy that produces color and brightness (pyrometers). Figure 7.1 charts the devices and the temperature ranges they measure. The chart also divides each of

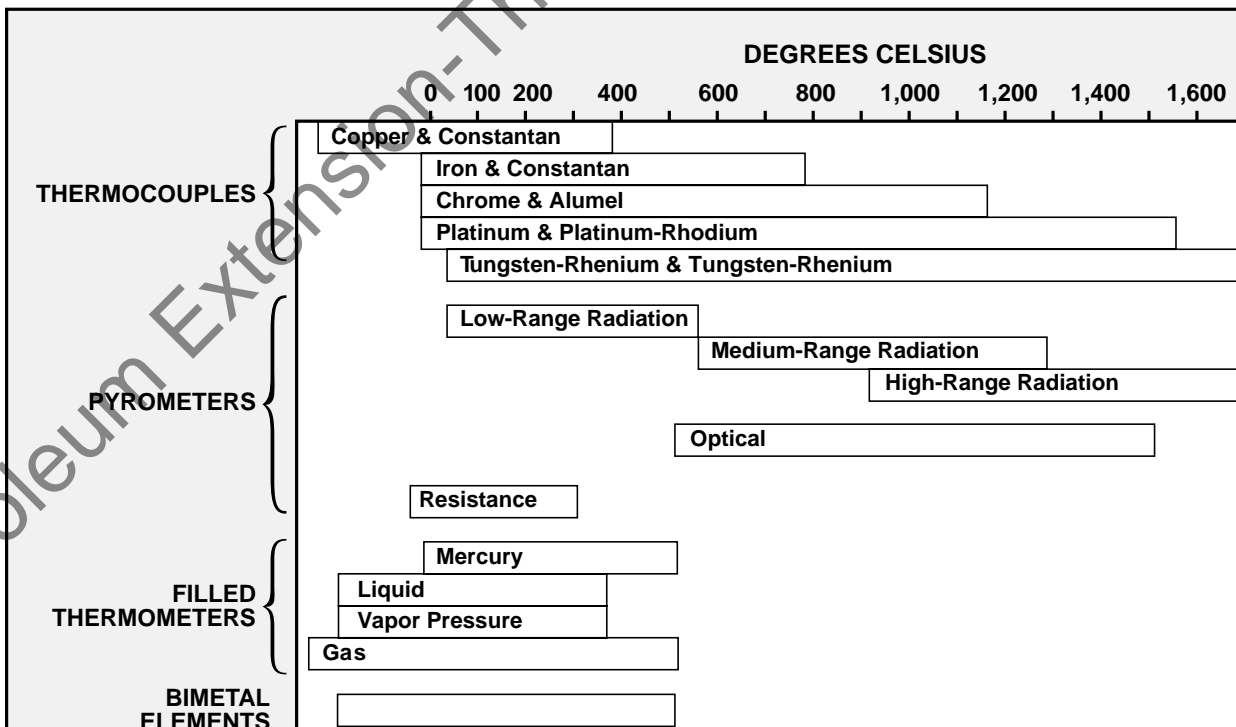


Figure 7.1 Types of temperature-measuring devices and their ranges



# 8

## Liquid-Level Measurement and Control

Liquid level is a process measurement that can be achieved directly and is therefore easy to understand. In simple terms, level is a length measurement. However, its value can also be inferred by using various techniques and devices.

Many processes that deal with liquid products include level measurement. In flow processes, for example, level is often measured and controlled to keep enough fluid in a tank to equalize inflow and outflow. Also, accurate level measurement and control is very important to companies that sell products. The amount of revenue a liquid product generates is usually based on how much of it is in a sales tank, or a container. Consequently, accurate measurement of liquid level is vital.

### DEFINING LEVEL MEASUREMENT

Liquid level is usually measured in length units such as in., ft, m, cm, and yards. The length, or height, of the liquid is based on a reference point located at or near the bottom of its container and the top surface of the liquid. Measuring actual liquid height is a direct measurement—that is, nothing is inferred by indirect means.

On the other hand, level measurement can be made by inference. For example, level can be determined from the weight, or *head pressure*, that a liquid exerts in a tank. In this case, the specific gravity of the liquid must be known so it can be related to a standard reference, which is the specific gravity of water. Since water has a specific gravity of 1.0, other liquids are either heavier or lighter and their head pressures vary accordingly. Since water is the reference when measuring level by means of head pressure, liquid level is usually stated in terms of in. of water ( $H_2O$ ) in the conventional system. In the SI system, kPa is the preferred term, but millimetres (mm) of water can also be used.

### MECHANICAL LEVEL SENSORS

#### Direct-Reading Instruments

People probably first measured liquid levels with a stick or rod. The stick determined the depth of a pond or a stream. In many instances, we still use graduated sticks and rods. For example, we use dipsticks to check oil level in an engine and gauge, or sounding, rods to measure fuel in buried storage tanks. Chains, or lead lines, fitted with weights on their ends, gauge the depth of water off the bow of a ship. And, personnel unwind steel tapes fitted with plumb bobs to determine, or *gauge*, liquid level in petroleum storage tanks. These methods are reasonably accurate when correlated to a specific temperature. Such measurements must be correlated with temperature because liquids in a vessel or tank expand and contract with temperature changes. Expansion and contraction alter the level of the liquid in the tank.

A *gauge cock* is a valve mounted on the side of a storage tank. When opened, liquid flows from it if the liquid in the tank is at least as high as the gauge cock. Several gauge cocks installed on the side of a tank can give an approximate measure of liquid level.

A *sight*, or *gauge glass*, mounted on the side of a liquid tank gives a visual indication of level (fig. 8.1A and B). Open-ended sight glasses are used on

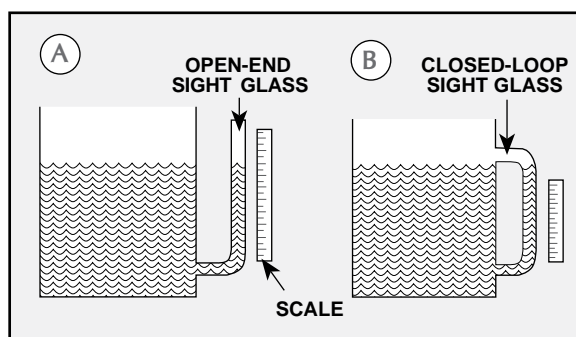


Figure 8.1 Basic types of sight glasses. A, open or vented vessel; B, pressurized vessel

# 9

## Flow Measurement

Fluid flow must be controlled if the flow regulates such variables as temperature, pressure, or liquid level. Controlling fluid flow to regulate variables requires that the flow itself be a manipulated variable. The fluid is the control agent, and temperature, pressure, or liquid level is the controlled variable. In flow measurement, fluid flow is treated as a controlled variable because it is measured and controlled to determine the quantity of fluid used or produced in a system or process.

