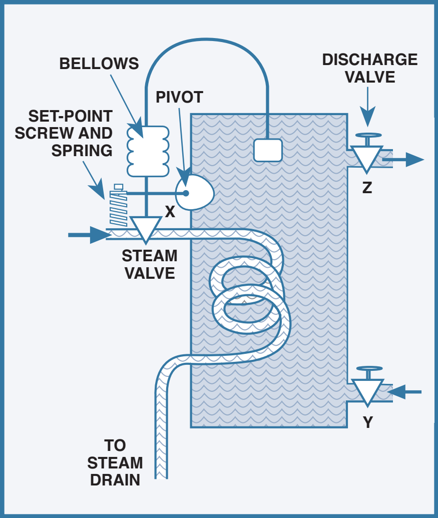
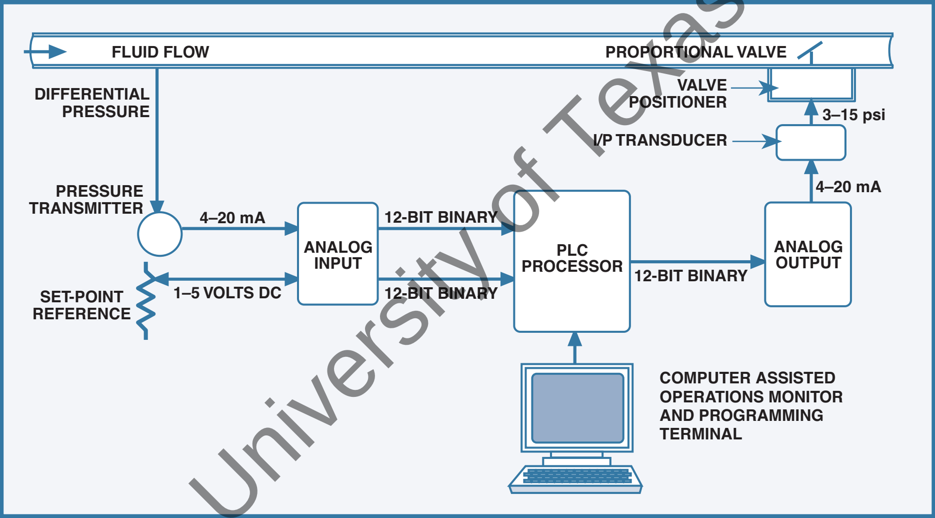
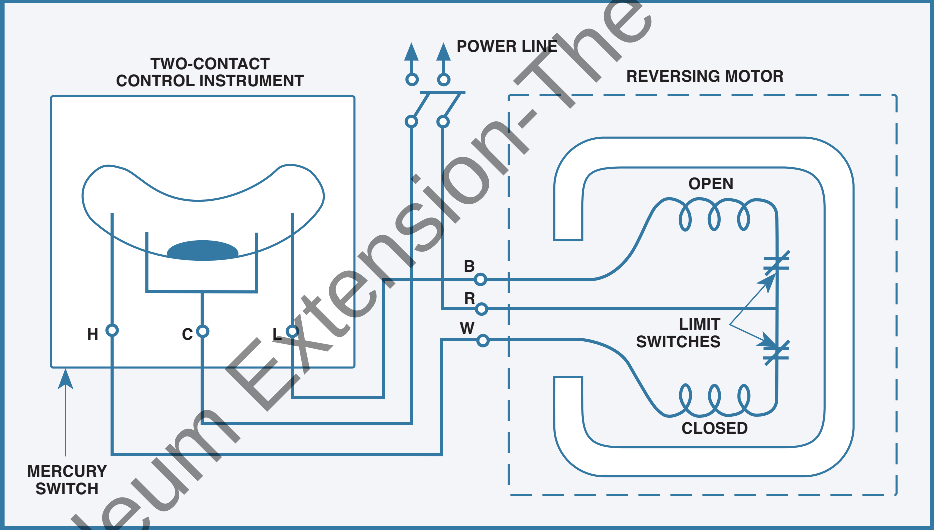
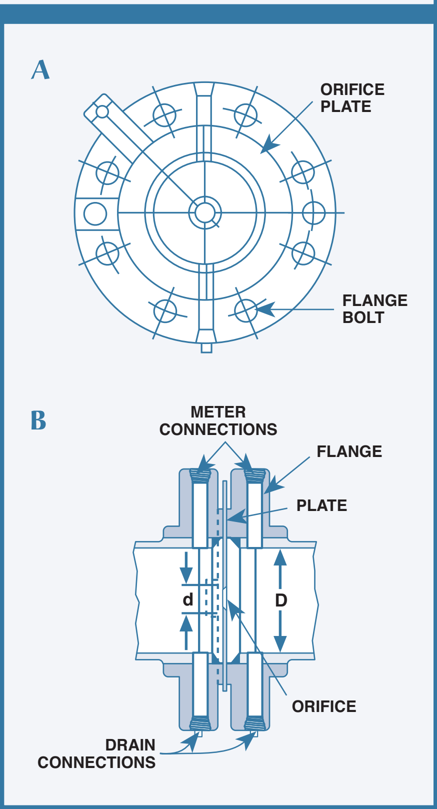
BASIC INSTRUMENTATION

