Chapter 2

Control Loop Hardware

2.1 Introduction

The hardware used to implement feedback control loops in the CPI has a direct effect on the performance of these control loops. Control loop hardware is comprised of mechanical and electrical devices that perform the functions of the actuator, sensor, and controller. For example, to implement the control loops shown in Section 1.3, control loop hardware is required. To maintain the efficient operation of control loops, the control engineer must understand the control-relevant aspects of these devices.

Choosing the proper hardware for a control application and ensuring that it operates effectively are major responsibilities of control engineers. In addition, when control loops are not functioning properly, control engineers must identify the source of the problem and correct it. Troubleshooting control loops is addressed in Chapter 8. To accomplish these tasks, control engineers must understand the control-relevant issues associated with each of the components that make up a control loop. This chapter will describe the hardware components that comprise a typical feedback control loop used in the CPI by providing an overview of the design approaches and performance measures for these components. Since a complete description of these devices is beyond the scope of this text, the descriptions here will focus on their control-relevant aspects.

Figure 2.1 is a schematic of a feedback control loop for a temperature controller on the CST thermal mixer (Figure 1.4). This feedback control loop consists of a controller, a final control element, a process, and a sensor. Figure 2.2 is a schematic of the hardware that comprises this feedback temperature control loop as well as the signals that are passed between the various hardware components. The sensor system in Figure 2.1 corresponds to the thermowell, thermocouple, and transmitter in Figure 2.2 while the actuator system in Figure 2.1 corresponds to the control valve, I/P converter, and instrument air system in Figure 2.2. Likewise, the controller in Figure 2.1 consists of the A/D and D/A converters, the DCS, and the operator console in Figure 2.2. The abbreviations used in this paragraph are described in the next several sections.

A thermocouple is used to measure the temperature inside the mixing tank and is placed in thermal contact with the process fluid leaving the mixing tank by means of

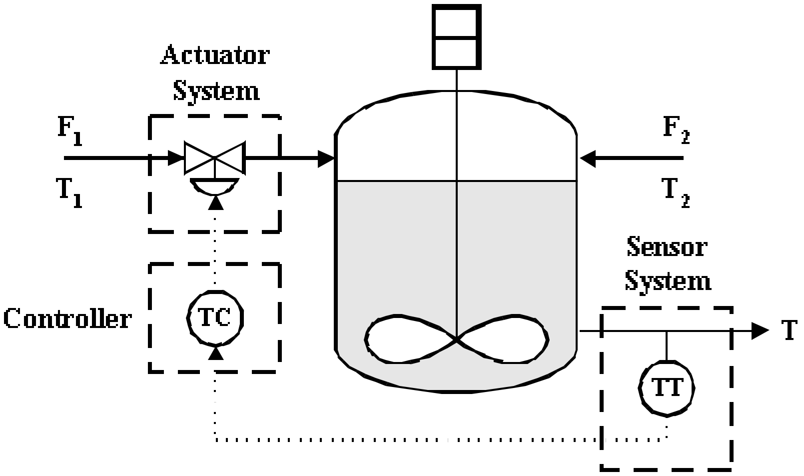

Figure 2.1 Schematic of the CST thermal mixer showing the actuator system, sensor system, controller, and the process.

a thermowell in the product line. The temperature transmitter converts the millivolt signal generated by the thermocouple into a 4-20 mA analog electrical signal that is proportional to the temperature inside the thermowell. When the thermocouple/transmitter system is calibrated properly and when the thermowell is correctly designed and located, the value of the analog signal will correspond closely to the temperature in the mixing tank. The thermocouple/thermowell/temperature transmitter comprises the sensor system for this process.

The 4-20 mA analog signal from the temperature transmitter is converted into a digital reading by the **analog-to-digital (A/D) converter**. The output of the A/D

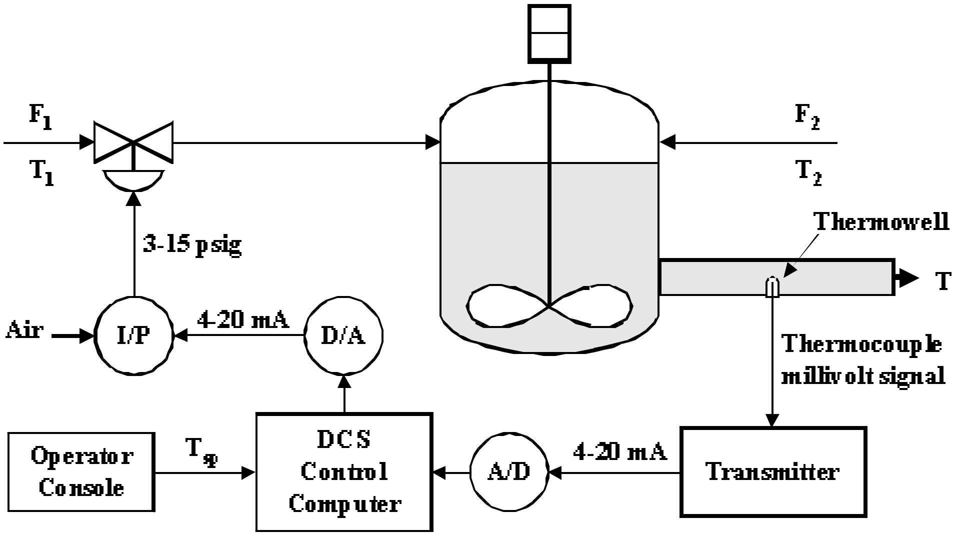

Figure 2.2 Schematic of the control system on the CST thermal mixer showing each component along with the various signals.

converter is a digital measurement of the temperature that is used in the control calculations. The operator console shown in Figure 2.2 allows the operator or control engineer to observe the performance of the control loop and to change the setpoint, T_{sp}, and controller tuning parameters for this loop. The value of T_{sp} and the digital value of the measured mixer temperature are used by the control algorithm in the **distributed control system**, (**DCS**, i.e., the control computer). The output from the controller is a digital signal that is converted into a 4-20 mA analog signal by the **digital-to-analog (D/A) converter**. The DCS, D/A and A/D converters, and the operator consoles are typically located in a centralized control room while the remaining equipment resides in the field near the process equipment.

The 4-20 mA analog signal from the D/A converter goes to the **current-to-air pressure** (**I/P**) **converter**. The I/P converter uses a source of instrument air to change the air pressure (3-15 psig) applied to the control valve corresponding to the value of the analog signal. That is, if I is the value of the analog signal and P is the instrument air pressure delivered to the control valve,

$$\frac{I-4}{16} = \frac{P-3}{12} \tag{2.1}$$

since a 4 to 20 mA range in the analog signal corresponds to a 3 to 15 psig range in the instrument air pressure and the zero of the analog signal is 4 mA and the zero of the pneumatic signal is 3 psig. Changes of instrument air pressure to the control valve cause changes in the stem position of the control valve, which result in changes in the flow rate to the process. These changes in the flow rate to the process cause changes in the temperature of the mixer, which are measured by the sensor, completing the feedback control loop. The final control element consists of the I/P converter, the instrument air system, and the control valve.

The ability to effectively troubleshoot a control loop requires the knowledge of the components that actually implement the control loop as well as the signals that are passed between these elements. This chapter considers the design and control-relevant aspects of the DCS, the actuator system, and several commonly encountered sensors.

Example 2.1 Conversion of Signals within a Feedback Loop

Problem Statement. Determine the value of the 4-20 mA signal to the I/P converter and the pneumatic signal to the control valve in Figure 2.2 if the controller output is 75% of full range.

Solution. A controller output signal equal to 75% of full range would result in a 4-20 mA signal of

$$I = 4 + 0.75\,[20 - 4] = 16\ mA$$

since a zero controller output corresponds to a 4 mA signal and the range of the analog signal is the maximum reading (20 mA) minus the minimum reading (4 mA). To calculate the strength of the pneumatic signal, rearrange Equation 2.1, i.e.,

$$P = 3 + \frac{12}{16}\left[16 - 4\right] = 12 \ psig$$

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2.2 Distributed Control System

Background. Pneumatic PID controllers were introduced in the 1920's and were in widespread use by the mid 1930's. Pneumatic controllers use bellows, baffles, and nozzles with a supply of air pressure to apply control action. That is, the pneumatic controller receives a pneumatic signal corresponding to the error between the measured value of the controlled variable and the setpoint and acts on this signal with a bellows, baffle, and nozzle in conjunction with the instrument air system to produce a pneumatic signal that is sent to the control valve. For the early versions of pneumatic controllers, the controllers were installed in the field near the sensors and control valves. In the late 1930's, transmitter-type pneumatic controllers began to replace the field-mounted pneumatic controllers because of the increase in size and complexity of the processes being controlled. For the transmitter-type pneumatic controllers, the sensor readings were converted into pneumatic signals (i.e., 3-15 psig) that were conveyed by metal tubing into the control room where the pneumatic controller determined the control action. In turn, the control action was pneumatically transmitted to the actuator on the process. Since the transmitter-type pneumatic controllers were typically located in a central control room, operators could conveniently address the overall control of the process using a number of controllers from a centralized location.

In the late 1950's, electronic controllers (i.e., electronic analog controllers) became commercially available. These devices use capacitors, resistors and inductors to implement control action. Since electronic transmitters were used (i.e., the output from the sensor was converted to a 4-20 mA signal and the 4-20 mA controller output signal was converted to a pneumatic signal by the I/P converter), the use of electronic analog controllers eliminated the need for long runs of metal tubing by using electrical wires greatly reducing the installation costs and resulting in faster responding controllers. By 1970, the sales of electronic controllers exceeded the sales of pneumatic controllers in the CPI[1].

The first supervisory computer control system was installed in a refinery in 1959. A simplified schematic of a supervisory computer control system is shown in Figure 2.3. Note that this system offered data storage and acquisition as well as control loop alarms that previous control systems did not offer. In addition, the centralized computer could use the available operating data to determine the setpoints for certain

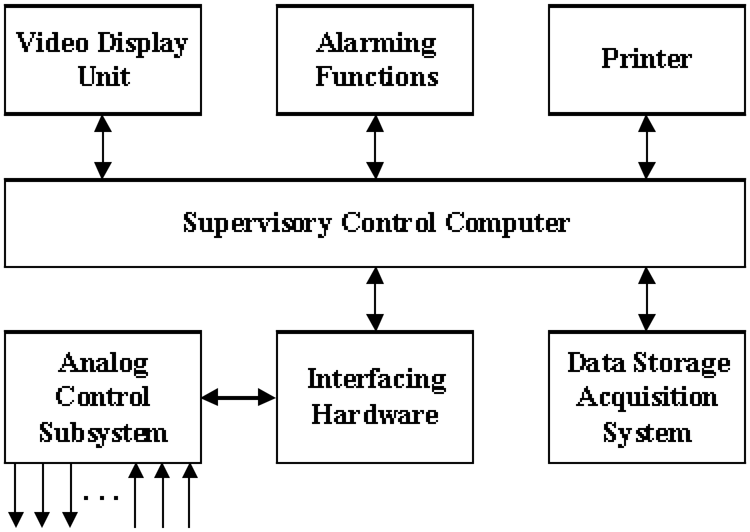

Figure 2.3 Block diagram of a supervisory control system.

key control loops in an effort to obtain the most efficient operation of the plant (i.e., process optimization).

The biggest disadvantage of the centralized control computer approach was that if the control computer failed, the entire control system would be shut down. A redundant control computer was an expensive alternative and not always reliable. Due to the technological breakthroughs in computers and associated systems in the 1970's, a new computer control architecture was developed and introduced by vendors in the late 1970's. This architecture was based on using a number of **local control units (LCUs)**, which had their own microprocessors and were connected together by **shared communication lines** (i.e., a **data highway**) as well as connected to operator/engineer consoles, a data acquisition system, and a general purpose computer. This computer control architecture became known as a **distributed control system (DCS)** (Figure 2.4) since it involved a network with various control functions distributed for a variety of users.

The advantages of a DCS over a centralized control computer result from the use of microprocessors for the local control function. Even if a microprocessor were to fail, only the control loops serviced by that LCU would be affected. A redundant microprocessor that performs the same calculations as the primary microprocessor (i.e., a hot backup) greatly increases the system's reliability. As a result, the probability that all the control loops will fail at the same time, or even a major portion of the control loops will fail, is greatly reduced in comparison to a centralized control computer. In addition, the DCS is much easier to expand. That is, to increase the number of control loops serviced by the DCS, only a primary and a redundant LCU need to be added. The modular nature of DCSs can be a major economic advantage for plants that undergo expansion. In comparing a DCS to electronic analog controllers, the application of conventional controls is generally equivalent, but implementing controllers is much easier and less expensive per loop using a DCS.

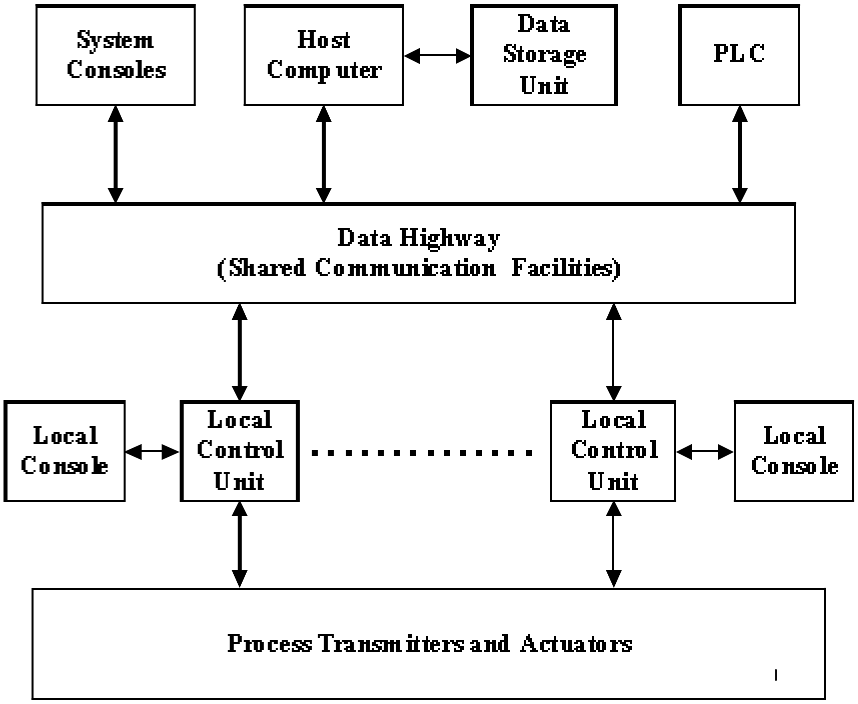

Figure 2.4 Generalized block diagram of a DCS.

Structure of a DCS. A generalized schematic of a DCS is shown in Figure 2.4. A number of LCUs, which contain redundant microprocessors, perform the control functions for the process in a distributed fashion. Each LCU has several consoles attached to it. The consoles (**video display units**, **VDUs**), which utilize **cathode ray tubes** (**CRTs**), have video displays that show process schematics with current process measurements. Operators and control engineers use these displays to monitor the behavior of the process, set up control loops, and enter setpoints and tuning parameters. A photograph of a typical control room for a DCS is shown in Figure 2.5. Normally, these consoles have touch screen capability so that if operators want to make a change to a control loop, they touch the icon for the controller in which they are interested. Then a screen pops up that allows the operator to make the desired changes. On some DCSs, control loops can be conveniently set up by clicking and dragging the tags for the desired sensor readings and the final control elements and connecting them to the type of controller that is chosen. Since the LCU is attached to the shared communications facility, a local display console can view schematics and current operating data for other parts of the plant, but typically can make changes only to the control loops associated with its LCU. The local console can also be used to display historical trends of process measurements. To do this, the local console must access historical data in the data storage unit by using the data highway (i.e., the shared communication facilities).