### DEFINING FLOW MEASUREMENT

#### Units

Flow measurement is the process of determining the quantity of fluid that passes a particular point in a given interval of time. Thus, gallons (gal) or litres (L) of water per minute (min), cubic feet (ft<sup>3</sup>) or cubic metres (m<sup>3</sup>) of gas per hour (hr), and barrels (bbl) or m<sup>3</sup> of oil per day are measurements of flow.

A quantity of fluid can be expressed as a volume or as a mass. Expression as volume is often flawed because of temperature effects. For example, a gal or L of gasoline at 40°F (4.4°C) becomes more than a gal or L at 100°F (37.8°C). Automobile owners of earlier days sometimes experienced an example of fluid expansion with temperature increases. If they filled their fuel tanks to the very top with cool gasoline and parked the car in the sun, they shortly noticed that gasoline ran out the vent hole of the filler cap. The warmth caused the gasoline to expand in volume. (Modern environmental practices prohibit gasoline or its vapors from being vented to the atmosphere.)

Wide variations in volume that accompany temperature changes in a liquid present a problem so troublesome that volume measurement has, in some cases, been abandoned. In many cases, operators and organizations use mass measurement to determine

fluid volumes because the mass of a quantity of liquid or gas does not change with temperature. For example, military and commercial aviation express the quantity of gasoline, or other fuel that an aircraft carries, in terms of mass, usually in pounds (lb). Mass measurement is a much more accurate indication of the energy available from a fuel than volume measurement.

In many areas, however, volume measurement of fluids still prevails, despite its deficiencies. We still buy gasoline by the gal (L) and natural gas by the ft<sup>3</sup> (m<sup>3</sup>). But, when companies transport and sell large quantities of fluid, they often state the conditions of temperature and pressure, which provide a way to determine the mass of the fluid.

#### Dimensions

Liquid-level measurement has one simple dimension: length. Flow measurement is more complex because it has two dimensions: volume and time, or mass and time. We can determine fluid mass if we know its density and volume because the mass of a fluid equals its density times its volume.

Sometimes only the total quantity of fluid transported, produced, or used is important. In this case, time is not a factor or dimension because quantity is more important than the speed with which it is transported or used. Many meters, such as those used for measuring the quantity of natural gas, register only the amount of fluid that passes, and not the time-rate of its passage. For example, a meter may indicate only that 25,000 ft<sup>3</sup> (700 m<sup>3</sup>) of gas passed through the meter. Operators call such devices *quantity meters*. On the other hand, some meters measure quantity and time-rate. Such a meter registers, for example, 25,000 ft<sup>3</sup>/hr (700 m<sup>3</sup>/hr) of gas. Operators call meters that measure flow in terms quantity per unit of time *rate meters*.



# 10

## Flow Control

Controlling the flow of fluids is important when controlling such process variables as pressure, temperature, and liquid level. When fluid flow controls process variables, it is a *manipulated variable*. When fluid flow produces a change in the rate of flow from a set point to bring about a corrective action in a control system, it is a *controlled variable*. Flow control's use as a controlled variable is limited.

This chapter discusses types of flow-control devices, considerations involved in flow control, and applications of flow control.

### MECHANICAL FLOW CONTROL ELEMENTS

Many mechanical devices control fluid flow. One such device is a manual valve that an operator adjusts (opens or closes) to control the flow rate and quantity of fluid. A simple water faucet, or tap, is an example of a mechanical flow-control device. It not only controls the quantity of water applied to a lawn or garden, but also the rate at which water is applied. The position of the water tap's adjustment valve is important. For example, if you open the valve too wide, water runs off and is wasted.

#### Fixed Flow Beans

A *flow bean*, or *choke*, provides fixed flow control—that is, the bean, or choke's opening is not adjustable; it is a fixed size. Of course, flow beans are available in several fixed sizes, so that operators can select a size that is appropriate for a particular application. Flow beans often control the flow of natural gas from a well (fig. 10.1). The flow bean is a constriction that is placed in a special nipple. The nipple is part of the piping. The flow bean is a metal plug with a hole drilled through it. It has external threads and a socket for an Allen, or hex, wrench. The threads and wrench socket allow an operator to easily change the flow bean.

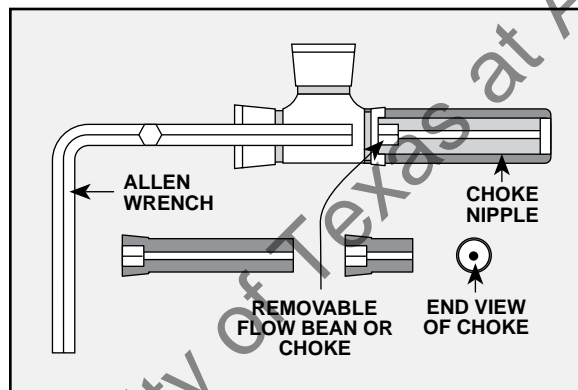


Figure 10.1 Fixed flow bean

#### Variable Flow Beans

Another flow bean is adjustable (fig. 10.2). It is a needle valve in a right-angle body. Adjustable flow

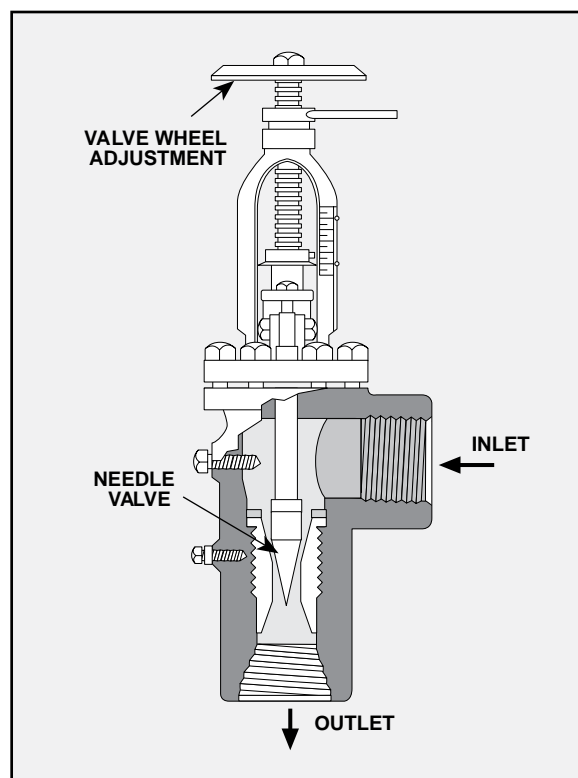


Figure 10.2 Adjustable flow bean

# 11

## Gravity, Viscosity, Humidity, and pH

Variable factors such as specific gravity, density, viscosity, humidity, and pH often modify automatic control of pressure, temperature, liquid level, and flow rate. Consequently, these variable factors must also be accurately measured and controlled.