FOURTH EDITION









PETROLEUM EXTENSION SERVICE • THE UNIVERSITY OF TEXAS AT AUSTIN

ABOUT THE AUTHOR

Will L. McNair is a graduate Electrical Engineer from Mississippi State University with over 20 years of experience as a design and development engineer with companies that include General Electric, Varo, and Baylor Company. After his employment with these companies, he has been a consultant and technical trainer for companies worldwide under his company, TRAINCO, focusing on instrument and electrical applications for the petroleum industry. He has taught instrumentation, electrical and electronic courses in seminars and schools to over 5,000 personnel within the past 20 years. These subjects range from electronic instrumentation, programmable logic controllers, basic electricity, to sophisticated solid-state topics such as SCR motor drives, variable frequency drives, SCADA, and many others.

During this period, McNair headed the Energy Training Division at Texas A&M University for 2 years, has written three other textbooks, and has been published in various industry magazines, including *Oil & Gas Journal*, *World Oil*, *Drilling Contractor*, and others. He has contributed to several patents related to solid-state technology and developed several advanced products for the oil and gas industry.

Will McNair is a registered engineer in Texas and member of ISA, IEEE, TSPE, Society of Petroleum Engineers, IADC, and NFPA.

Contents

Units of Measurement

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^3)
		159	litres (L)
	gallons per stroke (gal/stroke)	0.00379	cubic metres per stroke (m^3/stroke)
	ounces (oz)	29.57	millilitres (mL)
	cubic inches (in.^{3})	16.387	cubic centimetres (cm^3)
	cubic feet (ft^3)	28.3169	litres (L)
		0.0283	cubic metres (m^3)
	quarts (qt)	0.9464	litres (L)
	gallons (gal)	3.7854	litres (L)
	gallons (gal)	0.00379	cubic metres (m^3)
	pounds per barrel (lb/bbl)	2.895	kilograms per cubic metre (kg/m^3)
	barrels per ton (bbl/tn)	0.175	cubic metres per tonne (m^3/t)
Pump output and flow rate	gallons per minute (gpm)	0.00379	cubic metres per minute (m^3/min)
	gallons per hour (gph)	0.00379	cubic metres per hour (m^3/h)
	barrels per stroke (bbl/stroke)	0.159	cubic metres per stroke (m^3/stroke)
	barrels per minute (bbl/min)	0.159	cubic metres per minute (m^3/min)
Pressure	pounds per square inch (psi)	6.895	kilopascals (kPa)
		0.006895	megapascals (MPa)
Temperature	degrees Fahrenheit (°F)	$\frac{^\circ F - 32}{1.8}$	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^3)
	pounds per cubic foot (lb/ft^3)	16.0	kilograms per cubic metre (kg/m^3)
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^2)	0.48	pascals (Pa)
Gel strength	pounds per 100 square feet (lb/100 ft^2)	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.^{2})	6.45	square centimetres (cm^2)
	square feet (ft^2)	0.0929	square metres (m^2)
	square yards (yd^2)	0.8361	square metres (m^2)
	square miles (mi^2)	2.59	square kilometres (km^2)
	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.