Data acquisition is accomplished by transferring the process measurements from the LCUs, through the data highway, and into the host computer where the

Figure 2.5 Photograph of a control room for a DCS. Courtesy of Honeywell.

process data are passed on to the data storage unit. The archived process data can be accessed from one of the system consoles or one of the local consoles. In control rooms that used electronic analog controllers, data storage for important control loops was typically accomplished using a strip chart recorder, which printed measurements on a small roll of paper in different colors of ink.

The data highway holds the entire DCS together by allowing each modular element and each global element to share data and communicate with each other. The data highway is composed of one or more levels of communication hardware and the associated software. System consoles are directly attached to the data highway and can act as a local console for any of the local control units. In addition, system consoles can be used to change linking functions of the distributed elements. The host computer is a mainframe computer that is used for data storage, process optimization calculations, and the application of advanced process control approaches. Attached to the host computer is the data storage unit (usually a magnetic tape-based system) where archived data are stored.

DCS Performance and Use. The goal of a DCS is to apply the control calculations for each control loop so fast that the control appears continuous. Since DCSs are based upon sequential processors, each control loop is applied at a discrete point in time and the control action is held constant at that level until the next time the controller is executed. The time between subsequent calls to a controller applied by the DCS is called the **controller cycle time** or the **control interval**. Unfortunately, **the fastest cycle times for controller calls within a DCS are typically in the range of**

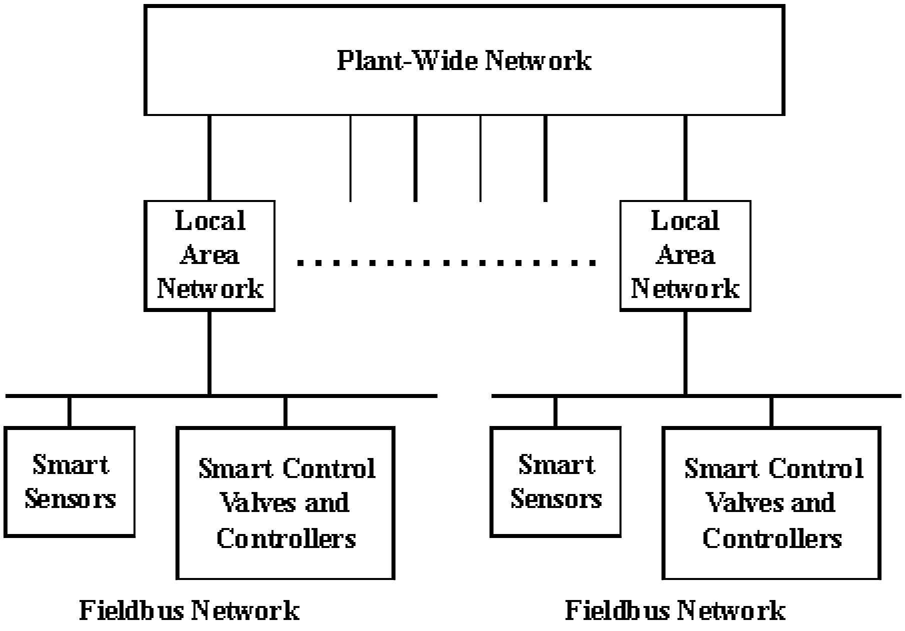

Figure 2.6 Schematic of the integration of the fieldbus with plant networks.

0.2 seconds while most loops are called only every 0.5 to 1.0 seconds. The regulatory control loops typically use control intervals in the range of 0.5 to 2.0 seconds while supervisory control is typically applied with control intervals of 20 seconds up to several minutes. While this controller cycle time does not present a limitation for slower control loops such as level, temperature, and composition control loops, it does present a limitation for fast control loops such as flow controllers and some pressure controllers. A real-time control system for the DCS is used to enforce a priority ranking of control functions. That is, certain high-priority control loops are maintained at the expense of less important loops.

Since DCSs are based on digital controller calculations, a wide variety of special control options are available in self contained modular form and can be easily selected by “click and drag” action on most DCSs. In this manner, complex control configurations can be conveniently assembled, interfaced, and implemented. In addition, a variety of signal conditioning techniques, including filtering and validity checks, can be applied to process measurements.

Programmable Logic Controllers (PLCs). **Programmable logic controllers** have been used primarily in the CPI for controlling batch processes and for sequencing of process startup and shutdown operations. PLCs have been traditionally based on **ladder logic**, which allows the user to specify a series of discrete operations, e.g., start the flow to the reactor until the level reaches a specified value, next start steam flow to the heat exchanger until the reactor temperature reaches a specified level, next start catalyst flow to the reactor, etc. A small PLC can be responsible for monitoring about 100 separate operations while a large PLC can handle over 1000 operations. Today the distinction between PLCs and DCSs has become less clear since PLCs are being designed to implement conventional and advanced control algorithms and DCSs that provide control for sequenced operations are being offered. PLCs are typically attached to the data highway in a DCS (Figure 2.4) and provide sequenced control functions during startup, shutdown, and override of the normal controllers in the event of an unsafe operating condition.

Fieldbus Technology. The fieldbus approach to distributed control is shown in Figure 2.6. The fieldbus approach distributes control to intelligent field-mounted devices (i.e., sensors, valves, and controllers with onboard microprocessors, which are used for complex operations and diagnostics) using a high-speed, digital two-way communication system that connects the field-mounted devices with **Local Area Networks** (**LAN**'s), process automation systems, and the plant-wide network. This high-speed communication system is similar to the data highway used by DCSs. While supervisory and advanced control functions are implemented in the LANs, the regulatory control functions are handled by the field mounted devices on the fieldbus network. The advantage of the fieldbus design comes from the fact that instead of running electrical wires from each sensor/transmitter to the centralized control room and from the control room to each final control element, a large number of field mounted devices can be attached to a single two-wire communication line. This results in a significant reduction in the time and cost associated with system installation. Fieldbus technology is just beginning to be available commercially, but is expected to move regulatory controls from DCSs into the field in the future.

A conventional DCS is not equipped to handle the extra information assoicated with fieldbus devices. DCSs are currently being designed with the compatability to fieldbus devices. As an example of this, Fisher-Rosemont's Delta-V DCS has an architecture that affords the complete utilization of fieldbus systems and other special purpose control hardware, and one DCS can service up to 30,000 control loops. The Delta-V DCS uses an ether net as its data highway and uses off-the-self PC's as its LCU microprocessors; therefore, this architecture is significantly less expensive than a traditional DCS.

2.3 Actuator Systems (Final Control Elements)

The actuator system for a process control system in the CPI is typically comprised of the control valve, the valve actuator, the I/P transmitter, and the instrument air system. The actuator system is known industrially as the final control element. In addition, there is a variety of optional equipment, such as valve stem positioners and instrument air boosters, that is designed to enhance the performance of the actuator system.

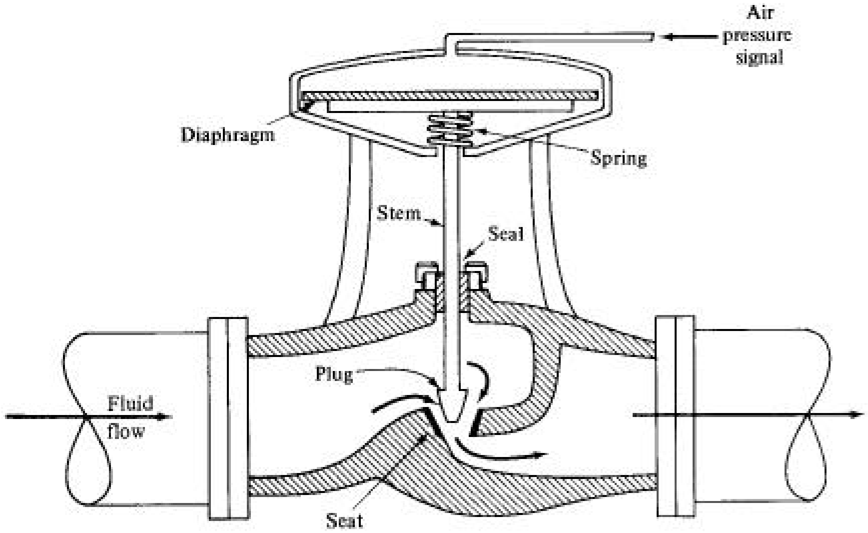

Figure 2.7 Schematic globe control valve. Reprinted with permission from the McGraw-Hill Publishing Company.

Control Valves. The most common type of control valve in the CPI is the globe valve. Figure 2.7 shows a schematic of a globe valve. For globe valves, the closure member is called a **valve plug** and is positioned at the end of the **valve stem**. As the valve stem is lowered, the plug approaches the **valve seat**, restricting the area for flow through the valve. When the plug makes contact with the valve seat, the valve is closed and flow through the valve is shut off. Globe valves are characterized by the fact that the plug travels in a direction perpendicular to the valve seat. The top of the valve stem is attached to a diaphragm and a spring, which opposes the force of the instrument air on the diaphragm. As an example, consider Figure 2.7 for which, as the instrument air pressure is increased, the diaphragm moves against the spring, moving the stem downward, thus moving the valve plug closer to the valve seat, reducing the flow through the valve. Likewise, when the air pressure is decreased, the flow through the valve increases. Therefore, changes in the instrument air pressure coming from the I/P converter are able to affect changes in the flow rate through the control valve.

Figure 2.8 shows a detailed cross-section of a globe control valve with a plug in a **cage-guided valve** arrangement along with notation indicating some of the key components of a control valve and valve actuator. The cage provides guidance for the plug as the plug moves toward or away from valve seat. The cage also provides part of the flow restriction produced by the control valve. An example of a cage for a globe valve is shown in Figure 2.9. The valve packing reduces the leakage of the process stream into the environment but provides resistance to movement of the valve stem and contributes to sticking of the valve. The travel indicator provides a visual indication of the valve stem position.

Figure 2.10 shows the valve body assembly for a globe valve with an unbalanced plug. The unbalanced plug is subject to a static force directly related to the

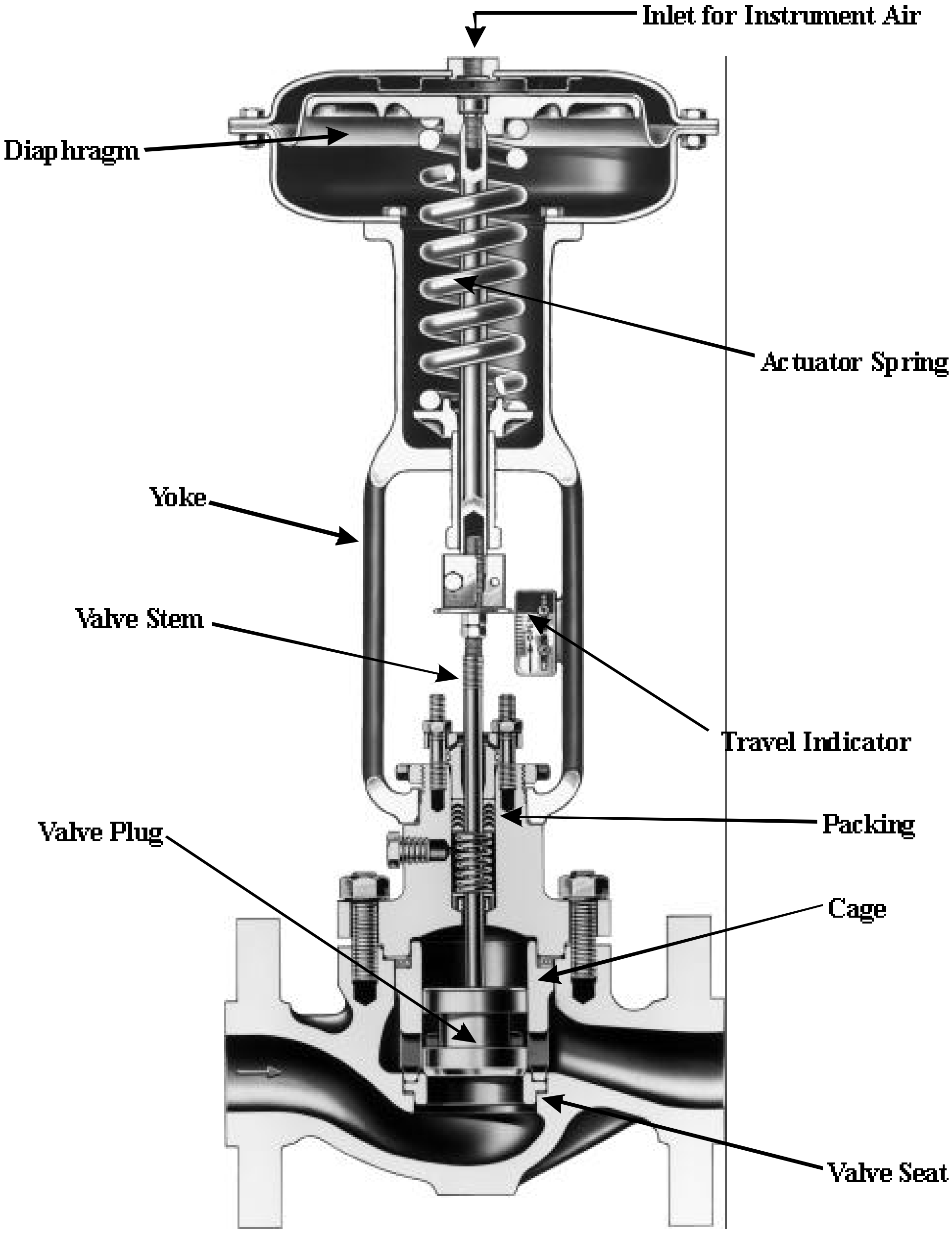

Figure 2.8 Cross-section of a globe valve with an unbalanced plug. Courtesy of Fisher-Rosemont.

Figure 2.9 Photograph of a cage for an equal percentage valve. Courtesy of Fisher-Rosemont.