### MEASURING SPECIFIC GRAVITY AND DENSITY

Specific gravity expresses a comparison between the densities of a particular substance and a reference substance, which is usually water or air. If water is the reference substance, its specific gravity is 1. In gas-flow measurement, air is the reference substance. Water and air are used almost exclusively for specific gravity measurements, although oxygen is sometimes used for critical scientific measurement of gases.

Temperature and pressure affect density, and therefore they must be taken into account when making specific gravity measurements. However, ordinary pressures can be ignored when dealing with incompressible liquids. For accurate measurement of liquid density, scientists usually specify double-distilled water at 4°C (39.2°F) as the standard. (Water is densest at 4°C.) For accurate measurements of gas density, they usually specify air at a standard temperature of 0°C and a pressure of 760 mm of mercury. On the other hand, U.S. engineering standards often specify 60°F and 14.73 psia for temperature and pressure, although deviations from these values are common.

### Measuring Scales

Ordinarily, people do not measure specific gravity as often as they do temperature, humidity, or atmospheric pressure, which are pertinent to weather forecasting. However, automobile enthusiasts may be aware of making specific gravity measurements

to determine the charge in a lead-acid battery or to establish the strength of an antifreeze solution in a cooling system. Although specific gravity measurements may not be important in everyday life, such measurements are very important in science and technology.

In industrial processes, measuring a solution's specific gravity is often the simplest and most accurate way to determine the solution's composition. The petroleum industry and the Bureau of Mines measure the specific gravity of petroleum using *API gravity*, which is based on the specific gravity of water. The strength of acid solutions is readily determined by specific gravity. The higher the specific gravity, the higher is the acid concentration. The charge of a lead-acid storage battery is inferred by measuring the specific gravity of its acid.

### *API Scale*

During the 1920s, the American Petroleum Institute (API) devised and adopted a scale of specific gravity measurement units called degrees (°) API. Although the scale is different from the ordinary specific gravity scale, it bears a definite relation to it. The equation for determining API gravity is—

$$^{\circ}\text{API} = \frac{140}{G} - 130 \quad (\text{Eq. 11.1})$$

where

$G$  = specific gravity of petroleum with reference to water, both at 60°F (15.55°C).

As an example, determine the API gravity of water that has a specific gravity of 1.

$$\begin{aligned} ^{\circ}\text{API} &= \frac{140}{1} - 130 \\ &= 140 - 130 \\ ^{\circ}\text{API} &= 10. \end{aligned}$$

As another example, determine the API gravity of oil whose specific gravity is 0.9462.

# I2

## Programmable Logic Controllers

The programmable logic controller (PLC) represents a significant advance in instrumentation. Since the PLC's introduction into automobiles in 1969, it has virtually replaced electromechanical relays in control circuits. Using solid-state electronic components, a PLC's reliability and flexibility are ideally suited for harsh industrial environments. Further, with only minimal hardware changes, technicians can easily reprogram the control circuit's ladder logic to suit a particular application.

A computer is the heart of a PLC, and those who first marketed it knew that people were initially skeptical of computer devices. So, they named it a controller to make it sound familiar to field operators and engineers. In addition, they added the terms programmable logic to indicate that operators could change the device's operation with software.

Early PLCs replaced relay logic circuits and hard-wired, solid-state controllers and were known as discrete, or on-off, controllers. Today's PLCs are more complex and powerful, and can handle analog signals from instruments in the form of current, frequency, and resistance. They can also perform mathematical comparisons; multiply and divide; extract square roots; and perform proportional, integral, and derivative (PID) functions.

### PLC OPERATING CONCEPTS

Most PLCs have five common building blocks that originated from relay ladder logic in control circuits. Figure 12.1 is a ladder logic diagram that shows several functions. The two vertical lines on either end of the diagram are bus voltage, or power supply, lines. The left line is the hot bus and the right line is the common, or neutral, bus. These lines are also called rails in ladder logic terminology.

The two horizontal lines (the rungs) contain the logic control circuit. Figure 12.1 shows, in

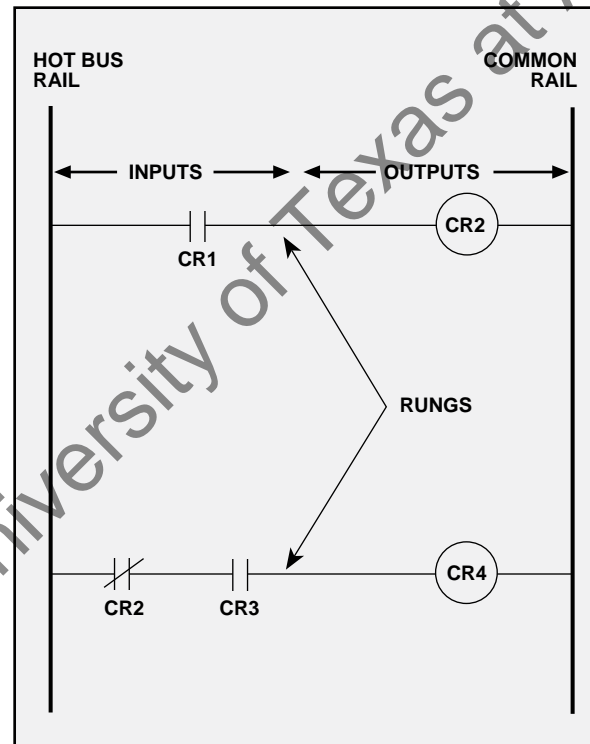


Figure 12.1 Typical relay ladder logic diagram

symbol form, five relays, contacts, or coils on the rungs. They are labeled CR1, CR2, CR3, and CR4. Devices and contacts (such as CR1) on the left side of the rung are inputs. The devices on the right side, such as the coil labeled CR2, are outputs. The lines that connect the input devices to the output devices on a particular rung are hard wired in relay circuits. However, software in the PLC's programming terminal also logically connects them. (Logic, in this sense, means the computer and its software not only recognize the electrical connection, but also recognize the function each component is designed to perform, and ensures that the components perform them properly.)