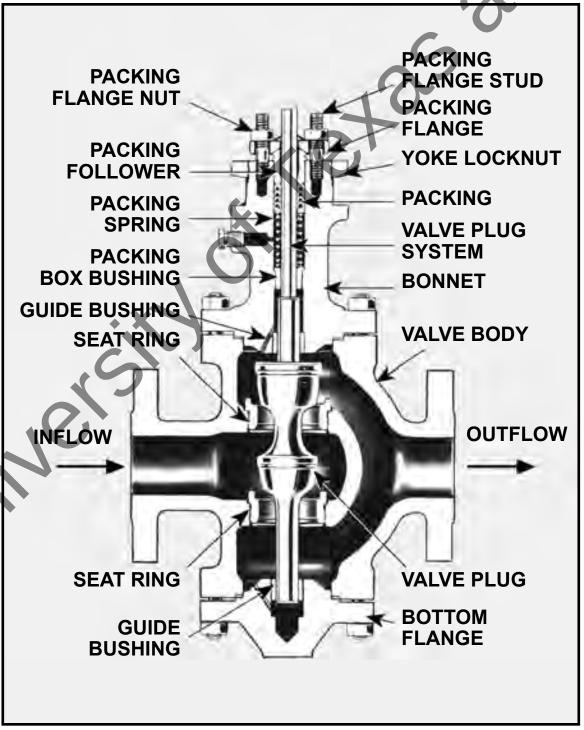


Figure 3.1. Double-ported valve (Courtesy Fisher Controls)

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

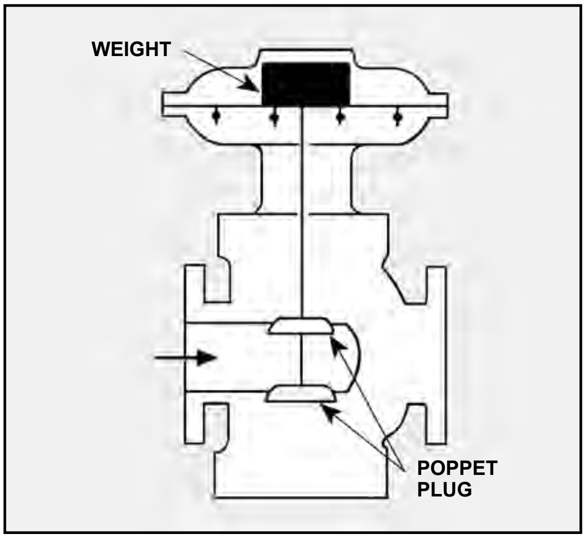


Figure 4.1 A self-contained force-loaded pressure regulator

5

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-Ω resistor converts current to voltage in accordance with Ohm's law. Ohm's law is stated mathematically as—

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

where

V = voltage drop across resistor, volts (V)

I = current in signal loop, amperes (A)

R = resistance of signal terminating resistor, ohms (Ω).

Thus, if I is 0.004 A (4 mA), and R is 250 Ω, 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.