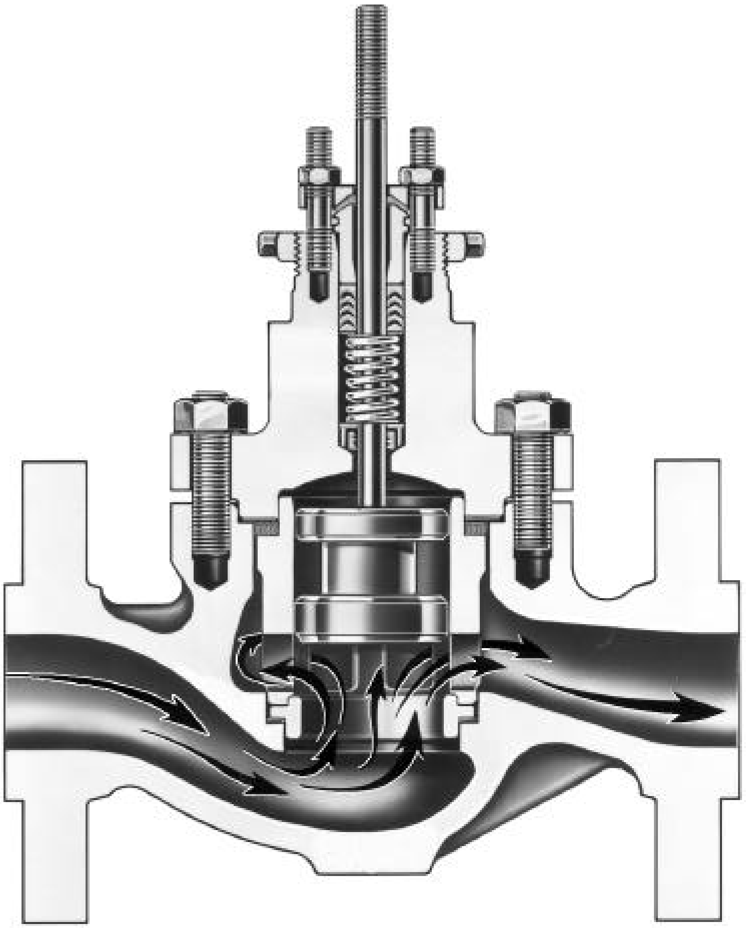

Figure 2.10 Cross-section of a globe valve body assembly with an unbalanced plug. Courtesy of Fisher-Rosemont.

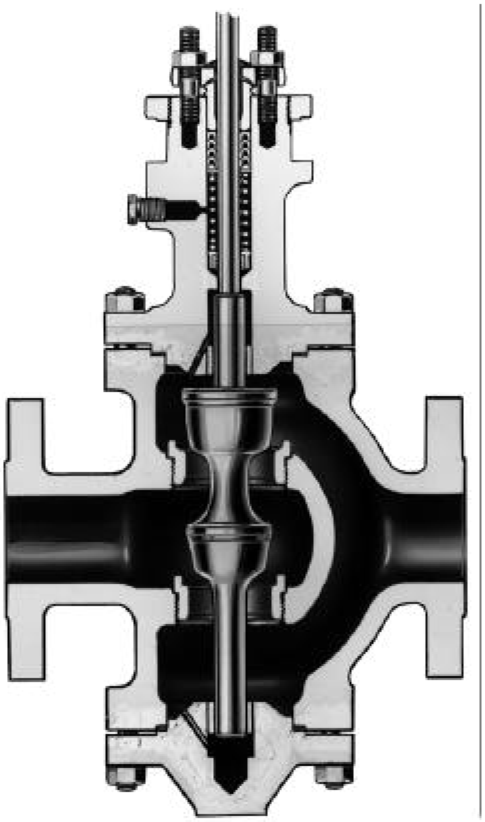

Figure 2.11 Cross-section of a globe valve body assembly with a balanced plug. Courtesy of Fisher-Rosemont.

pressure drop across the valve and a shear force due to the fluid velocity past the plug. The greater these forces, the more force that is required to close the valve and the less force that is required to open the valve. Note that for Figure 2.7, it requires more force to open than to close due to the pressure drop and shear forces on plug. Figure 2.11 shows the valve body assembly for a globe valve with balanced plugs. This valve is referred as having balanced plugs because the top and bottom of the plug are subjected to the same downstream pressure when the valve is closed. Thus, the static force on the valve stem is low. In addition, the shear forces also cancel each other. Valves with balanced plugs are preferred because they tend to be faster responding than valves with unbalanced plugs and require smaller valve actuators, but they should only be used with clean liquids. For example, an unbalanced plug would be preferred for service with a liquid that tends to crystallize on the surface of the valve plug unless shear forces are present to prevent the buildup of crystals. A balanced plug will be more susceptible to buildup due to the lower velocity by the plug because there are two separate flow paths.

Sizing of control valves is important because if the valve is oversized or undersized, it can significantly affect the range over which the valve provides precise flow metering. When the valve is oversized, the valve is not sufficiently open to allow

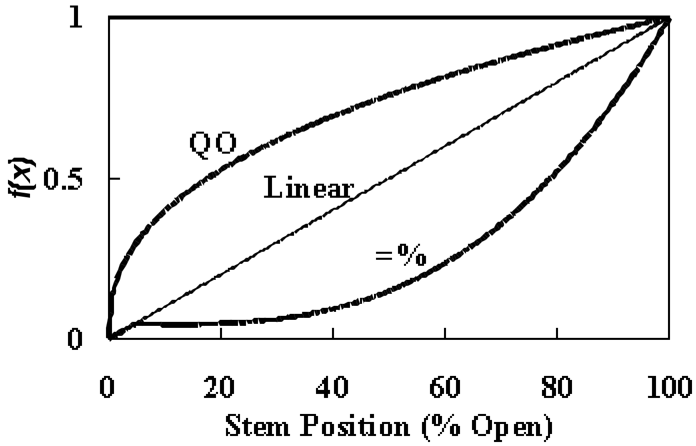

Figure 2.12 Inherent valve characteristics for a quick opening (QO), linear, and equal percentage valve (=%).

the valve to accurately control the flow rate. That is, when the valve plug is very close to the valve seat, large shear forces act on the plug, which tend to completely close the valve. A similar situation occurs when one tries to slowly put a drain plug in a bath tub drain while water in flowing into the drain. When the valve is undersized, the valve may be almost fully open so that accurate control is not possible or in certain cases the required flow cannot be met even when the valve is fully open. A simplified valve flow equation based on incompressible flow is given by

$$Q_f = K C_v(x) \sqrt{(P_1 - P_2)/\rho} \qquad \textbf{2.2}$$

where Q_f is the flow rate through the valve, K is a constant that depends on the units used in this equation, $C_v(x)$ is the valve coefficient, which is dependent upon the stem position (x) [i.e., $C_v(x) = C_v^{\max}$ when the valve is fully open (i.e., x equal to 100%) and $C_v(x)=0$ when the valve is closed], ρ is the density of the fluid, P_1 is the pressure at the inlet to the control valve, and P_2 is the pressure at the exit of the control valve. **Note that the values of C_v are chosen such that K is equal to unity when the density is expressed as the specific gravity, presssure drop (i.e., P_1-P_2) is given in psi, and the flow rate is expressed in GPM.** A more complex representations is required for compressible flow through a control valve.

In general, control valves should be designed so that the valve provides accurate metering of the flow over a wide operating range conservatively below fully open and above the closed position. This will reduce the likelihood that the valve will be expected to operate nearly fully open or fully closed where flow control performance is generally poor. The correct size of the valve should be selected as well as the proper type of valve to provide a wide operating range.

Figure 2.12 shows how $f(x)$ varies with stem position for three types of valves: a quick opening valve, an equal percentage valve, and a linear valve where

$$f(x) = \frac{C_v(x)}{C_v^{\max}} \tag{2.3}$$

This figure shows the **inherent valve characteristics** for these types of control valves, which indicate how the flow rate through the valve varies with stem position for a **fixed pressure drop across the valve**. The design of the plugs, valve seats, and cages (where applied) determine the particular flow versus stem position that a control valve provides. That is, the shape of the valve plug and the flow openings in the cage determine the shape of the flow restriction as the valve stem position is changed. For example for a quick opening valve, as the valve is opened from fully closed, the cross-sectional area of the restriction of the valve increases much faster than the linear or equal percentage valves. Quick opening valves are not usually used for feedback flow control applications but are used in cases where it is important to start a flow rate as quickly as possible (e.g., coolant flow through a by-pass around a control valve for an exothermic reactor). Linear and equal percentage valves are primarily used for flow control applications in the CPI. Table 2.1 list the C_v's for various sizes of a specific equal percentage valve as a function of stem position expressed as a percentage of total travel. Other types of equal percentage valves will have different values of C_v's than the ones listed in Table 2.1. Note that the values in Table 2.1 could be used to generate the inherent valve characteristics for the different valve sizes by applying Equation 2.3 recognizing that C_v^{max} is the value of C_v for the stem position a 100% open. The following equation represents C_v for a linear valve as a function of total valve travel, x.

$$C_v(x) = C_v^{\max}\left[\frac{x}{100}\right] \tag{2.4}$$

Table 2.1 Representative C_v's for an Equal Percentage Globe Valve.

	Body Size (in)	**Stem Position as a Percentage of Total Travel**									
		10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
C_v	1	0.79	1.25	1.80	2.53	3.63	5.28	7.59	10.7	12.7	13.2
	1.5	0.80	1.23	1.91	2.95	4.30	6.46	9.84	16.4	22.2	28.1
	2	1.65	2.61	4.30	6.62	11.1	20.7	32.8	44.7	50.0	53.8
	3	3.11	5.77	9.12	13.7	21.7	36.0	60.4	86.4	104	114
	4	4.90	8.19	13.5	20.1	31.2	52.6	96.7	140	170	190

Example 2.2 Flow Rate through a Control Valve

Problem Statement. Calculate the flow rate of water through a 4-inch equal percentage control valve that is 80% open with an available pressure drop across the valve of 30 psi. Obtain the C_v for this valve from Table 2.1

Solution. Using Equation 2.2 with C_v equal to 140 from Table 2.1 and the specific gravity and K are equal to unity:

$$Q_f = 140\sqrt{30/1} = 767\ GPM$$

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Example 2.3 Pressure Drop Across a Control Valve

Problem Statement. Calculate the required pressure drop across a 2-inch equal percentage control valve that is 40% open for a flow rate of water of 35 GPM. Obtain the C_v for this valve from Table 2.1

Solution. Rearranging Equation 2.2 to solve for ΔP yields

$$\Delta P = \frac{\rho Q_f^2}{K^2 C_v^2}$$

Substituting C_v equal to 6.62 with the specific gravity and K equal to unity yields 28.0 psi.

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The inherent valve characteristics of a control valve are based on a fixed pressure drop across the valve. For most applications, however, the pressure drop across a control valve varies with the flow rate. The **installed valve characteristic** gives the flow rate through the valve as a function of stem position for a valve in service in a flow system. The pressure drop across the valve is a function of the flow rate; therefore, the installed valve characteristics depend on the particular flow system to which the valve is applied. From a process control standpoint, it is desirable to have a control valve that exhibits a linear relationship between flow rate and stem position over a wide range for the installed valve. As a rule of thumb, **the slope of the installed valve characteristic versus stem position should not vary greater than a factor of four over the range of operation for effective flow control.**

Table 2.2 Pressure Drop of an Installed 3-inch Equal Percentage Valve versus Flow Rate

Q (GPM)	ΔP (psi)	Q (GPM)	ΔP (psi)
50	19.3	74	18.0
54	19.1	78	17.8
58	18.9	82	17.5
62	18.7	86	17.2
66	18.5	90	16.9
70	18.3	94	16.6

Example 2.4 Determine the Installed Flow Rate for a Known Valve Stem Position.

Problem Statement. Determine the flow rate though a 3-inch equal percentage control valve that is 40% open for the C_v data given in Table 2.1 and the installed pressure drop presented in Table 2.2.

Solution. From Table 2.2, ΔP is a function of flow rate; therefore, an iterative solution of Equation 2.2 is required. From Table 2.1, C_v is 13.7 for a 3-inch valve that is 40% open. From Table 2.2, it is clear that installed pressure drop is not a strong function of flow rate; therefore, a flow rate can be assumed to calculate the pressure drop for the installed valve, and this value used to update the flow rate. Assuming that the flow rate is 94 GPM, the installed pressure drop is equal to 16.6 psi using Table 2.2, and then Equation 2.2 yields a flow rate of 55.8 GPM. Using this flow rate in Table 2.2, the pressure drop for the installed valve is 19.0 psi by linear interpolation. Once again, Equation 2.2 is applied, resulting a calculate flow rate of 59.7 GPM. Updating ΔP (18.8 psi) yields a flow rate of 59.4 GPM, which is the converged solution for this problem.

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Example 2.5 Comparison between Linear and Equal Percentage Valves

Problem Statement. Consider the flow system shown schematically in Figure 2.13. This schematic represents the flow system that is used to deliver reflux from the accumulator to the top tray of the column. Compare the installed valve characteristics for a 4-inch linear and a 4-inch equal percentage valve for this system. Use the C_v's for the equal percentage valve from Table 2.1. Assume that the lines are 3-inch schedule 40 piping.

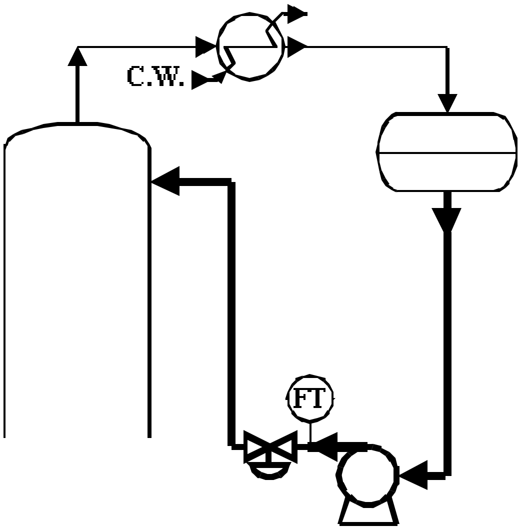

Figure 2.13 Schematic of a flow system for delivering reflux from the accumulator to the top tray of the column.

Solution. There are three sources of pressure changes in this flow system: (1) pressure drop through the straight run pipe, elbows and fittings, and the orifice for the flow sensor/transmitter, (2) the head increase provided by the pump, and (3) the pressure drop across the control valve. The first type of pressure drop varies directly with the square of the flow rate. The head increase provided by the pump (e.g., a centrifugal pump) decreases nonlinearly as the flow rate is increased. Because, for this example, the pressure above the liquid in the accumulator and the discharge pressure on the top tray of the column are approximately equal, the pressure drop across the control valve (ΔP_{valve}) is set by the difference between the head developed by the pump (ΔP_{pump}) and the pressure drop created by the line devices (ΔP_{line}), i.e.,

$$\Delta P_{valve} = \Delta P_{pump} - \Delta P_{line}$$

Figure 2.14 shows the pressure developed by the pump, the pressure drop due to line losses, and the available pressure drop for the control valve as a function of flow rate for the flow system shown in Figure 2.13. The relationships shown in this figure can be understood by recognizing that, at low flow rates, the pump head is at its largest value while the line losses are at their smallest. At this flow rate, the control valve must provide a relatively large pressure drop to maintain a low flow rate in the flow system. At large flow rates, the pump head is significantly reduced while the line losses are at their highest level. As a result, the control valve must provide a relatively small pressure drop to maintain the large flow rate in the flow system. For this case, the pressure drop across the control valve varies significantly with flow rate.