A PLC requires five major hardware components (fig. 12.2). They are—

# Index

12-bit A/D converter, 200  
135-ohm resistors, 46

## A

abscissa, 32  
absolute pressure, 85, 86  
absolute viscosity, 27, 177–78  
acceleration, 20  
acid, 185  
actuators, 39–48  
    air-loaded diaphragm, 41–42  
    combination, 48  
    diaphragm, 40  
    electric, 43–46  
    electric-motor-operated, 44–46  
    electrohydraulic, 48  
    electropneumatic, 48  
    hydraulic, 46–48  
    mechanical, 40  
    overview, 39–40  
    piston, 40, 42, 102–3  
    pneumatic, 40–43  
    reverse-acting diaphragm, 40  
    solenoid, 43–44  
    spring-loaded diaphragm, 40–41  
A/D converter, 200  
adjustable flow beans, 157–58  
air-bubble (air-purge) system, 133, 172–75  
air compressor controllers, PLC, 104, 105  
air compressors, pressure-controlled, 97–98  
air-loaded diaphragm actuators, 41–42  
air-operated injection pumps, 48–49  
air-purge (air-bubble) system, 133, 172–75  
air relays, 54–55, 62, 68  
air-to-open valves, 67  
Allen-Bradley Panelview, 83  
Allen-Bradley PLC-5, 196–203  
ambient temperature, 110  
American Petroleum Institute (API) scale, 171–72  
American Standard Code for Information Interchange (ASCII), 82, 195, 209–12  
amount of substance, 17  
analog circuits and equipment, 71–73  
analog modules, in PLCs, 201–2  
angle-body valves, 31  
API (American Petroleum Institute) scale, 171–72  
area measurement, 16, 17

ASCII (American Standard Code for Information Interchange), 82, 195, 209–12  
asynchronous transmission, 82  
atmospheric pressure, 85, 86  
automatic control, 5–6  
automatic reset, for pneumatic controllers, 58

## B

back-pressure regulators, 103–4  
baffle plates, 66, 67–68  
baffles, 53–57  
Bakelite sliding valves, 156  
balancing relay, 47  
barometric pressure, 86  
bauds, 82  
Baumé scale, 172  
BCD (binary coded decimal), 195, 209  
bellows, 90–91  
    and rate of change, 61  
    in relief valves, 122  
    and valve positioners, 66–68  
bellows orifice meters, 150  
bellows-spring assembly, 56  
bell-type gauges, 91  
benefits of instrumentation, 1–2  
beta factors, 147  
bimetal thermometers, 112  
binary coded decimal (BCD), 195, 209  
binary numbering system, 193, 194, 195, 207  
BISYNC standard, 82  
boilers, pressure-controlled, 97–98  
bonnets, 38  
Boolean symbols, 190–91  
booster relays, 64–65  
bottom product discharge rate, 168  
Bourdon gauges, 95  
Bourdon tubes/springs, 54, 85, 87–88, 130  
B-type thermocouple, 215–22  
bubble tube, 133  
bulbs, rubber, 92  
buoyancy instruments, 126–28  
Bureau of Mines dew-point tester, 184–85  
butterfly valve bodies, 32

## C

cabling, parallel vs. serial, 82  
CAOs (computer assisted operations), 203

capacitance level measurement and controls, 135–36  
 capacitor plates, 135  
 capacitors, 135  
 capacity, 7  
 capsules, 89  
 Celsius, Anders, 109  
 Celsius scale, 16, 18, 109  
 centimetre-gram-second (cgs), 27  
 centrifugal pumps, 50, 164, 165  
 cgs (centimetre-gram-second), 27  
 characterized V-port valve plugs, 34  
 Charles, Jacques, 109  
 chokes, 157  
 closed-loop control system, 6, 48–49, 80  
 closed-loop sight glasses, 125–26  
 closed-tank liquid-level indication, 132  
 coefficient of expansion, 109  
 coil CR1, 191, 192  
 combination actuators, 48  
 commercial pneumatic controllers, 61–64  
 common buses, 189  
 computer assisted operations (CAOs), 203  
 concentric orifices, 147  
 continuous bleed air relays, 62  
 control agents, 6  
 control, defined, 1  
 controlled variables, 2, 4  
 controlled-volume pumps, 48–50  
 controller set-point regulation by vapor pressure differential, 168–69  
 controlling means, 6  
 control of processes  
   methods or modes of, 9–14  
     floating mode control, 10–11  
     on-off, or two-position mode, 9–10  
     PID controls, 13–14  
     proportional control, 11–12  
     proportional plus-reset mode control, 12–13  
     proportional plus-reset plus rate, 13  
   need for, 1–2  
   types of controls, 4–8  
 control variables, 6  
 conventional system of measurement, 15, 17  
 cooling, evaporative, 182  
 copper 295–96  
 copper-constantan thermocouple, 114  
 critically damped responses, 204  
 C-tube, 88  
 current transmitters, two-wire, 93–94, 118–20  
 $C_v$  (flow coefficient), 34  
 cycling, 6–7

## D

Dall tubes, 145–46  
 dampeners, 91–92  
 data code, 82  
 data communication equipment (DCE), 82  
 Data Highway Plus, 83  
 data terminal equipment (DTE), 82  
 data transfer protocols, 82  
 data transmission rate, 82  
 DCE (data communication equipment), 82  
 dead band, 7  
 dead time, 9  
 decimal numbering system, 192–93, 195  
 density, 171–77  
   measuring devices, 172–77  
   measuring scales, 171–72  
   SI units of measurement, 17  
 derivative control, 14  
 dew point, 184–85  
 diaphragm actuators, 40  
 diaphragms  
   in differential-pressure devices, 158  
   in gas meters, 155–56  
   for level measurement in open tanks, 132–33  
   in liquid-level gauges, 90  
   metallic and non-metallic, 88–90  
   in piston pneumatic actuators, 68  
   slack, 89–90  
   and valve positioners, 66–67  
   why not satisfactory for large differential pressures, 102  
 dielectric, 135  
 differential pressure, 85, 86, 88, 144  
 differential-pressure devices, 158–59  
 differential-pressure gauges, 90, 92  
 differential-pressure transmitters, 80, 137  
 dimensions, flow measurement, 143  
 dimensions of various quantities, 24–27  
 direct-acting ported valve, 30  
 direct measurement, 2–3  
 direct-reading instruments, 125–26  
 discharge rate, 167–68  
 displacer floats, 175–77  
 displacer instruments, 128–30  
 distributed control systems, 81–83  
 double-ported valves, 29, 30  
 draft gauges, 90  
 dry-bulb thermometers, 183  
 DTE (data terminal equipment), 82  
 D valves, 156  
 dynamic viscosity, 177–78  
 dyne, 27