7

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 interrelated 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

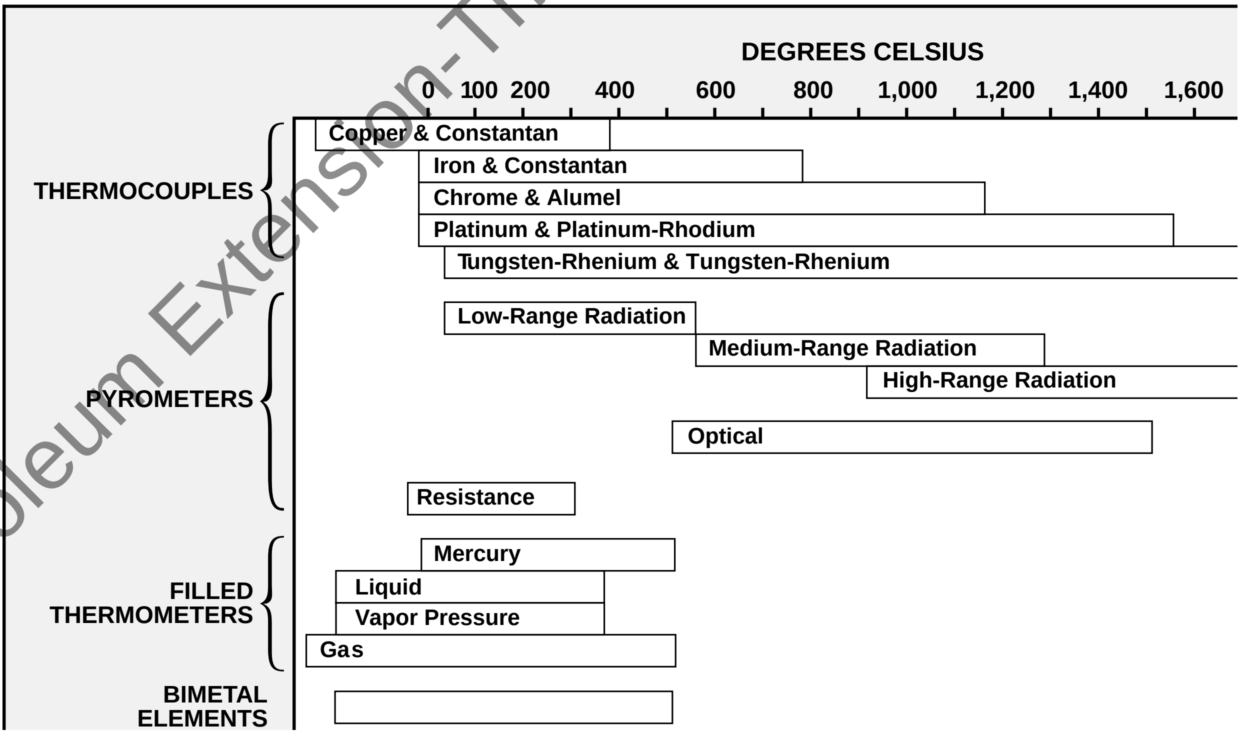


***Figure 7.1** Types of temperature-measuring devices and their ranges*

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

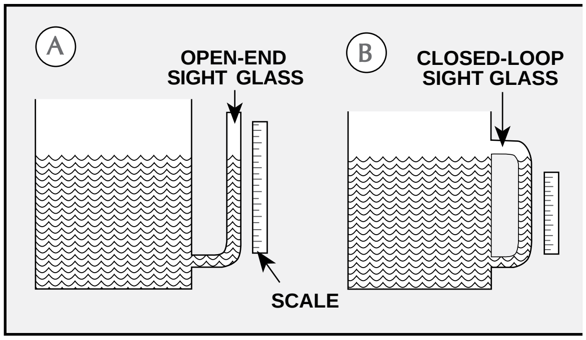


Figure 8.1 Basic types of sight glasses. A, open or vented vessel; B, pressurized vessel

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^3) or cubic metres (m^3) of gas per hour (hr), and barrels (bbl) or m^3 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^3 (m^3). 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^3 (700 m^3) 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^3/hr (700 m^3/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.