Using the pressure drop available for the control valve and the C_v's for a linear valve and an equal percentage valve (Table 2.1), the installed valve characteristics can be calculated using Equation 2.2. The C_v for a fully-open linear valve was assumed

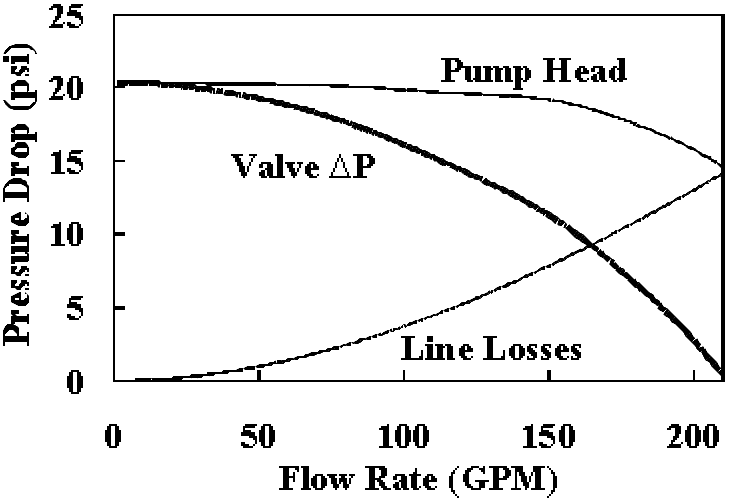

Figure 2.14 Pressure drops versus flow rate for the reflux flow system.

equal to the C_v for the fully open equal percentage valve. Then, the C_v for the linear valve is given using Equation 2.4. Since the available pressure drop is given as a function of flow rate in Figure 2.14, an iterative procedure is required to calculate the installed valve characteristics as shown in Example 2.4. Figure 2.15 shows the installed valve characteristics for a linear and equal percentage valve for this example.

While it is clear from Figure 2.15 that there are differences between the installed valve characteristics for a linear and an equal percentage valve, at first glance the performance of these two valves may not appear to be significantly different. Since the performance criterion for a valve is based on the change in the slope of the installed

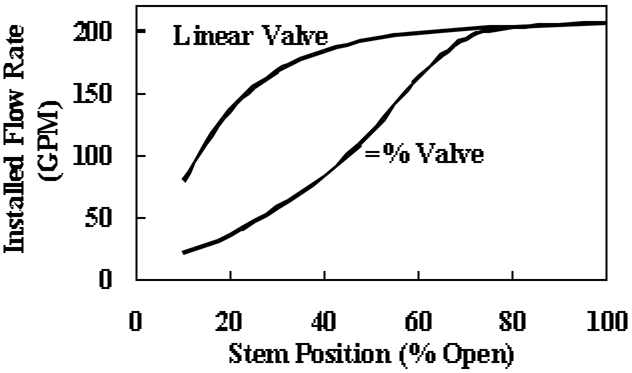

Figure 2.15 The installed valve characteristics of a linear and equal percentage valve for the reflux flow system.

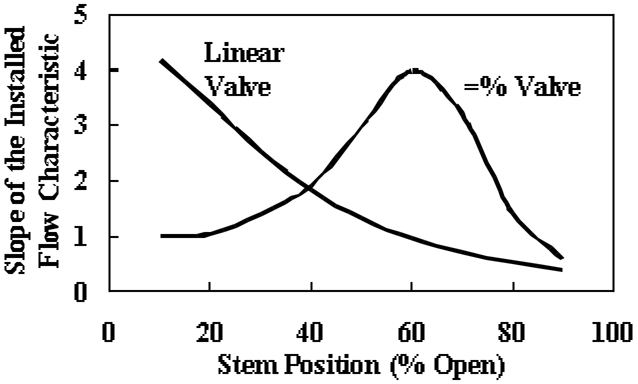

Figure 2.16 Slope of the installed valve characteristics for a linear and equal percentage valve.

valve characteristic, the slope of the installed valve characteristic (Figure 2.15) for the linear and equal percentage valves is shown in Figure 2.16. Based on the heuristic rule (i.e., the slope of the installed valve characteristic should be less than 4), the linear valve could operate effectively between 10% and 50% or between 50% and 90%. On the other hand, the equal percentage valve can operate effectively between 10% and 85%. **This example demonstrates the advantage of equal percentage valves compared to linear valves for cases in which the pressure drop across the control valve varies significantly with flow rate.**

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Example 2.6 Comparison between Linear and Equal Percentage Valves

Problem Statement. Consider the flow system shown in Figure 2.17. The 5-inch line discharges liquid from the tank to an open reservoir. Compare the installed valve characteristics for a 4-inch linear and a 4-inch equal percentage valve for this system. Use the C_v's for the equal percentage valve from Table 2.1.

Solution. The hydrostatic head (30 ft) provides the driving force for flow through this system while the line losses and the control valve cause pressure drop. Similar to the previous example, since the pressure above the liquid in the tank and the discharge pressure are assumed equal to atmospheric pressure, the pressure drop required by the control valve is given by

$$\Delta P_{valve} = \Delta P_{head} - \Delta P_{line}$$

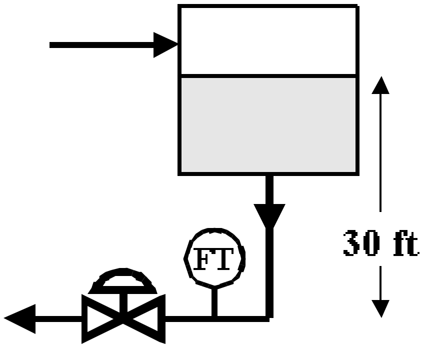

Figure 2.17 Schematic of a control valve in a line from an elevated tank to an open discharge.

Figure 2.18 shows the hydrostatic head, the pressure drop due to line losses, and the required pressure drop across the control valve as a function of flow rate. Since the level in the elevated tank is assumed to remain constant, the hydrostatic head is constant. Because **an oversized line was used for this example**, the line losses, which were modeled in a manner similar to the approach used for the last example, remain moderate even for the largest flow rate. As a result, the pressure drop for the control valve remains relatively constant for the full range of flow rates considered.

The installed valve characteristics for a linear valve and an equal percentage valve for this case are shown in Figure 2.19. These results were generated by choosing valve positions for the valves and applying the procedure demonstrated in Example 2.4 to determine the flow rate through the system. The available pressure drop for the control valve versus flow rate shown in Figure 2.18 was used in this procedure. The

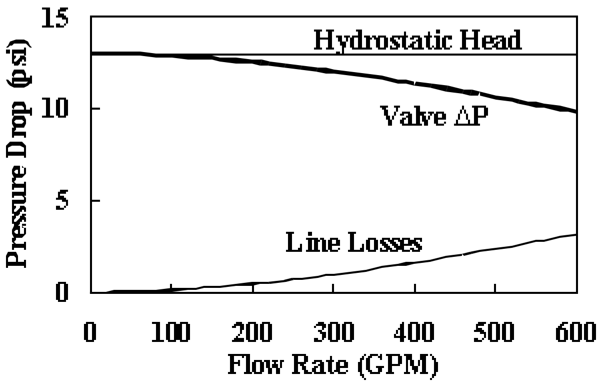

Figure 2.18 Pressure drop versus flow rate for the discharge line from the elevated tank.

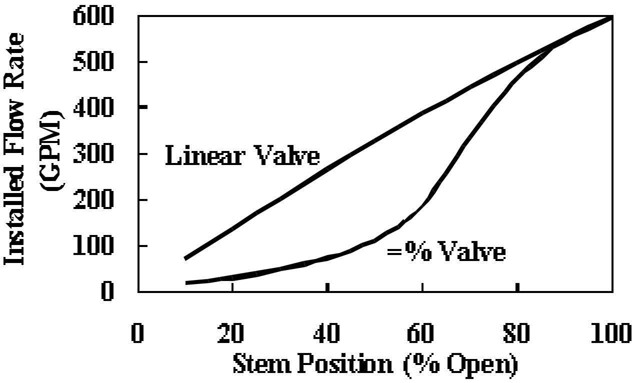

Figure 2.19 Installed valve characteristics for a linear and equal percentage valve applied to the discharge line for the elevated tank.

C_v's for the equal percentage value were taken from Table 2.1. The C_v's for the linear valve were determined using Equation 2.4 assuming that the maximum value of C_v for the linear valve is equal to the maximum C_v for the equal percentage valve. From an examination of Figure 2.19, it is clear that the linear valve is the preferred choice in this case because its installed valve characteristic is much more linear than for the equal percentage valve. **This example demonstrates the advantage of linear valves compared to equal percentage valves for cases in which the pressure drop across the control valve does not vary significantly with flow rate.**

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In approximately 10% of the control valve applications in the CPI, the pressure drop across the control valve remains relatively constant, and a linear control valve is preferred. Figure 2.20 shows a case in which the flow rate of steam is manipulated to heat a process stream. Since the pressure losses in the lines are usually relatively small compared to the pressure difference between the steam header and the steam pressure in the heat exchanger, the pressure drop across the control valve remains relatively constant for the wide range of steam flow rates to the heat exchanger. Since a linear control valve combined with a constant pressure drop across the valve results in a relatively linear installed characteristic, linear control valves are preferred when the pressure drop across a control valve remains relatively constant.

If the ratio of pressure drop across the control valve for lowest flow rate to highest flow rate is greater than 5, an equal percentage valve is recommended[2]. For Example 2.5 using Figure 2.16, the maximum flow rate is approximately 200 GPM. Then using Figure 2.14, the maximum pressure drop is approximately 20 psi and the minimum is approximately 3 psi; therefore, the ratio is 6.6, indicating that an equal percentage valve should be used. For Example 2.6, using Figure 2.19, the

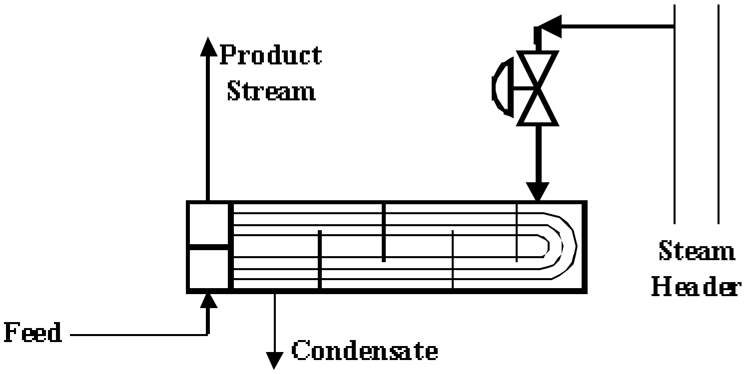

Figure 2.20 Schematic of a flow system from a steam header to a heat exchanger.

maximum flow rate is approximately 600 GPM. Then using Figure 2.18, the maximum pressure drop is approximately 13 psi and the minimum is approximately 10 psi; therefore, the ratio of the maximum to minimum pressure drops is 1.3, indicating that a linear valve should be used. It should be emphasized that the pressure drop remained relatively constant for Example 2.6 because an oversized line was used. Therefore, Examples 2.5 and 2.6 are consistent with this guideline. **A control valve can be converted to either a linear or equal percentage valve by changing the cage**, which is relatively easy to accomplish.

An important characteristic of a control valve is the **valve deadband**, which is a measure of how precisely a control valve can control the flow rate. The deadband for a steering system on an automobile would be the maximum positive and negative turn in the steering wheel that does not result in a noticeable change in direction of the automobile. For a control valve, deadband is the maximum positive or negative change in the signal to a control valve that does not produce a measurable change in the flow rate. Valve deadband is caused by the friction between the valve stem and valve packing and other forces on the valve stem. Typically, industrial control valves have a deadband of 10% to 25%. That is, for a 25% deadband, a change in the signal to the control valve that is greater than 25% will result in a measured change in the flow rate through the valve. On the other hand, a change that is less than 25% may not produce a change in the flow rate. Generally, the larger and older the control valve, the larger the deadband. A properly functioning valve with a valve positioner typically should have a deadband less than 0.5%. Note that deadband is reported in percent and represents the maximum relative change in the signal to the control valve that does not cause a measurable change in the flow rate through the valve.

Example 2.7 Control Valve Design Problem

Problem Statement. Size a control valve for service on a line carrying water with a maximum flow rate of 150 GPM and a minimum flow rate of 30 GPM. Assume an equal percentage valve with the pressure drop versus stem position shown in Figure

2.14. The C_v's for equal percentage valves of different sizes are presented in the Table 2.1.

Solution. A simplified design procedure will be used to size the valve for this application. The average flow rate (100 GPM) will be assumed to result when the valve is 67% open. This will allow us to size the valve, but after sizing, it is necessary to check to ensure that the valve can accurately control the flow at the maximum and minimum flow rates.

Equation 2.2 will be used to determine the C_v of the valve at 67% open. Then the valve size will be selected based on matching C_v values listed in Table 2.1. To apply Equation 2.2, the pressure drop at the average flow rate is used. From Figure 2.13, ΔP is approximately 16 psi at a flow rate of 100 GPM. Using Equation 2.2, C_v is calculated equal to 25.0. Using the C_v values given in Table 2.1, a 1.5-inch control valve would be approximately 95% open, a 2-inch value would be approximately 63% open, and a 3-inch value would be 52% open; therefore, based on the assumed design criterion, the 2-inch valve should be selected.

Now that the valve has been sized, check to ensure that accurate flow metering will be available for the maximum and minimum flow rates. First, check the valve stem position for the maximum flow rate (150 GPM). From Figure 2.14, the available pressure drop is approximately 11 psi; therefore, using Equation 2.2, C_v is equal to 45.2, which corresponds to a valve position of 81% using linear interpolation applied to Table 2.1 for a 2-inch valve. For the minimum flow rate (30 GPM), the available pressure drop is approximately 19 psi; therefore, C_v is equal to 6.9, which corresponds to a valve position 40% open. While this sizing should work, the largest flow rate is near the upper limit for controllability for a 2-inch valve. For a 3-inch valve, it would be 65% open at the maximum flow rate and 23% open at the minimum flow rate. From an examination of Figure 2.16, it is clear that the 3-inch valve is more nearly centered in the linear operation range of a control valve, and therefore, is preferred in this case. In fact, if the **turndown ratio** (i.e., the ratio of the maximum to minimum controllable flow rates) had been larger approaching the upper limit for a control valve (i.e., a turndown ratio of 9) while keeping the maximum flow rate set at 150 GPM, a 2-inch valve would have been selected. Since the turndown ratio is only 5, a 3-inch valve provides a more flexible solution, affording larger flow rates if necessary in the future.

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As the turndown ratio for a control valve increases, the proper sizing of the valve and specification of the valve plug and valve cage geometry, to meet the controllability requirement for the maximum and minimum flows, becomes a much more challenging problem because the valve must be able to accurately control the flow rate at the minimum and maximum flow rates. Control valve vendors typically offer software to size control valves, but the control engineer should ensure that the available pressure drop across the control valve versus flow that is used by the vendor to size the valve adequately represents the process.

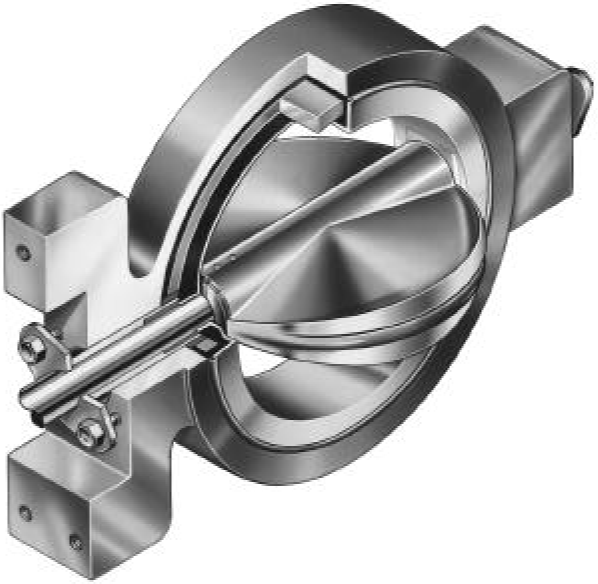

Figure 2.21 Partial cutaway view of a butterfly valve. Courtesy of Fisher-Rosemont.