## E

eccentric orifices, 147  
 EEPROM memory, 121, 190  
 EIA (Electrical Industries Association), 82  
 electric actuators, 43–46  
 electrical current, units of measurement for, 17  
 Electrical Industries Association (EIA), 82  
 electrical level measuring devices, 134–38  
 electrical noise, 93–94  
 electric fields, 20  
 electric liquid-level controllers, 134, 135  
 electric-motor-operated actuators, 44–46  
 electric variable-speed drive, 50  
 electrodes, 135  
 electrohydraulic actuators, 48  
 electrolytes, 186  
 electronic automatic controls, 71–84  
   analog circuits and equipment, 71–73  
   distributed control systems, 81–83  
   human-machine-interface (HMI), 83–84  
   modes of control and control loops, 73–78  
     overview, 73–74  
     proportional control mode, 74–76  
     proportional-plus-integral control (PI), or  
     proportional-plus-reset mode, 76–77  
     proportional-plus-integral-plus-derivative (PID)  
     control, or proportional-plus-reset-plus-rate  
     mode, 77–78  
   programmable logic controllers (PLC) control  
   systems, 79–81  
   specialized flow computers, 81  
   system stability and loop tuning, 78–79  
 electronic differential-pressure flowmeters, 151  
 electronic flow controllers, 159–62  
 electronic flow sensors and meters, 150–56  
   electronic differential-pressure flowmeters, 151  
   magnetic flowmeters, 151–52  
   mass flowmeters, 152–53  
   positive displacement meters, 154–56  
   turbine flowmeters, 153  
   vortex flowmeters, 153–54  
 electronic pressure measurement, 92–95  
 electronic temperature sensors, 112–17  
 electronic temperature transmitters, 117–21  
 electronic transmitter configurations, 94  
 electropneumatic actuators, 48  
 elevation of zero, 137, 138  
 end connections, for valves, 38–39  
 energy  
   kinetic, 16, 23, 24  
   potential, 23, 24  
   units of measurement for, 17, 22–24

Engler degree system, 179  
 Engler seconds system, 178  
 English system of measurement, 15  
 ephemeris second, 18  
 equal percentage valve plugs, 35  
 ergonomics, 83  
 error control, 82–83  
 E-type thermocouple, 223–28  
 evaporative cooling, 182  
 expansion, coefficient of, 109

## F

Fahrenheit, Gabriel, 108  
 Fahrenheit scale, 18–19, 108  
 feedback, 5–6  
 feed-rate control, 166–67  
 filled temperature systems, 110–12  
 filters, for pneumatic actuators, 43  
 final control elements, 29–50  
   actuators, 39–48  
     combination, 48  
     electric, 43–46  
     hydraulic, 46–48  
     mechanical, 40  
     overview, 39–40  
     pneumatic, 40–43  
   controlled-volume pumps, 48–50  
   overview, 6  
   sizing and piping arrangements, 39  
   valves, 29–39  
     characteristics of, 32–34  
     design details, 37–39  
     guides and seats for, 36  
     plugs for, 34–36  
     trim of, 36–37  
     valve bodies, 29–32  
   variable-volume pumps, 50  
 fixed flow beans, 157  
 flappers, 53–57  
   in differential-pressure devices, 158  
   in displacer instruments, 130  
   in Foxboro Model 40 pneumatic controller, 64  
   and rate of change, 61  
 flexure tube, 130  
 floating control, 10–11, 45  
 floats, 126–28, 129–30, 175–77  
 flow beans, 157–58  
 flow characteristics of valves, 32–34  
 flow coefficient ( $C_v$ ), 34  
 flow control, 157–70  
   electronic flow controllers, 159–62  
   in fractionating columns, 166

integral flow controllers, 162–69  
 control of fraction withdrawal rate, 166–69  
 flow control in fractionating columns, 166  
 gas and steam flow control, 162–63  
 liquid flow control, 163–65  
 mechanical flow control elements, 157–59

flow measurement, 143–56  
 defining, 143  
 electronic flow sensors and meters, 150–56  
 electronic differential-pressure flowmeters, 151  
 magnetic flowmeters, 151–52  
 mass flowmeters, 152–53  
 positive-displacement meters, 154–56  
 turbine flowmeters, 153  
 vortex flowmeters, 153–54

flow rate, 2, 26

mechanical flow sensors and meters, 144–50  
 bellows orifice meters, 150  
 calculating flow velocity, 148–49  
 installation arrangements for primary elements, 148  
 mercury manometer orifice meters, 149  
 restrictive elements, 144–47  
 variable-area meters, 150

flow nozzles, 144, 146

flow regulators, 123

flow velocity, calculating, 148–49

fluidity, 178

fluid-straightening vanes, 148

force, units of measurement for, 17, 19–22

force-balance sensing devices, 158

four-wire voltage transmitters, 72, 92–93

Foxboro Model 40 pneumatic controller, 63, 64

fractionating columns, 166

frequency, units of measurement for, 17

frequency-counter-to-binary converter, 201–2

friction, and valve positioners, 65–66

## G

gain, 12

gallons, 16

gas and steam flow control, 162–63

gases, measuring electrical effects occurring in, 95–96

gas-filled systems, 111–12

gas lines, pressure relief valves in, 99–100

gas meters, 154–56

gas-operated injection pumps, 48–49

gas thermal conduction, 95

gate valve bodies, 32

gauge cocks, 125

gauge glasses, 125–26

gauge pressure, 85, 86

gauges  
 bell-type, 91  
 Bourdon, 95  
 differential-pressure, 90, 91, 92  
 draft, 90  
 liquid-level, diaphragms used in, 90  
 McLeod, 87, 95  
 Pirani, 95–96  
 thermocouple vacuum, 96–97

GENET system, 83

globe valve bodies, 29–30

gold-leaf grids, 184

gram, 20

gravitational force, 19

gravitational force, determining mass by balancing, 21

gravity, specific, 26, 171–77

Gray binary code, 195, 212

guides and seats, for valves, 36

## H

*Handbook of Chemistry and Physics*, 182

HART (highway addressable remote transducer), 160

HAT pressure switches, 191, 192

head meters, 144

head pressure, 87, 125, 144

heat, units of measurement for, 17

helical Bourdon tube, 88

helical elements, 112

hexadecimal numbering system, 194, 195, 208–9

H-H pressure switches, 191

high high-level switch (hi-hi LS), 138–39

high-pressure regulators, 102–3

high-vacuum range, 95

highway addressable remote transducer (HART), 160

hi-hi LS (high high-level switch), 138–39

HMI (human-machine-interface), 83–84, 195

horsepower, 24

hot buses, 189

hot-water temperature, 4–5

human-machine-interface (HMI), 83–84, 195

humidity  
 measuring, 180–85  
 overview, 107

hunting. *See* cycling

hydrates, 184

hydraulic actuators, 46–48

hydrogen ions, 185

hydrometers, 172

hydrostatic level measurements, 134

hydrostatic pressure, 3, 86, 98

hydrostatic pressure instruments, 131

hygroscopic materials, 182

## I

IBM's BISYNC standard, 82  
 Imperial gallon, 16  
 inferential measurement, 2–3  
 injection pumps, 48–49  
 instrument, defined, 1  
 instrumentation  
   defined, 1  
   need for, 1–2  
 integral control, 14, 76. *See also* PID controls  
 integral flow controllers, 162–69  
   control of fraction withdrawal rate, 166–69  
   flow control in fractionating columns, 166  
   gas and steam flow control, 162–63  
   liquid flow control, 163–65  
 integrator, 76  
 intermediate-pressure regulators, 100–101  
 International System of Units (Système International  
   D'unités), 16, 17  
 I/P transducer, 159  
 iron-constantan thermocouple, 114  
 ISO 646, 82  
 isobutane, 168  
 isolation seal, 92