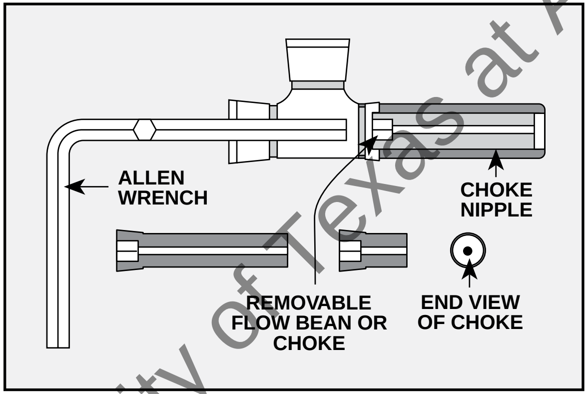


Figure 10.1 Fixed flow bean

Variable Flow Beans

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

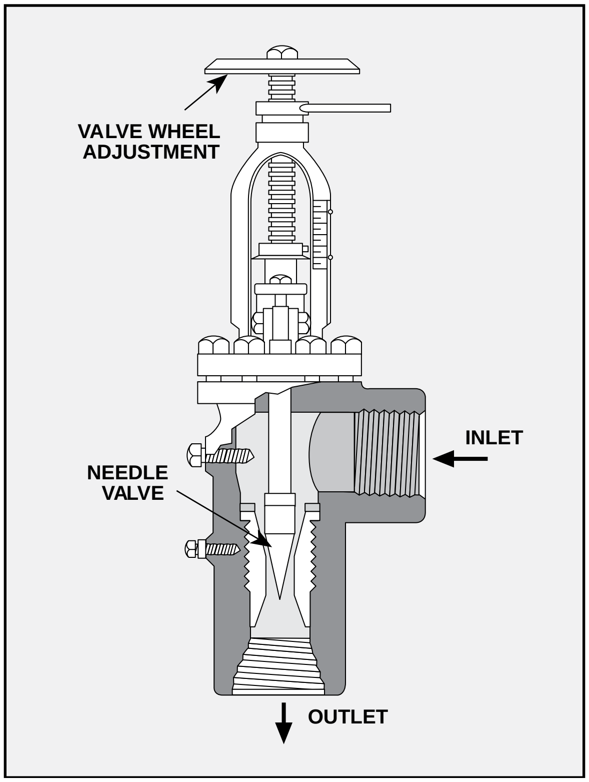


Figure 10.2 Adjustable flow bean

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—

$$^{\circ}\text{API} = \frac{140}{1} - 130 \qquad \text{(Eq. 11.1)}$$

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.

12

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 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.)

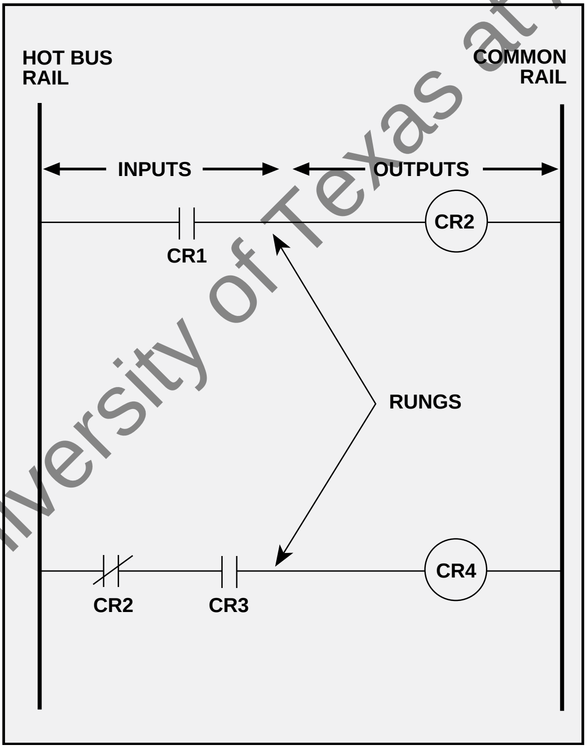


Figure 12.1 Typical relay ladder logic diagram

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

Index

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