When the turndown ratio is moderate (e.g., less than 3), a detailed valve sizing is not required. As a rule of thumb, when the turndown ratio is moderate, the valve size is usually set equal to the line size or one size smaller. For example, for a 4-inch line, a 3-inch or a 4-inch control valve would be selected. The key issue here is to ensure that the control valve can handle the maximum flow rate. That is, the control valve should be no more than 80% open for the maximum anticipated flow rate.

Butterfly valves. Figure 2.21 shows a cutaway drawing of a butterfly valve. A disk is attached to a shaft so that, as the shaft is rotated, the restriction to flow is changed. Butterfly valves are flanged into a line and have a motor and positioner attached to move the disk to a specified orientation and, therefore, regulate the flow rate through the valve. Butterfly valves are much less expensive than globe valves, but they usually have a range of accurate flow metering that is about half that of a globe valve. Butterfly valves become economically attractive as control valves for application with pipe diameters above 6 inches[2].

Cavitation. Cavitation results when the liquid vaporizes and implodes inside the control valve. As a fluid flows through a control valve the pressure drops sharply near the restriction between the valve plug and the valve seat due to high velocity in this region. As the fluid passes the valve restriction region and enters a region with a larger cross-section, the pressure increases sharply (i.e., pressure recovery) due to the drop in the fluid velocity. If the pressure in the valve restriction region is less than the vapor pressure of the liquid, a portion of the liquid will vaporize and, when the pressure recovers due to a drop in the velocity, the bubbles will violently collapse. Cavitation results in noise, vibration, reduced flow, and erosion of the body of the valve.

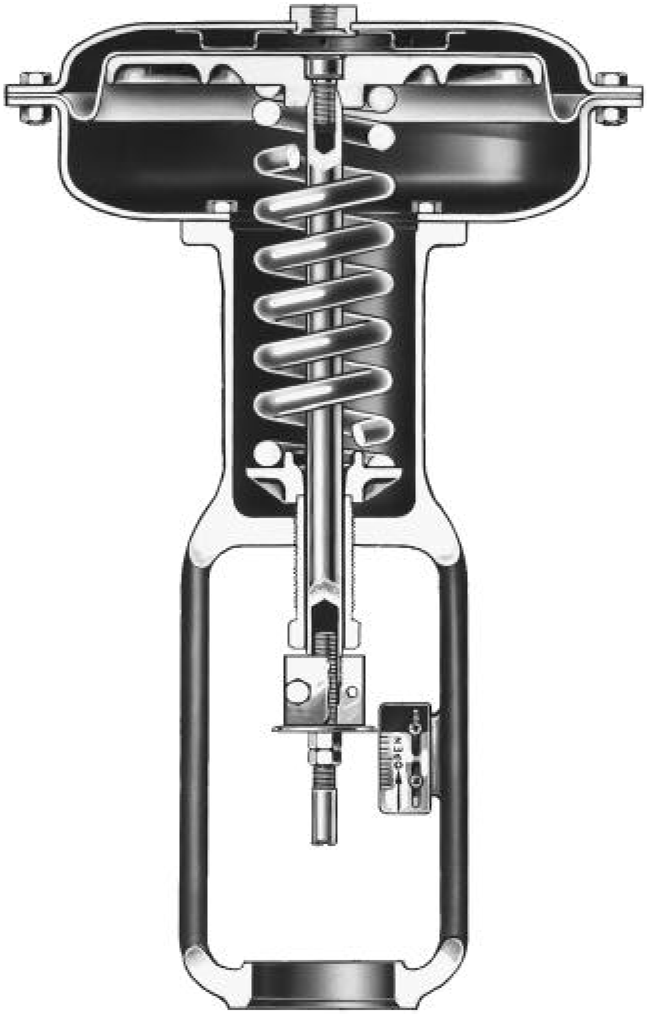

Figure 2.22 Cross-section of a valve actuator. Courtesy of Fisher Controls.

Valve Actuator. The valve actuator provides the force necessary to change the valve stem position and alter the flow rate through the valve. The valve actuator must provide the force necessary to overcome pressure forces, flow forces, friction from valve packing, and friction from the plug contacting the valve cage.

Figure 2.22 shows a cross-section of a typical **air-to-close actuator**. The pressure of the instrument air acts on the diaphragm/spring system from the top causing the valve to close as the air pressure supplied to the valve actuator is increased. The diaphragm is constructed of an air impermeable, flexible material that allows the valve plug to move from closed to fully open as the instrument air pressure is increased from 3 to 15 psig. Note that the force generated by the instrument air pressure on the

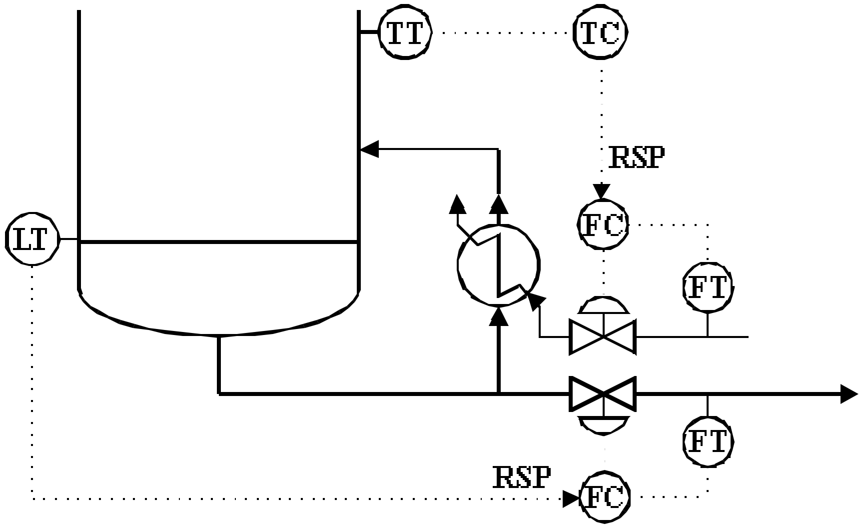

Figure 2.23 Stripping section of a distillation column.

surface of the diaphragm is balanced by the force of the compressed actuator spring (Figures 2.7, 2.8, and 2.22). An actuator with a control valve with an air-to-close valve actuator is also known as a **reverse-acting final control element** because the valve position decreases as the air pressure to the valve is increased. For an **air-to-open actuator**, the instrument air enters below the diaphragm so that, as the air pressure is increased, the valve stem moves upward, opening the valve. An actuator with a control valve with an air-to-open valve actuator is also known as a **direct-acting final control element** because the valve position increases as the air pressure to the valve is increased. Valve actuators generally provide a fail-safe function. That is, in the event of a loss of instrument air pressure, the valve actuator will cause the valve to open fully or to close. An actuator with an air-to-open unit will fail closed and an air-to-close unit will fail fully open. In this manner, a valve actuator can be chosen such that the proper failure mode is obtained. For example, consider the valve on the cooling water to an exothermic reactor. Obviously, an air-to-close actuator would be selected so that the loss of instrument air pressure would open the value and, therefore, cool down the reactor instead of allowing a thermal runaway.

Example 2.8 Valve Actuator Selection

Problem Statement. Consider the control valves for the stripping section of a distillation column shown in Figure 2.23. Determine whether air-to-open or air-to-close valve actuators should be used for the two valves in this case.

Solution. First consider the valve on the product line from the reboiler. If this valve fails (e.g., a loss of instrument air pressure), is it better for the valve to fail open or fail closed? In this case, if the valve was to fail open, the reboiler level could be lost, and the reboiler tubes could be exposed, causing damage due to overheating by the steam;

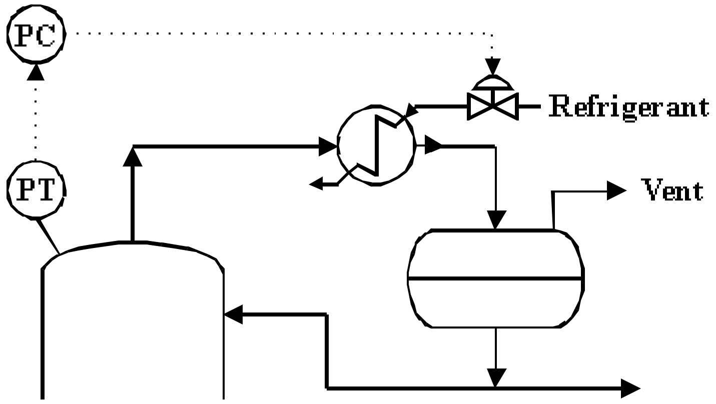

Figure 2.24 Schematic of an overhead condenser of a distillation column.

therefore, an air-to-open valve actuator should be selected for the valve actuator on the valve on the bottoms product line. Likewise, an air-to-open valve should be selected to prevent excessive steam flow to the reboiler in the event that the actuator on the steam valve were to fail. Excessive steam flow to the reboiler could also expose the reboiler tubes even though the valve on the bottom product line is closed.

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Example 2.9 Valve Actuator Selection

Problem Statement. Consider the control valve on the refrigerant for the overhead condenser for the rectifying section of a distillation column shown in Figure 2.24. Determine whether an air-to-open or an air-to-close valve actuator should be used for this valve.

Solution. If the valve on the refrigerant were to fail closed, the pressure in the column would increase sharply and require venting of a significant amount of overhead product; therefore, an air-to-close valve should be selected for this application. During a valve failure, the column would use more refrigerant than necessary and the column will over-purify the overhead product if an air-to-close actuator were used, but venting from the column would be avoided.

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I/P Transmitter. The I/P transmitter is an electro-mechanical device, which converts the 4-20 mA signal from the controller to a 3-15 psig instrument air pressure signal to the valve actuator, which in turn affects the valve stem position.

Figure 2.25 Photograph of a globe valve with a pneumatic valve positioner. Courtesy of Fisher-Rosemont.

Optional equipment. Several devices are available for improving the overall performance of final control elements.

Valve positioners. The **valve positioner** (Figure 2.25), which is usually contained in its own box and is mounted on the side of the valve actuator, is designed to control the valve stem position at a prescribed position in spite of packing friction and other forces on the stem. The valve positioner itself is a feedback controller that compares the measured stem position with the specified stem position and makes adjustments to the instrument air pressure to provide the desired stem position. In this case, the setpoint for the valve positioner can be a pneumatic signal coming from an I/P converter or the 4-20 mA analog signal coming directly from the controller. Due to the friction from the packing, it is not possible to move the valve stem position to a precise value. As a result, the valve positioner opens and closes the valve bracketing the desired stem position. This high frequency, high-gain feedback provided by the valve positioner can result in precise metering of the **average** flow rate. A valve with a deadband of 25% can provide a repeatability of the flow rate of less than ±0.5% for the average flow rate using a valve positioner. Valves with low levels of valve friction can control the average flow rate to a precision approaching ±0.1% using a valve positioner.

For flow control loops that are controlled by a DCS, a valve positioner is a necessity because the control interval for a DCS (i.e., 0.5 to 1.0 seconds) is not fast enough for most flow control loops. There are two general types of valve positioners: pneumatic positioners and digital positioners. Pneumatic positioners receive a pneumatic signal from the I/P converter and send a pneumatic signal to the valve actuator. A more modern type of valve positioner is a digital positioner, which receives the 4-20 mA analog signal directly and adjusts the instrument air pressure sent to the valve actuator. Digital positioners have the advantage that they can be calibrated, tuned, and tested remotely, and they can also be equipped with self-tuning capabilities.

Booster relays. Booster relays are designed to provide extra flow capacity for the instrument air system, which decreases the **dynamic response time** of the control valve (i.e., the time for most of a change to occur). Booster relays are used on valve actuators for large valves that require a large volume of instrument air to move the valve stem. Booster relays use the pneumatic signal as input and adjust the pressure of a high flow rate capacity instrument air system that provides air pressure directly to the diaphragm of the valve actuator.

Adjustable speed pumps. Adjustable speed pumps can be used instead of the control valve systems just discussed. A centrifugal pump directly driven by a variable speed electric motor is the most commonly used form of adjustable speed pump. Another type of adjustable speed pump is based on using a variable speed electric motor combined with a positive displacement pump. Adjustable speed pumps have the following advantages compared with control-valve based actuators: 1) they use less energy; 2) they provide fast, accurate flow metering without additional device requirements; 3) they do not require an instrument air system. Their major disadvantage is capital cost particularly for large flow rate applications. Another disadvantage of adjustable speed pumps is that they do not fail open or closed like a control valve with an air-to-close or air-to-open actuator, respectively. As a result, the CPI almost exclusively use control-valve-based actuators except for low flow applications, such as catalyst addition systems or base injection pumps for wastewater neutralization, which typically use adjustable speed pumps.

2.4 Sensor Systems

Sensor systems are composed of the sensor, transmitter, and associated signal processing capabilities. The sensor measures certain quantities (e.g., voltage, currents, or resistance) associated with devices in contact with the process such that the measured quantities correlate strongly with the actual controlled variable value. There are two general classifications for sensors: continuous measurements and discrete

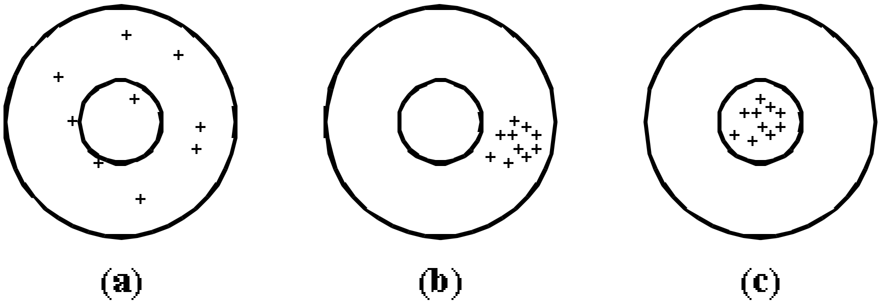

Figure 2.26 Targets which demonstrate the difference between accuracy and repeatability. (a) Neither accurate nor repeatable. (b) Repeatable but not accurate. (c) Accurate and repeatable.

measurements. Continuous measurements are, as the term implies, generally continuously available while discrete measurements update at discrete times. Pressure, temperature, level, and flow sensors typically yield continuous measurements while certain composition analyzers (e.g., gas chromatographs) provide discrete measurements.

Several terms are used to characterize the performance of a sensor:

- **Zero** is the lowest reading available from the sensor/transmitter, i.e., the sensor reading corresponding to a transmitter output of 4 ma.
- **Span** is the difference between the largest measurement value made by the sensor/transmitter and the lowest.
- **Accuracy** is the difference between the value of the measured variable indicated by the sensor and its true value (Figure 2.26). The true value is never known; therefore, accuracy is estimated by the difference between the sensor value and an accepted standard.
- **Repeatability** is related to the difference between the sensor readings while the process conditions remain constant (Figure 2.26).
- **Process measurement dynamics** indicate how quickly the sensor responds to changes in the value of the measured variable.
- **Rangeability** is the ratio of the largest accurate sensor reading to the smallest accurate reading.
- **Calibration** involves the adjustment of the correlation between the sensor output and the predicted measurement so that the sensor reading agrees with a standard.