## J

J-type thermocouple, 229–33

## K

Kelvin, Lord, 108, 109  
 Kelvin scale, 16, 18, 109  
 kilogram, 20  
 kilopascals (kPa), 85  
 kilowatt-hours, 24  
 kinematic viscosity, 27, 178  
 kinetic energy, 16, 23, 24  
 K-type thermocouple, 234–41

## L

ladder logic programming, 190–92  
 lathe-turned valve plugs, 35  
 length, units of measurement for, 16–18  
 level measurement. *See* liquid-level measurement  
 linearity, 73  
 linear valve plugs, 35–36  
 line pressure, 86  
 liquid-and-mercury-filled thermometers, 110, 111  
 liquid flow control, 163–65  
 liquid-heating system, proportional controller  
   in, 57

liquid-in-glass thermometers, 109–10  
 liquid-level control, 4, 138–40  
 liquid-level controllers, electric, 134, 135  
 liquid-level gauges, diaphragms used in, 90  
 liquid-level measurement, 125–38  
   defined, 125  
   electrical level measuring devices, 134–38  
   mechanical level sensors, 125–34  
     air-bubble (air-purge) system, 133  
     buoyancy instruments, 126–28  
     direct-reading instruments, 125–26  
     displacer instruments, 128–30  
     hydrostatic level measurements in pressurized  
       vessels, 134  
     hydrostatic pressure instruments, 131  
     level measurement in open tanks, 131–33  
 liquid manometers, 91  
 lithium chloride, 184  
 litmus paper, 186  
 logarithmic flow, 32  
 logarithms, 185  
 logic numbering systems, 192–95  
 loop tuning, 78–79  
 LOPs (low oil pressure switches), 191, 192  
 louvers, 50  
 lower range value (LRV), 72, 73, 136  
 low flows, valve plugs for, 36  
 low oil pressure switches (LOPs), 191, 192  
 low-pressure regulators, 101–2  
 LRV (lower range value), 72, 73, 136  
 luminous intensity, 17

## M

magnetic fields, 19–20  
 magnetic flowmeters, 151–52, 162  
 manipulated variables, 6  
 man-machine-interface (MMI). *See* human-machine-  
   interface (HMI)  
 manometers, 25–26  
   liquid, 91  
   mercury manometer orifice meters, 149  
   U-tube, 25–26, 149  
 manual control, 4–5  
 mass  
   converting to volume, 26  
   determining by balancing gravitational force, 21  
   units of measurement for, 17, 19–22  
 mass flowmeters, 26, 152–53  
 McLeod gauges, 87, 95  
 measured variable (MV) feedback signal, 75  
 measurement  
   need for, 1–2



units of, 15–28  
 comparison of systems of units, 15–16  
 for dimensions of various quantities, 24–27  
 for length, 16–18  
 for mass, weight and force, 19–22  
 Système International (SI) D'unités  
 (International System of Units), 16  
 for temperature, 18–19  
 for time, 18  
 for work and energy, 22–24

mechanical actuators, 40

mechanical flow sensors and meters, 144–50  
 bellows orifice meters, 150  
 calculating flow velocity, 148–49  
 installation arrangements for primary  
 elements, 148  
 mercury manometer orifice meters, 149  
 restrictive elements, 144–47  
 variable-area meters, 150

mechanical level sensors, 125–34  
 air-bubble (air-purge) system, 133  
 buoyancy instruments, 126–28  
 direct-reading instruments, 125–26  
 displacer instruments, 128–30  
 hydrostatic level measurements in pressurized  
 vessels, 134  
 hydrostatic pressure instruments, 131  
 level measurement in open tanks, 131–33

mechanical pressure instruments, protection  
 of, 91–92

mechanical pressure measurement, 87–92

mechanical reset adjustments, for pneumatic  
 controllers, 58

mechanical temperature sensors, 109–12

mercury manometer orifice meters, 149

mercury, millimetres of, 87

mercury thermometers, 109–10

Meritape liquid-level sensor, 136

metallic diaphragms, 88–90

metres, 16

micrometres, 87

miles, 16

millimetres of mercury, 87

millivoltmeter with thermocouple, 115

mixing valves, regulated, 122

MMI (man-machine-interface). *See* human-machine-  
 interface (HMI)

Modbus system, 83

modified linear valve plugs, 34

molecular motion, 108

multiple-capacity system, 7

multivariable flowmetering, 160

MV (measured variable) feedback signal, 75

## N

network sharing, 83

neutral buses, 189

newton, 16, 20, 25

nickel 112, 292–94

nickel-iron alloy, 112

noise, electrical, 93–94

nonbleed air relays, 62

non-metallic diaphragms, 89–90

nozzles, 53–57  
 in differential-pressure devices, 158  
 in displacer instruments, 130  
 flow, 144, 146  
 in Foxboro Model 40 pneumatic controller, 64  
 and rate of change, 61  
 and valve positioners, 66–67

N-type thermocouple, 242–49

numbering systems and codes, 207–12  
 American Standard Code for Information  
 Interchange (ASCII), 209–12  
 Binary Coded Decimal (BCD) Code, 209  
 binary number system, 207  
 gray code, 212  
 hexadecimal number system, 208–9  
 octal number system, 194, 195, 207–8

## O

octal numbering system, 194, 195, 207–8

Ohm's law, 71

one-fourth amplitude responses, 204

on-off level control, 134, 138–39

on-off mode, 9–10

on-off programmable logic controllers (PLCs), 104, 105

op amps (operational amplifiers), 72

open air trap, 133

open-ended sight glasses, 125–26

open-loop control system, 203–4  
 combined with closed-loop system, 48–49  
 compared with proportional-plus-integral control, 77  
 overview, 6

open-sequence control system. *See* open-loop control  
 system

open-tank liquid-level indication, 132

operational amplifiers (op amps), 72

operators. *See* actuators

optical pyrometers, 115–17

ordinate, 33

orifice plates, 146–47, 163, 164

orifices, 144, 147

orifice-to-pipe diameter, 147

overdamped responses, 204

oxides of thermoresistive elements, 114

## P

- Panelview, 83
- parallel cabling, 82
- pascals, to express pressure, 25
- pH factor, 27, 185–87
- PI (proportional-plus-integral control), or proportional-plus-reset mode, 76–77
- PID controls, 13–14, 202–3
- PID input modules, 202–3
- piezometer ring, 175
- pilot-operated controller, 128
- pilot valve, 128
- pipeline pumps, 193
- pipng arrangements, for valves, 39
- Pirani gauges, 95–96
- piston actuators, 40, 42, 102–3
- platinum, 113–14
- platinum 100, 272–81
- platinum 200, 282–86
- platinum 500, 287–91
- PLC (programmable logic controller) card, 139
- PLCs. *See* programmable logic controllers (PLCs)
- plugs, for valves, 34–36
- pneumatic actuators, 40–43
- pneumatic automatic controls, 51–69
  - automatic reset, 58–59
  - commercial pneumatic controllers, 61–64
  - fixed and variable orifices, 52–55
  - mechanical reset adjustments, 58
  - operation of, 57–58
  - pressure regulators, 51–52
  - proportional controllers, 55–57
  - rate of response adjustments, 59–60
  - summary of controller action, 60–61
  - valve positioners, 65–69
  - volume booster relays, 64–65
- pneumatic piston actuators, 42
- poise, 27
- poppets, 34, 51
- positioners, for valves, 41, 42, 65–69
- positive-displacement meters, 154–56
- positive-displacement pumps, 48, 164, 165
- positive-flow indicator, 133
- potential energy, 23, 24
- potentiometer, 74
- pound, 15, 20–21
- power
  - relation to work and energy, 24
  - units of measurement for, 17
- pressure
  - absolute, 85, 86
  - atmospheric, 85, 86
  - barometric, 86
  - differential, 85, 86, 88, 144
  - hydrostatic, 3, 86, 98
  - measurement of, 2, 25–26, 85–97
    - electronic, 92–95
    - mechanical, 87–92
    - pressure scales, 85
    - sensors for, 87
    - units of, 17, 85–87
    - vacuum, 95–97
  - overview, 2
- pressure control, 97–105
  - devices for, 97–102
  - overview, 97–98
  - pressure regulators, 100–104
  - pressure relief valves, 98–100
  - pressure controllers, 104
- pressure regulators, 51–52, 100–104
- pressure relief valves, 98–100
- pressure taps, 144–45, 148
- pressurized vessels, hydrostatic level measurements
  - in, 134
- primary elements, 4, 6
- process reaction rate, 8
- process variables. *See* variable quantities
- programmable logic controller (PLC) card, 139
- programmable logic controllers (PLCs), 79–81, 104, 105, 151, 189–205
  - analog inputs and outputs, 198–202
  - applications and loop tuning, 203–5
  - brands of, 195–203
  - and electronic flow controllers, 159–62
  - operating concepts, 189–95
    - ladder logic programming, 190–92
    - logic numbering systems, 192–95
    - processor characteristics, 192
  - special interface modules, 202–3
  - temperature control, 123–24
- proportional band, 11–12, 13
- proportional band controllers, 104
- proportional control, 11–12
- proportional controllers, 55–57
- proportional control mode, 74–76
- proportional level measurement and controls, 135–37
- proportional-plus-integral control (PI), or proportional-plus-reset mode, 76–77
- proportional-plus-integral-plus-derivative (PID) controls, 13–14, 202–3
- proportional-plus-reset controller, 59–60
- proportional plus-reset mode control, 12–13
- proportional plus-reset plus rate, 13
- proportional-plus-reset-plus-rate mode, 77–78
- protocols, data transfer, 82

psychrometers, 183  
 pulsation dampeners, 91–92  
 pumping wells, injection pumps for, 48–49  
 pumps  
   air-operated injection, 49  
   centrifugal, 50, 164, 165  
   controlled-volume, 48–50  
   gas-operated injection, 48–49  
   injection, 48–49  
   pipeline, 193  
   positive-displacement, 48, 164, 165  
   reciprocating piston, 48  
   variable-volume, 50  
 pyrometers, optical, 115–17

## Q

QR (quadrate rate) card, 160  
 quadrate rate (QR) card, 160  
 quantity meters, 143  
 quick-opening valve plugs, 34

## R

rails, 189  
 range, of voltage transmitters, 72  
 Rankine scale, 18, 108  
 Rankine, William J.M., 108  
 rate meters, 143  
 rate of change, for pneumatic controllers, 60–61  
 rate of flow, 26  
 rate of response adjustments, for pneumatic controllers,  
   59–60  
 rate response, 13  
 ratio flow control, 168  
 reciprocating piston pumps, 48  
 Redwood Admiralty seconds system, 178  
 Redwood seconds system, 178  
 reflux, 167, 168  
 regulated mixing valves, 122  
 regulators  
   flow, 123  
   pressure, 51–52, 100–104  
   spring-loaded, 52  
 relative viscosity, 178  
 relays  
   air, 54–55, 62, 68  
   balancing, 47  
   booster, 64–65  
 relief valves, 122  
 rerange, 72  
 reset, for pneumatic controllers, 58, 60–61  
 resistance, 7–8

resistance-level measurement, 136–37  
 resistance temperature detector (RTD), 118, 160. *See*  
   also RTD-type thermocouple  
 resistance vs. wire diameter, 213  
 response lag, 6  
 restricted range level controller, 127  
 restrictive elements, 144–47  
 reverse-acting diaphragm actuators, 40  
 reverse-acting ported valve, 30  
 reversible motors, floating control of, 45  
 RTD (resistance temperature detector), 118, 160  
 RTD-type thermocouple, 272–96  
   copper 10, 295–96  
   nickel 120, 292–94  
   platinum 100, 272–81  
   platinum 200, 282–86  
   platinum 500, 287–91  
 R-type thermocouple, 250–58  
 rubber bulbs, 92

## S

safety valves. *See* pressure relief valves  
 Saybolt, George M., 178  
 Saybolt Seconds Furol (SSF), 178  
 Saybolt Seconds Universal (SSU), 178  
 Saybolt viscometers, 179  
 scalar quantity, 23  
 scales  
   API (American Petroleum Institute), 171–72  
   Baumé, 172  
   Celsius, 16, 18, 109  
   Fahrenheit, 18–19, 108  
   Kelvin, 16, 18, 109  
   pressure, 85  
   Rankine, 18, 108  
   spring, 21–22  
   weight-scale modules, 202  
 seals, for valves, 37  
 segmental orifices, 147  
 sensors. *See names of specific sensors*  
 serial cabling, 82  
 set points, 4  
   adjustment signal, 75  
   changing with electronic controllers, 12  
   and proportional plus-reset mode control, 12–13  
   responses to changes above, 204  
 sg (specific gravity), 26, 171–77  
 SI (Système International) D'unités (International  
   System of Units), 16, 17  
 sight glasses, 125–26  
 signal inaccuracy, 93–94  
 single-capacity system, 7