Example 2.10 Sensor Signals

Problem Statement. Determine the temperature reading corresponding to a 10 mA analog signal from a temperature transmitter that has a span of 200ºC and a zero equal to 20ºC.

Solution. The position between the maximum and minimum analog signal is given by

$$\frac{10\,mA - 4\,mA}{20\,mA - 4\,mA} = 0.375$$

This corresponds to a 37.5% position on the temperature span of the transmitter or $0.375 \times 200^{\circ}C$, i.e., 75ºC. Then the temperature sensor reading is simply 75ºC plus the temperature of the zero (20ºC) for a sensor reading of 95ºC.

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Example 2.11 Sensor Signals

Problem Statement Determine the value of the electric analog reading in mA for an actual level of 45% for a level transmitter that has a span of 40% and a zero of 20%.

Solution. A 45% level measurement represents a position between the maximum level measurement (60%) and the minimum level measurement (20%) of

$$Position\ in\ span = \frac{45\% - 20\%}{60\% - 20\%} = 0.625$$

Then the electric analog signal is given by

$$4\,mA + 0.625\left[20\,mA - 4\,mA\right] = 14\,mA$$

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Overview. A wide variety of sensors are available for measuring process variables[3]. Choosing the correct sensor for a particular application depends on the controlled variable that is to be sensed, the properties of the process, accuracy and repeatability requirements, and costs, both initial and maintenance. Best practice[4] for instrument selection, for instrument installation, and to reduce maintenance costs has been identified for the CPI. Following is an analysis of the control-relevant issues associated with some of the most commonly used sensors for feedback control in the CPI.

Smart sensors. Smart sensors have built-in microprocessor-based diagnostics. For example, some smart pH sensors are able to identify the buildup of coatings on the pH electrode surface and trigger a wash cycle to reduce the effect of these coatings. In general, smart sensors are moderately more expensive than conventional sensors but, when they are properly selected and implemented, smart sensors can be an excellent investment due to greater sensor reliability and reduced maintenance.

Figure 2.27 Photograph of hardware for measuring process temperature. Included are a thermowell and transmitter housing (left) and several TCs. Courtesy of Fisher-Rosemount.

Temperature Measurements. The two primary temperature sensing devices used in the CPI are **thermocouples (TCs)** and **resistance thermometer detectors (RTDs)**.

Thermocouples. Thermocouples are based on the fact that two metal junctions (i.e., the contacting of two different types of metal wire) at different temperatures will generate a voltage and the magnitude of the voltage is proportional to the temperature difference. Thermocouples are constructed of two different types of wire that are connected at both ends (i.e., junctions). The cold junction of a thermocouple is normally at ambient temperature but is electrically compensated so that it behaves as if it were at a constant temperature. The hot junction is used to measure the process temperature of interest. In general, the voltage generated by the hot junction, inside a thermowell in contact with a process fluid, varies quite linearly with the process temperature. Thermocouples are constructed of metal pairs including iron-constantan, copper-constantan, chromel-alumel, and platinum-rhodium, which is the most popular material of construction and results in the most accurate thermocouples. (Alumel, chromel, and constantan are trade names for alloys that are used to make these thermocouples.)

RTDs. RTDs are based on the observation that the resistance of certain metals depends strongly upon their temperature. A Wheatstone bridge or other type of resistance measuring bridge can be used to measure the resistance of the RTD element and thus estimate the process temperature. Platinum and nickel are typically used for RTDs. Platinum has a much wider useful range (i.e., -200°C to 800°C) while nickel is more limited (-80°C to 320°C) but is less expensive than platinum. Each of these metals has a known temperature dependence for its resistance; therefore, calibration requires only applying the RTD to a known temperature condition. Unlike TCs, RTDs require a separate power supply.

Thermowells. Thermowells are typically cylindrical metal tubes that are capped on one end and protrude into a process line or vessel to bring the TC or RTD in thermal contact with the process fluid. Thermowells provide a rugged, corrosion resistant barrier between the process fluid and the sensor that allows for removal of the sensor while the process is still in operation. Thermowells that are coated with polymer or other adhering material can significantly increase the lag associated with the temperature measurement, i.e., significantly increase the response time of the sensor. For example, Figure 2.27 shows a typical thermowell and housing as well as several thermocouples.

Overall comparison of TCs and RTDs. TCs are less expensive and more rugged than RTDs but are an order of magnitude less repeatable than RTDs. Typically, RTDs should be used for important temperature control points, such as on reactors and distillation columns.

Repeatability, accuracy and dynamic response. TCs typically have a repeatability of ±1°C while RTDs have a repeatability of ±0.1°C. Accuracy is a much more complex issue. Errors in the temperature reading can result from heat loss along the length of the thermowell, electronic error, sensor error, error from nonlinearity, calibration errors, and other sources[5].

The dynamic response time of a TC or RTD sensor within a thermowell can vary over a wide range and is a function of the type of process fluid (i.e., gas or liquid), the fluid velocity past the thermowell, the separation between the sensor and inside wall of the thermowell, and material filling the thermowell (e.g., air or oil). Typical well-designed applications result in time constants of 6-20 seconds for measuring the temperature of most liquids.

Pressure Measurements. The most commonly used pressure sensing devices are strain gauges. Strain gauges are based upon the property that when a wire is stretched elastically, its length increases while its diameter decreases, both of which increase the resistance of the wire. Serpentine lengths of elastic resistance wires can be bonded to the surface of an elastic element (diaphragm). When deformation of the diaphragm occurs as the result of a pressure increase, the wires elongate and, therefore, the resistance of these wires increases, indicating an increased pressure reading. These pressure sensing devices actually measure the differential pressure across the diaphragm, but can be used to measure a process pressure in gauge pressure by allowing the low pressure side of the device to be exposed to the atmosphere. Another approach is to use a strain gauge to measure the effect of a pressure change on a coiled tube. The resistance of the strain gauge is usually measured using a Wheatstone bridge. Pressure sensors are very fast responding. Repeatability for pressure measurement is generally less than ±0.1%.

Flow Measurements. The most commonly used flow meter is an orifice meter. An orifice meter uses the measured pressure drop across a fixed-area flow restriction (an orifice) to predict the flow rate. An example of a paddle type orifice plate is shown in Figure 2.28. The pressure drop across an orifice is usually measured using a **DP cell** (Figure 2.29). The pressure drop across an orifice plate, ΔP, is related to the volumetric flow, Q, by the following equation:

$$Q = \frac{C_d A_2}{\sqrt{1-(A_2/A_1)^2}} \sqrt{\frac{2 g_c \Delta P}{\rho}} \qquad \textbf{2.5}$$

where A_1 is the pipe cross-sectional area, A_2 is the cross-sectional area of the orifice, ρ is the density of the fluid, g_c is a unit conversion factor (32.2 $\mathrm{lb_m}$-ft/$\mathrm{lb_f}$-$\mathrm{s^2}$), and C_d is the discharge coefficient. C_d is a function of the Reynolds number and the type of fluid, but typically is approximately 0.6. A straight run of pipe preceding the orifice meter is required to develop uniform flow at the orifice meter. If not, an error as large as 15% can result in the predicted flow rate. Since the orifice meter is based upon a measured pressure drop, it is a very fast responding measurement. Orifice meters typically provide a repeatability in the range of ±0.3 to ±1%.

Example 2.12 Flow Rate through an Orifice Plate

Problem Statement. Calculate the flow rate of water through a 1.5-inch diameter orifice in a schedule 40 3-inch line if the pressure drop across the orifice is 5 psi.

Solution. The inside diameter of a schedule 40 3-inch line is 3.068 inches. Then A_2 is calculated to be 1.767 $\mathrm{in^2}$ and A_1 is 7.393 $\mathrm{in^2}$. The density of water is taken as 62.4 $\mathrm{lb_m/ft^3}$. Equation 2.5 can be applied directly to solve this problem, but care should be taken with the associated unit conversions. For example, g_c (32.2 $\mathrm{lb_m}$-ft/$\mathrm{lb_f}$-$\mathrm{s^2}$) and the conversion of $\mathrm{in^2}$ to $\mathrm{ft^2}$ is required to cancel the units. Applying Equation 2.5 yields

$$Q = \frac{(0.6)(1.767\, in^2)(ft^2/144\, in^2)}{\sqrt{1-(1.767/7.393)^2}} \sqrt{\frac{(2)(5\, lb_f/in^2)(32.2\; lb_m - ft/lb_f - s^2)}{(62.4\, lb_m/ft^3)(ft^2/144\, in^2)}}$$

$$= 0.2067\; ft^3/s = 92.8\; GPM$$

♠

Example 2.13 Pressure Drop across an Orifice Plate

Problem Statement. For the system described in Example 2.12, calculate the pressure drop across the orifice for a flow rate of 75 GPM.

Solution. Solving for ΔP by rearranging Equation 2.5 yields

Figure 2.28 Photograph of a paddle type orifice plate against a flanged pipe. Courtesy of Thermocouple Instruments, Limited.

Figure 2.29 Photograph of a differential pressure sensor/transmitter (DP cell). Courtesy of Fisher-Rosemount.

$$\Delta P = \frac{Q^2 \rho \left[1-(A_2/A_1)^2\right]}{2 g_c C_d^2 A_2^2}$$

Substituting the numerical values and performing the necessary unit conversions yields

$$\Delta P = \frac{(75\,gal/\min)^2 (\min/60\,s)^2 (ft^3/7.481\,gal)(62.4\,lb_m/ft^3)[1-(1.767/7.393)^2]}{(2)(32.2\,lb_m - ft/lb_f - s^2)(0.6)^2(1.767\,in^2)^2(ft^2/144\,in^2)}$$

$$\Delta P = 3.27\ psi$$

A simpler method to solve this problem would be to apply Equation 2.5 twice, i.e., once for Example 2.12 and once for this example, and take the ratio, noting that all the parameters of the problem cancel except ΔP and Q. Then the pressure drop for 75 GPM can be calculated directly by

$$\Delta P_{75GPM} = \Delta P_{92.8GPM} \left[\frac{75GPM}{92.8GPM}\right]^2 = 3.27\,psi$$

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Example 2.14 Sizing an Orifice Meter

Problem Statement. Size an orifice meter for service on a 2½-inch schedule 40 pipe carrying water with a maximum flow rate of 180 GPM and a minimum flow rate of 60 GPM. Assume that the line pressure is 150 psig.

Solution. The design of an orifice meter is directly related to the differential pressure sensor that is used. Typically, differential pressure sensors are available in various sizes indicated by the maximum pressure drop, e.g., 1 psi, 2 psi, 5 psi, and 10 psi sizes. Sizing an orifice meter involves choosing a pressure drop across the orifice plate and then calculating β, the ratio of the diameter of the opening in the orifice to the inside pipe diameter, while honoring the following three restrictions: (1) β should be greater than 0.2 and less than 0.7 for most orifice designs[3], (2) the pressure drop measured across the orifice should be less than 4% of the line pressure[3], and (3) the Reynolds number for flow in the pipe must be between 10^4 and 10^7 for normal operation[3]. Since the maximum turndown ratio for a differential pressure sensor is about 9 and because there is a square root relation between flow rate and pressure drop, the maximum turndown ratio for the flow rate through an orifice meter is about 3. On other hand, an orifice meter that uses a smart transmitter can provide a turndown ratio of 10:1.

Assume that a differential pressure sensor with a 2 psi maximum is used for this application. For the maximum flow, it is assumed that the resulting differential pressure is 1.33 psi (67% of full reading). This result corresponds to 0.9% of the line pressure, which satisfies the second requirement. Recognizing that $A_2=\beta A_1$ and rearranging Equation 2.5 to solve for β yields

$$\beta = \sqrt{\frac{Q_f^2}{Q_f^2 + 2C_d^2 A_1^2 g_c \Delta P / \rho}}$$

This equation, with the diameter of 2½-inch schedule 40 ferrous pipe (2.469 in), a pressure drop of 1.33 psi, C_d equal to 0.61, and a flow rate of 180 GPM yields a β of 0.742. Because this β is greater than 0.7, this is not an acceptable design for an orifice meter. Since a larger pressure drop across the orifice is required, the next largest size differential pressure sensor should be used, i.e., a 5 psi differential sensor. For the maximum flow, it is now assumed that the resulting differential pressure is 3.33 psi (67% of full reading). This result corresponds to 2.2% of the line pressure, which satisfies the second restriction. Using the previous equation for β, a pressure drop of 3.33 psi at a flow rate of 180 GPM yields a β of 0.573. The Reynolds number for the pipe is 1.9×10^5, which is also within the specified range. The turndown ratio for the flow is 3; therefore, the low flow rate should also be accurately measured. As a result, β equal to 0.573 (i.e., an orifice bore equal to 1.41 inches) with a 5 psi differential pressure sensor appears to be a viable orifice meter design for this application.

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Other types of flow meters are used for flow rate control in special situations, including vortex shedding flow meters and magnetic flow meters. Vortex shedding flow meters (Figure 2.30) are based on inserting an unstreamlined obstruction (i.e., a blunt object) in the pipe and measuring the frequency of downstream pulses created by the flow past the obstruction. The flow rate is directly related to the frequency of the pulses. Vortex shedding meters are recommended for clean, low viscosity liquids and gases, and can typically provide a rangeability of about 15:1. Care should be taken to ensure that (1) cavitation does not occur in the measuring zone and (2) the velocity does not become less than its lower velocity limit. Vapor bubbles resulting from cavitation increase the noise and decrease the accuracy of the measurement; therefore, care should be taken to ensure that the pressure in the line remains above a lower limit. Vortex shedding meter are usually accurate at Reynolds number greater than 10,000.

Magnetic flow meters (Figure 2.31) can be used to measure the flow rate of electrically conducting fluids. The conductivity of typical tap water is sufficient to use a magnetic flow meter. Magnetic flow meters are based on the principle that a voltage is generated by an electronically conducting fluid flowing through a magnetic field. The magnetic flow meter creates a magnetic field using an electromagnet and measures the resulting voltage, which is proportional to the flow rate in the pipe. Magnetic flow meters provide accurate flow measurements over a wide range of flow rates and are especially accurate at low flow rates. Deposition on the electrodes is a limitation of magnetic flow meters in certain cases. Typical applications of magnetic flow meters are for metering the flow rates of viscous fluids, slurries, and highly

Figure 2.30 Photograph of a vortex shedding flow meter. Courtesy of Yokogawa Corporation of America.

corrosive chemicals[6]. Magnetic flow meters are used extensively in water treatment facilities. The lower velocity limit for magnetic flow meters is about 1 ft/s for water and increases for more viscous fluids.

The purchase price for vortex shedding flow meters and magnetic flow meters are much higher than for orifice meters, but their maintenance costs are usually much lower since they do not use pressure taps, which are prone to plugging. **Flow meters**, whichever type is chosen, **are typically installed upstream of the control valve to provide the most accurate, lowest noise measurement** to avoid the effects of flashing and/or nonuniform flow. Installing the flow sensor downstream of a control valve will subject the sensor to flow fluctuations and even two phase flow, which reduce the sensor accuracy and increase the measurement noise.

Level measurements. The most common type of level measurement is based upon measuring the hydrostatic head in a vessel using a differential pressure measurement. This approach typically works well as long as there is a large difference between the density of the light and heavy phases. Because it is based on a pressure measurement, this approach usually has relatively fast measurement dynamics. If the pressure tap connections between the process and the DP cell become partially

Figure 2.31 Photograph of a magnetic flow meter. Courtesy of Sparling, Inc.

blocked, the dynamic response time of the sensor can be significantly increased, resulting in slower-responding level measurements. Level measurements typically have a repeatability of approximately ±1%.

Figure 2.32 shows how a differential pressure measurement can be used to determine the level in a vessel. This approach directly measures the hydrostatic head in the vessel. Because of plugging and corrosion problems, it may be necessary to keep the process fluid from entering the differential pressure transmitter. In addition, it is

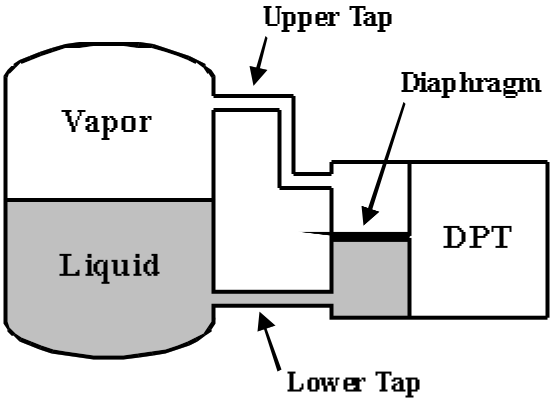

Figure 2.32 Schematic of a typical differential pressure level measurement system.

important to keep vapor from condensing in the upper tap and collecting in the low pressure side of the differential pressure transmitter. This can usually be accomplished by insulating the pressure tap and wrapping it with resistive heating tape. There are other level measuring approaches that are based upon a variety of physical phenomena and are used in special cases. Float activated devices, which are similar to the level measuring approach used in the water reservoir in toilets, are sometimes used in the CPI.

Chemical Composition Analyzers. The most commonly used on-line composition analyzer is the **gas chromatograph (GC)** while inroads have been recently made by infrared analyzers and ultraviolet and visible-radiation analyzers. On-line composition measurements are generally much more expensive than temperature, pressure, flow rate, and level measurements with much lower reliability. The annual cost of an on-line composition analyzer can easily be in excess of $100,000 due to high capital costs and large maintenance costs. Due to its large associated cost, the decision to use an on-line composition analyzer is normally based on process economics. For example, for refineries and high volume chemical intermediate plants, on-line analyzers (usually GCs) are used extensively because 1) due to the large flow rates used in these large plants, process improvement due to on-line composition analysis easily economically justifies the application and 2) the measurement techniques are generally well established for this industry. On the other hand, for the specialty chemicals industry, much less use of on-line analyzers is made due to 1) lower production rates and 2) unavailability of reliable analyzers.

Gas chromatographs. GCs process a volatile sample, along with a carrier gas, through a small diameter (approximately 3/8 inch) packed column. As a result of different affinities of the sample components for the column packing, the various sample components have different residence times in the packed column. As each component emerges from the column, it passes through a detector process. The most commonly used detectors are thermal conductivity detectors and hydrogen-flame ionization detectors. Hydrogen-flame ionization detectors are more complicated than thermal conductivity detectors but are much more sensitive for hydrocarbons and organic compounds. Repeatability for GCs can vary over a wide range and is dependent on the particular system being measured. New analyzer readings are typically updated every 3 to 10 minutes for GCs.

Infrared, ultraviolet and visible radiation. These analyzers are based on the property that each compound absorbs specific frequencies of radiation and the greater the concentration, the higher the degree of absorption. To identify a component from among several components, only the absorption frequencies of the component of interest are required.

Sampling system. The sampling system is responsible for collecting a representative sample of the process and delivering it to the analyzer for analysis. Obviously, the reliability of the sampling system directly affects the reliability of the overall composition analysis system. The transport delay associated with the sampling system contributes directly to the overall deadtime associated with an on-line composition measurement. For example, an improperly designed sampling system can result in a transport time of one hour for the sample to be taken from the process and delivered to the analyzer while a properly designed system can result in a transport delay of 10 seconds or less. This difference in sampling deadtime can have a dramatic effect on the performance of a control loop.

Table 2.3

Summary of Control-Relevant Aspects of Actuators and Sensors

	Time Constant (sec)	Valve Deadband or Sensor Repeatability	Turndown Ratio, Rangeability or Range
Control valve *	3 - 15	10 - 25%	9:1
Control valve w/valve positioner*	0.5 - 2	0.1 - 0.5%	9:1
Flow control loop w/valve positioner*	0.5 - 2	0.1 - 0.5%	9:1
TC w/ thermowell	6 - 20	±1.0 ºC	-200ºC to 1300ºC
RTD w/ thermowell	6 - 20	±0.1 ºC	-200ºC to 800ºC
Magnetic flow meter	<1	±0.1%	20:1
Vortex shedding meter	<0.1	±0.2%	15:1
Orifice flow meter	<0.2	±0.3 - ±1%	3:1
Orifice meter w/smart transmitter	<0.2	±0.3 - ±1%	10:1
Differential Pressure Level Indicator	<1	±1%	9:1
Pressure sensor	<0.2	±0.1%	9:1

* Based on globe valves.

Table 2.1 summarizes the dynamic characteristics, repeatability, and rangeabiltiy or turndown ratio of control valve systems and several different types of sensors.

Transmitters. The transmitter converts the output from the sensor (i.e., a millivolt signal, a differential pressure, a displacement, etc.) into a 4-20 mA analog signal that represents the measured value of the controlled variable. Consider a transmitter that is applied to a temperature sensor. Assume that the maximum temperature that the transmitter is expected to handle is 200ºC and that the minimum temperature is 50ºC, then the span of the transmitter is 150 ºC and the zero of the transmitter is 50ºC. Transmitters are typically designed with two knobs that allow for independent adjustment of the span and the zero of the transmitter. Properly functioning and implemented transmitters are so fast that they do not normally contribute to the dynamic lag of the process measurement. Modern transmitters have features that, if not applied properly, can reduce the effectiveness of the control loop. For example, excessive filtering (Appendix B) of the measurement signal by the transmitter can add extra lag to the feedback loop, thus degrading control loop performance.

2.5 Summary

An industrial feedback control loop consists of a controller, an actuator system, a process, and a sensor system. The sensor generates an output that is related to the controlled variable and the transmitter converts this reading into a 4-20 mA analog signal. The A/D converter converts the analog signal into a digital value for the sensor reading. The DCS accepts the digital sensor reading, compares it to the setpoint, and calculates the digital value of the controller output. The D/A converter converts this digital reading into a 4-20 mA analog signal which, in turn, is converted to a 3-15 psig instrument air pressure by the I/P converter. The instrument air pressure acts on the control valve, which causes the manipulated flow to the process to change. This change to the process, as well as other input changes, causes the value of the controlled variable to change. The sensor reading changes and the control loop is complete.

The evolution of controllers from pneumatic controllers to analog controllers to DCSs has been driven by economics, functional performance, and reliability. From a process control performance perspective, the only influence from a controller is the effect of its control interval. Even though an analog controller has a smaller control interval than a DCS, the DCS has a much lower cost per control loop, greater functional capability, and superior reliability. The DCS is made up of a number of different elements and is held together by the data highway. The DCS is responsible for performing control calculations, providing displays of current and previous operating conditions, providing a means to modify control functions, archiving process data, providing process alarms, and performing process optimization.

The actuator system consists of the control valve, the valve actuator, the I/P converter, and the instrument air system. A typical industrial control valve has a deadband from 10% to 25%. If a valve positioner is installed, the deadband should drop to less than 0.5%. Depending on the design of the valve plug and valve seat, a control valve can have different inherent valve characteristics, i.e., different flow rate versus stem position for a constant pressure drop across the control valve. Equal percentage valves are used in about 90% of the control valve applications in the CPI while linear valves are used in the remaining cases for which the pressure drop across the valve remains relatively constant. The valve actuator determines whether the valve will fail open or closed when instrument air pressure is lost.

The sensor system is composed of the sensor, the transmitter, and the associated signal processing. TCs and RTDs are used to measure process temperatures and are implemented on processes using thermowells. RTDs are more expensive and less rugged than TCs , but they provide much more repeatable temperature measurements. Pressure measurements are typically made using strain gauges, which are based on measuring the resistance of a serpentine wire bonded to the surface of a flexible diaphragm. Flow measurements are typically made from the pressure drop across an orifice plate. Level measurements are commonly based upon the differential pressure between two taps on the process vessel. GCs are used to measure product compositions on-line by passing a sample through a packed column and detecting the separated components as they exit the GC column.

2.6 Additional Terminology

A/D Converter - analog-to-digital converter. Converts a 4-20 mA electrical analog signal into a digital reading that can be processed by the DCS.

Accuracy - the difference between the true value and the measurement.

Air-to-close actuator - a valve actuator that causes the valve to close as its instrument air pressure is increased (i.e., fails open).

Air-to-open actuator - a valve actuator that causes the valve to open as its instrument air pressure is increased (i.e., fails close).

Cage-guided valve - a valve with a cage around the valve plug that guides the plug toward the valve seat.

Calibration - an adjustment of the correlation between the sensor output and the predicted measurement so that the sensor reading agrees with the standard.

CRT - cathode ray tube. A computer console that allows the operators and engineers to access process operating conditions and adjust the process control activities of a DCS.

Control interval - the time period between adjacent calls to a controller from a DCS.

Controller cycle time - the time period between adjacent calls to a controller from a DCS.

D/A converter - digital-to-analog converter. Converts a digital value from the DCS into a 4-20 mA electrical analog signal.

Data highway - communication hardware and the associated software in a DCS that allows the distributed elements of a DCS to exchange data with each other.

Deadband - the maximum percentage change in the input that can be implemented without an observable change in the output.

DCS - distributed control system. A control computer that is made up of a number of distributed elements that are linked together by the data highway.

Direct-acting final control element - a final control element with an air-to-open valve actuator.

DP cell - a differential pressure sensor/transmitter.

Dynamic response time - the time for a system to make most of its change after an input change has occurred.

GC - gas chromatograph. A composition analyzer that is based on separating the components of a mixture in a small diameter packed column.

I/P converter - an electro-mechanical device that converts a 4-20 mA electrical signal to a 3-15 psig pneumatic signal, i.e., a current to pressure converter.

Inherent valve characteristics - the flow rate versus stem position for a fixed pressure drop across the valve.

Installed valve characteristics - the flow rate versus stem position for a valve installed in service.

LCU - local control unit. A microprocessor in a DCS that is responsible for performing control functions for a portion of a plant.

Ladder logic - a programming language used in PLC’s to implement a sequence of actions.

LAN - local area network.

PLC - programmable logic controller. A process computer typically used to apply a sequence of control actions, e.g., startup, shutdown, and batch operations.

Process measurement dynamics - a measure of the speed with which a sensor responds to a change in the process.

RTD - resistance thermometer detector. A temperature sensor that is based on the known temperature dependence of a pure metal resistor.

Repeatability - the variation in a sensor reading not due to process changes. It provides an indication of consistency of the sensor reading.

Reverse-acting final control element - a final control element with an air-to-close valve actuator.

Shared communication facility - communication hardware and the associated software in a DCS that allows the distributed elements of a DCS to exchange data with each other.

Smart sensor - a sensor that is equipped with a microprocessor that provides onboard diagnostics and/or calibration.

Span - the difference between the maximum and the minimum value of a measurement that can be made by a sensor/transmitter.

TC - thermocouple. A temperature sensor that is based upon the fact that metal junctions at different temperatures generate an electrical voltage.

Turndown ratio - the ratio of the maximum to minimum controllable flow rates for a control valve.

VDU - video display unit. A computer console that allows the operators and engineers to access process operating conditions and adjust the process control activities of a DCS.

Valve deadband - the maximum percentage change in the input to the valve that can be implemented without an observable change in the flow rate through the value.
Valve plug - the device in a valve that is responsible for restricting flow through the valve.
Valve positioner - a device that adjusts the instrument air pressure to a control valve to maintain a specified value for the stem position.
Valve seat - the portion of the valve against which the valve plug rests when the valve is fully closed.
Valve stem - a rod that connects the diaphragm in the valve actuator with the valve plug so that, as the air pressure acts on the diaphragm, the plug provides more or less restriction to flow through the valve.
Zero - the lowest sensor/transmitter reading possible, i.e., the sensor reading corresponding to a transmitter output of 4 mA.

2.8 References

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2.9 Preliminary Questions

2.1 For a typical feedback loop in the CPI, where are 4-20 mA signals used?

2.2 For a typical feedback loop in the CPI, where are 3-15 psig signals used?

2.3 For a typical feedback loop in the CPI, where are A/D and D/A converters used?

2.4 (2.2) For Figure 2.2, what hardware is located in the field and what hardware is located in the control room?

2.5 For a pneumatic controller, what mechanical devices are used to implement PID control?

2.6 Why have electronic analog controllers replaced pneumatic controllers?

2.7 Why have DCSs replaced electronic analog controllers?

2.8 What type of device is used as a local control unit?

2.9 What system in a DCS allows a user on a local console to observe operation of the plant controlled by other LCUs?

2.10 Based on Figure 2.4, where are CRTs used in a DCS?

2.11 How frequently can a DCS execute most regulatory control loops?

2.12 (2.6) Using Figure 2.4, explain how process data are stored and later displayed on a system console.

2.13 (2.7) What is a PLC and how is it different from a DCS? How are they alike?

2.14 For what type of control function were PLCs originally designed?

2.15 What is the difference between a DCS and the fieldbus approach to distributed control?

2.16 For Figure 2.5, in what locations are control calculation performed?

2.17 (2.3) What hardware comprises the final control element?

2.18 (2.4) What is the difference between the actuator system and the final control element? What is the difference between the actuator system and the valve actuator?

2.19 (2.9) How would you choose between selecting a globe valve with an unbalanced plug and one with a balanced plug?

2.20 (2.10) Why are globe valves generally used for flow control applications?

2.21 (2.11) What is the difference between inherent and installed valve characteristics?

2.22 (2.12) Why are equal percentage valves generally selected over linear and quick opening valves?

2.23 What determines whether a globe valve is linear, equal percentage, or quick opening?

2.24 Using Figure 2.7, indicate how you would measure the stem position of a valve in operation.

2.25 Why is the pressure drop across a control valve in a flow system usually a strong function of flow rate?

2.26 When are butterfly valves preferred over globe valves for flow control applications? Why are they preferred?

2.27 (2.13) Explain how cavitation in control valves occurs and what it causes.

2.28 (2.14) What physical characteristic of the process determines whether a valve actuator is air-to-open or air-to-close?

2.29 (2.15) Identify a case where an air-to-close valve actuator should be used and explain your reasoning.

2.30 (2.16) Why has an increased usage of DCS's resulted in a greater use of valve positioners?

2.31 (2.17) Under what conditions are adjustable speed pumps preferred over a flow control loop using a control valve?