single-ported globe valve bodies, 30  
 slack diaphragms, 89–90  
 sliding friction, and valve positioners, 65–66  
 sling psychrometers, 183  
 small flow-rate bodies, 32  
 smart mass-flow transmitter, 160, 161  
 smart temperature transmitters, 120–21  
 smart transmitters, 94  
 solenoid actuators, 43–44  
 span, of voltage transmitters, 72  
 specialized flow computers, 81  
 specific gravity (sg), 26, 171–77  
 specific viscosity, 178  
 spiral Bourdon tube, 88  
 split-body valves, 31  
 spring-loaded diaphragm actuators, 40–41  
 spring-loaded regulators, 52  
 springs, 20  
 springs, equations for energy in, 23, 24  
 spring scales, 21–22  
 square metres, 25  
 square units, 16  
 SSF (Saybolt Seconds Furol), 178  
 SSU (Saybolt Seconds Universal), 178  
*Standard RS232*, 82  
 state of equilibrium between liquid and vapor, 182  
 static friction, 65–66  
 static pressure, 86  
 steam flow control, 162–63  
 steam turbines, 47–48  
 stem-guided valve plugs, 36  
 step change, 8, 9  
 stoke, 27  
 Stokes, Sir Frederick, 177–78  
 stuffing boxes, 37  
 S-type thermocouple, 259–67  
 sumps, 43  
 suppression of transmitters, 138  
 synchronous transmission, 82  
 Système International (SI) D'unités (International System of Units), 16, 17

## T

TD1 pressure switches, 191  
 Teflon, 37  
 temperature  
   ambient, 110  
   control of, 121–24  
     automatic, 5  
     manual, 4–5  
   measurement of, 107–21

    conventional and SI units, 17  
     defining, 108–9  
     electronic temperature sensors, 112–17  
     electronic temperature transmitters, 117–21  
     mechanical temperature sensors, 109–12  
     methods of, 2  
     overview, 107–8  
     units of, 18–19  
 Wheatstone bridges, 117  
 temperature sensors, 213–95  
   electronic, 112–17  
   resistance vs. wire diameter, 213  
   thermocouple wire identification, 213  
   type B thermocouple, 215–22  
   type E thermocouple, 223–28  
   type J thermocouple, 229–33  
   type K thermocouple, 234–41  
   type N thermocouple, 242–49  
   type RTD thermocouple  
     copper 10, 295–96  
     nickel 120, 292–94  
     platinum 100, 272–81  
     platinum 200, 282–86  
     platinum 500, 287–91  
   type R thermocouple, 250–58  
   type S thermocouple, 259–67  
   type T thermocouple, 268–71  
   wire table for standard annealed copper, 214  
 thermocouples, 114  
   copper-constantan, 114  
   iron-constantan, 114  
   millivoltmeter with, 115  
   Type B, 215–22  
   Type E, 223–28  
   Type J, 229–33  
   Type K, 234–41  
   Type N, 242–49  
   Type R, 250–58  
   Type RTD, 272–96  
     copper 10, 295–96  
     nickel 120, 292–94  
     platinum 100, 272–81  
     platinum 200, 282–86  
     platinum 500, 287–91  
   Type S, 259–67  
   Type T, 268–71  
 thermocouple vacuum gauges, 96–97  
 thermocouple wire identification, 213  
 thermometers  
   bimetal, 112  
   dry-bulb, 183  
   filled temperature systems, 110–12  
   gas-filled, 111–12

liquid-and-mercury-filled, 110  
 liquid-in-glass, 109–10  
 vapor pressure, 110  
 wet-bulb, 183

thermoresistive elements, 113–14

Thompson, William, 108, 109

threaded fittings, for valves, 38

three-way valves, 31–32, 130

throttling range. *See* proportional band

throttling valve plugs, 35, 39

throttling valves, 163, 164, 165

time, units of measurement for, 17, 18

top product discharge rate, 167–68

torque tubes, 129–30

transfer lag, 9

transmission rate, data, 82

transmitters

- differential-pressure, 80, 137
- electronic temperature, 94, 117–21
- four-wire, 72
- smart mass-flow transmitters, 160, 161
- smart temperature transmitters, 120–21
- smart transmitters (in general), 94
- suppression of, 138
- two-wire current transmitters, 72, 93–94, 118–20
- voltage, 71–72, 92–93

transportation lag, 9

trim, of valves, 36–37

T-type thermocouple, 268–271

turbine flowmeters, 153, 160–61

turbines, steam, speed control system for, 47–48

two-position mode, 9–10

two-wire transmitters, 72, 93–94, 118–20

U

U.S. gallon, 16

ultra-high vacuum range, 95

underdamped responses, 204

units of measurement, 15–28

- comparison of systems of units, 15–16
- for dimensions of various quantities, 24–27
- flow measurement, 143
- for length, 16–18
- for mass, weight, and force, 19–22
- Système International (SI) D'unités (International System of Units), 16
- for temperature, 18–19
- for time, 18
- for work and energy, 22–24

upper range value (URV), 93

U-tube manometer, 25–26, 149

## V

vacuum pressure measurement, 95–97

valves, 29–39

- air-to-open, 67
- angle-body, 31
- Bakelite sliding, 156
- butterfly valve bodies, 32
- characteristics of, 32–34
- design details, 37–39
- direct-acting ported, 30
- double-porting, 29, 30
- D** valves, 156
- flow characteristics of, 32–34
- gate valve bodies, 32
- globe valve bodies, 29–30
- guides and seats for, 36
- pilot, 128
- plugs for, 34–36
- positioners for, 41, 42, 65–69
- pressure relief, 98–100
- regulated mixing valves, 122
- relief valves, 122
- reverse-acting, 30, 67
- safety. *See* pressure relief valves
- single-porting globe valve bodies, 30
- split-body, 31
- three-way, in displacer instruments, 130
- throttling, 163, 164, 165
- trim of, 36–37
- valve bodies, 29–32

vapor. *See* humidity

vapor pressure, 181

vapor pressure differential, 168–69

vapor pressure thermometers, 110, 111

variable-area meters, 150

variable flow beans, 157–58

variable orifices, 52

variable quantities, 1

variable-speed motors, 140

variable-volume pumps, 50

vector quantity, 23

velocity, 17

venturi effect, 101

venturi sections, 145–46

viscometers, 179

viscosity, 27, 177–80

voltage transmitters, 71–72, 92–93

volume

- converting from mass to, 26
- units of measurement for, 17

volume booster relays, 64–65

vortex flowmeters, 153–54, 162

V-port valve plugs, 34

## W

water vapor. *See* humidity  
weight-loaded pressure regulators, 51–52, 103  
weight-scale modules, 202  
weight, units of measurement for, 19–22  
welded ends, for valves, 39  
wells, injection pumps for, 48–49  
wet-bulb thermometers, 183  
wet leg measurement, 138  
Wheatstone bridges, 96, 117  
wire table for standard annealed copper, 214

work, units of measurement for, 17, 22–24  
working pressure, defined, 86

## Y

yard, 15

## Z

zero, elevation of, 137, 138  
Ziegler-Nichols open-loop tuning method, 204  
Ziegler-Nichols optimum performance method, 79

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