2.32 (2.18) From a process point of view, which is generally more important for a sensor, accuracy or repeatability? Explain your reasoning.

2.33 (2.19) When is the dynamic response time of a sensor important to a process control system and when is it not important?

2.34 (2.20) What are the two most important differences between TC's and RTD's ?

2.35 (2.21) Why is a straight run of pipe preceding an orifice meter required?

2.36 (2.22) Why are flow measurement devices usually located upstream of the control valve?

2.37 (2.24) What determines whether an on-line analyzer should be installed?

2.10 Analytical Questions and Exercises

2.38 For the control loop shown in Figure 1.3, make a drawing similar to Figure 2.2 and list all signals on your diagram.

2.39 For the control loop shown in Figure 1.4, make a drawing similar to Figure 2.2 and list all signals on your diagram.

2.40 For the control loop shown in Figure 1.5, make a drawing similar to Figure 2.2 and list all signals on your diagram.

2.41 For the control loop shown in Figure 1.6, make a drawing similar to Figure 2.2 and list all signals on your diagram.

2.42 For the control loop shown in Figure 1.7, make a drawing similar to Figure 2.2 and list all signals on your diagram.

2.43 (2.1) Choose an industrial process control loop and make a drawing similar to Figure 2.2 for your system and list all signals on your diagram.

2.44 Determine the 4-20 mA signal and the pneumatic signal if the controller output is 50% of its full scale reading for a system corresponding to Figure 2.2.

2.45 Determine the 4-20 mA signal and the pneumatic signal if the controller output is 25% of its full scale reading for a system corresponding to Figure 2.2.

2.46 Determine the 4-20 mA signal and the pneumatic signal if the controller output is 35% of its full scale reading for a system corresponding to Figure 2.2.

2.47 Determine the 4-20 mA signal and the pneumatic signal if the controller output is 72% of its full scale reading for a system corresponding to Figure 2.2.

2.48 Determine the 4-20 mA signal and the controller output in percent of full range, if the pneumatic signal is 9 psig for a system corresponding to Figure 2.2.

2.49 Determine the 4-20 mA signal and the controller output in percent of full range, if the pneumatic signal is 10 psig for a system corresponding to Figure 2.2.

2.50 Determine the 4-20 mA signal and the controller output in percent of full range, if the pneumatic signal is 14 psig for a system corresponding to Figure 2.2.

2.51 Determine the 4-20 mA signal and the controller output in percent of full range, if the pneumatic signal is 4 psig for a system corresponding to Figure 2.2.

2.52 (2.5) Why have DCSs replaced analog controllers and supervisory control computers in the CPI? Why is fieldbus technology likely to begin replacing DCSs in the future? Can you identify a pattern?

2.53 Explain why a valve with a 10% deadband may not produce a change in the flow rate through the valve for a 9% change in the signal to the control valve. Explain why a 2% change in the signal to the control valve may produce a change in the flow rate through the same control valve.

2.54 Calculate the flow rate of water through a 3-inch control valve that is 50% open with a pressure drop across the valve equal to 14 psi . Obtain the C_v for this valve from Table 2.1.

2.55 Calculate the flow rate of water through a 2-inch control valve that is 75% open with a pressure drop across the valve equal to 35 psi. Obtain the C_v for this valve from Table 2.1.

2.56 Calculate the flow rate of a hydrocarbon stream with a density of 44 lb/ft^3 through a 3-inch control valve that is 80% open with a pressure drop across the valve equal to 82 psi. Obtain the C_v for this valve from Table 2.1.

2.57 Calculate the flow rate of a hydrocarbon stream with a density of 44 lb/ft^3 through a 2-inch control valve that is 35% open with a pressure drop across the valve equal to 14 psi. Obtain the C_v for this valve from Table 2.1.

2.58 Calculate the pressure drop across a 3-inch valve that is 50% open for a flow of 65 GPM of water. Obtain the C_v for this valve from Table 2.1.

2.59 Calculate the pressure drop across a 4-inch valve that is 45% open for a flow of 165 GPM of water. Obtain the C_v for this valve from Table 2.1.

2.60 Calculate the pressure drop across a 3-inch valve that is 40% open for a flow of 100 GPM of a hydrocarbon stream with a density of 40 lb/ft^3. Obtain the C_v for this valve from Table 2.1.

2.61 Calculate the pressure drop across a 3-inch valve that is 63% open for a flow of 95 GPM of a hydrocarbon stream with a density of 45 lb/ft^3. Obtain the C_v for this valve from Table 2.1.

2.62 Calculate the pressure drop across a 2-inch valve that is 80% open for a flow of 35 GPM of a hydrocarbon stream with a density of 45 lb/ft^3. Obtain the C_v for this valve from Table 2.1.

2.63 Determine the flow rate of water though a 2-inch equal percentage valve that is 60% open for the C_v given in Table 2.1 and the installed pressure drop presented in Table 2.2.

2.64 Determine the flow rate of water though a 1.5-inch equal percentage valve that is 80% open for the C_v given in Table 2.1 and the installed pressure drop presented in Table 2.2.

2.65 Determine the flow rate of water though a 3-inch linear valve that is 40% open for the maximum value of C_v equal to 100 and the installed pressure drop presented in Table 2.2.

2.66 Determine the flow rate of water though a 1.5-inch linear valve that is 80% open for the maximum value of C_v equal to 30 and the installed pressure drop presented in Table 2.2.

2.67 Determine the flow rate of a hydrocarbon liquid (specific gravity equal to 0.65) though a 3-inch equal percentage valve that is 30% open for the C_v given in Table 2.1 and the installed pressure drop presented in Table 2.2.

2.68 Determine the flow rate of a hydrocarbon liquid (specific gravity equal to 0.65) though a 2-inch equal percentage valve that is 40% open for the C_v given in Table 2.1 and the installed pressure drop presented in Table 2.2.

2.69 Determine the valve position of a 4-inch equal percentage valve if 90 GPM of water flow through the system. Use Table 2.1 to determine the C_v and use Table 2.2 for the available pressure drop across the control valve.

2.70 Determine the valve position of a 3-inch equal percentage valve if 82 GPM of water flow through the system. Use Table 2.1 to determine the C_v and use Table 2.2 for the available pressure drop across the control valve.

2.71 Determine the valve position of a 2-inch equal percentage valve if 64 GPM of hydrocarbon liquid (specific gravity equal to 0.65) flow through the system. Use Table 2.1 to determine the C_v and use Table 2.2 for the available pressure drop across the control valve.

2.72 Determine the valve position of a 2-inch equal percentage valve if 64 GPM of hydrocarbon liquid (specific gravity equal to 0.65) flow through the system. Use Table 2.1 to determine the C_v and use Table 2.2 for the available pressure drop across the control valve.

2.73 Determine the valve position of a 4-inch equal percentage valve if 105 GPM of water flow through the system. Assume an equal percentage valve with the pressure drop versus stem position shown in the table for this problem. Use Table 2.1 to determine the C_v.

2.74 Size a control valve for service on a line carrying water with a maximum flow rate of 90 GPM and a minimum flow rate of 30 GPM. Assume an equal percentage valve with the pressure drop versus stem position shown in the table for this problem. The C_v's for equal percentage valves of different sizes are presented in the Table 2.1.

2.75 Size a control valve for service on a line carrying a hydrocarbon liquid (specific gravity equal to 0.65) with a maximum flow rate of 80 GPM and a minimum flow rate of 20 GPM. Assume an equal percentage valve with the pressure drop versus stem position shown in the table for this problem. The C_v's for equal percentage valves of different sizes are presented in the Table 2.1.

Pressure Drop of an Installed Valve versus Flow Rate for Problems 2.73-5

Q (GPM)	ΔP (psi)	Q (GPM)	ΔP (psi)
0	28.5	55	21.4
5	28.4	60	20.1
10	28.2	65	18.8
15	27.9	70	17.4
20	27.4	75	15.8
25	27.0	80	14.0
30	26.3	85	11.7
35	25.6	90	9.3
40	24.7	95	6.7
45	23.7	100	3.9
50	22.6	105	0.6

2.76 Size a control valve for service on a line carrying water with a maximum flow rate of 400 GPM and a minimum flow rate of 100 GPM. Assume an equal percentage valve with the pressure drop versus stem position shown in the table for this problem. The C_v's for equal percentage valves of different sizes are presented in the Table 2.1.

2.77 Size a control valve for service on a line carrying a hydrocarbon liquid (specific gravity equal to 0.65) with a maximum flow rate of 400 GPM and a minimum flow rate of 100 GPM. Assume an equal percentage valve with the pressure drop versus stem position shown in the table for this problem. The C_v's for equal percentage valves of different sizes are presented in the Table 2.1.

2.78 Size a control valve for service on a line carrying a hydrocarbon liquid (specific gravity equal to 0.65) with a maximum flow rate of 500 GPM and a minimum flow rate of 100 GPM. Assume an equal percentage valve with the pressure drop versus stem position shown in the table for this problem. The C_v's for equal percentage valves of different sizes are presented in the Table 2.1.

Pressure Drop of an Installed Valve versus Flow Rate for Problems 2.76-8

Q (GPM)	ΔP (psi)	Q (GPM)	ΔP (psi)
0	30.6	220	22.9
20	30.5	240	21.5
40	30.2	260	20.2
60	29.9	280	18.7
80	29.5	300	17.0
100	28.9	320	15.0
120	28.2	340	12.6
140	27.4	360	9.9
160	26.5	380	7.2
180	25.4	400	4.1
200	24.2	420	0.6

2.79 Determine the temperature reading corresponding to a 7 mA analog signal from a temperature transmitter that has a span of 150ºC and a zero of 50ºC.

2.80 Determine the pressure reading corresponding to a 5.5 mA analog signal from a pressure transmitter that has a span of 150 psi and a zero of 25 psig.

2.81 Determine the flow rate reading corresponding to a 12.2 mA analog signal from a flow transmitter that has a span of 10,000 lbs/hr and a zero of 1,000 lbs/hr.

2.82 Determine the temperature reading corresponding to a 3.7 mA analog signal from a temperature transmitter that has a span of 200ºF and a zero of 100ºF.

2.83 Determine the level reading corresponding to a 6.8 mA analog signal from a level transmitter that has a span of 75% and a zero of 10%.

2.84 Determine the value of the electric analog reading in mA from a temperature transmitter that has a span of 400ºF and a zero of 100ºF corresponding to a measured temperature of 300ºF.

2.85 Determine the value of the electric analog reading in mA from a pressure transmitter that has a span of 250 psi and a zero of 14.7 psia corresponding to a measured pressure of 202 psia.

2.86 Determine the value of the electric analog reading in mA from a pressure transmitter that has a span of 250 psi and a zero of 14.7 psia corresponding to a measured pressure of 300 psia.

2.87 Determine the value of the electric analog reading in mA from a flow transmitter that has a span of 100,000 lb/hr and a zero of 15,000 lbs/hr corresponding to a measured flow rate of 66,732 lb/hr.

2.88 (2.23) Consider a pressure sensor/transmitter that reads 80 psig when the transmitter output is 8 mA and reads 100 psig when the transmitter output is 10 mA. What are the zero and span of this pressure sensor/tranmitter?

2.89 Consider a temperature sensor/transmitter that reads 100ºF when the transmitter output is 8 mA and reads 150 ºF when the transmitter output is 10 mA. What are the zero and span of this temperature sensor/tranmitter?

2.90 Consider a flow sensor/transmitter that reads 10,000 lb/h when the transmitter output is 7 mA and reads 15,000 lb/h when the transmitter output is 12 mA. What are the zero and span of this flow sensor/tranmitter?

2.91 Consider a pressure sensor/transmitter that reads 180 psig when the transmitter output is 6 mA and reads 250 psig when the transmitter output is 10 mA. What are the zero and span of this pressure sensor/tranmitter?

2.92 Determine the value of the electric analog reading in mA from a level transmitter that has a span of 65% and a zero of 12% corresponding to a measured level of 47%.

2.93 Calculate the flow rate of water through an orifice with β equal to 0.5 in a schedule 40 4-inch line if the pressure drop across the orifice is 2 psi.

2.94 Calculate the flow rate of water through an orifice with β equal to 0.6 in a schedule 40 3-inch line if the pressure drop across the orifice is 10 psi.

2.95 Calculate the flow rate of a hydrocarbon liquid (specific gravity equal to 0.65) through an orifice with β equal to 0.67 in a schedule 40 2-inch line if the pressure drop across the orifice is 1.5 psi.

2.96 Calculate the flow rate of a hydrocarbon liquid (specific gravity equal to 0.65) through an orifice with β equal to 0.45 in a schedule 40 2-inch line if the pressure drop across the orifice is 2.3 psi.

2.97 Calculate the flow rate of water through an orifice with β equal to 0.87 in a schedule 40 4-inch line if the pressure drop across the orifice is 2 psi.

2.98 Calculate the pressure drop across an orifice with β equal to 0.6 in a schedule 40 4-inch line for a flow rate of water of 150 GPM.

2.99 Calculate the pressure drop across an orifice with β equal to 0.4 in a schedule 40 4-inch line for a flow rate of water of 150 GPM.

2.100 Calculate the pressure drop across an orifice with β equal to 0.43 in a schedule 40 3-inch line for a flow rate of a hydrocarbon liquid (specific gravity equal to 0.65) of 60 GPM.

2.101 Calculate the pressure drop across an orifice with β equal to 0.23 in a schedule 40 3-inch line for a flow rate of a hydrocarbon liquid (specific gravity equal to 0.65) of 60 GPM.

2.102 Calculate the pressure drop across an orifice with β equal to 0.59 in a schedule 40 2-inch line for a flow rate of a hydrocarbon liquid (specific gravity equal to 0.65) of 40 GPM.

2.103 Size an orifice meter for service on a 3-inch schedule 40 pipe carrying water with a maximum flow rate of 150 GPM and a minimum flow rate of 60 GPM. Assume that the line pressure is 100 psig.

2.104 Size an orifice meter for service on a 4-inch schedule 40 pipe carrying water with a maximum flow rate of 350 GPM and a minimum flow rate of 150 GPM. Assume that the line pressure is 100 psig.

2.105 Size an orifice meter for service on a 4-inch schedule 40 pipe carrying water with a maximum flow rate of 350 GPM and a minimum flow rate of 150 GPM. Assume that the line pressure is 10 psig.

2.106 Size an orifice meter for service on a 2-inch schedule 40 pipe carrying a hydrocarbon liquid (specific gravity equal to 0.65) with a maximum flow rate of 75 GPM and a minimum flow rate of 25 GPM. Assume that the line pressure is 50 psig.

2.107 Size an orifice meter for service on a 3-inch schedule 40 pipe carrying a hydrocarbon liquid (specific gravity equal to 0.65) with a maximum flow rate of 175 GPM and a minimum flow rate of 75 GPM. Assume that the line pressure is 150 psig.

2.11 Projects

Specify the instruments and design the orifice meters and control valves for each of the following cases. Size the lines (i.e., to available cast iron schedule 40 pipe sizes) based on assuming that the linear velocity in the lines is approximately 7 ft/s.

a. CST thermal mixer (Example 3.1)

b. CST composition mixer (Example 3.2)

c. Level in a tank (Example 3.3)

d. CSTR (Example 3.4)

e. Heat exchanger (Example 3.6)