Control Valve Selection

All control systems manipulate some end device. This end device has some impact, either direct or indirect, on the value of the controlled variable. For example:

- At a particular point in a duct system, the static pressure is held constant. A control system may do so by sending a signal to a variable speed drive, which in turn varies the rotational speed of the fan. As fan speed varies, so does the static pressure in the duct system.

- In a catalyst regeneration system, a control system must maintain the temperature of the hot air leaving the regenerator. This may be accomplished by controlling the volume flow rate of the air/fuel mixture entering a boiler. The boiler will increase or decrease the output temperature of hot air to the regenerator. This, in turn, impacts the temperature of the hot air leaving the regenerator.

- In a shell and tube heat exchanger, the water temperature leaving the exchanger on the tube side may be controlled by manipulating the flow rate of the hot fluid entering the shell side. This flow rate is manipulated with a liquid control valve.

There are a number of other end devices used for any number of purposes. These include air dampers, SCRs (Silicon Controlled Rectifiers), SSRs (Solid State Relays), etc. When dealing with fluid flow and heat transfer systems, the end device in question is a control valve. Although control valves come in a wide range of configurations, the parameters used to select a valve are essentially the same. These parameters include:

- Static Pressure Rating
- Close-off pressure
- Valve Action (Normally Open vs. Normally Closed)
- Valve Coefficient (C_v)
- Valve Authority
- Valve Rangeability
- Valve Cavitation Coefficient

Static Pressure Rating

The static pressure rating of a valve is simply the maximum static pressure the valve is designed to handle when placed in service. The rating is stated in manufacturers' literature. Obviously, the rating of the valve must be greater than the maximum static pressure attained in the system as determined when the system is designed. Although proper selection is important for safe and reliable operation of the system, it does not impact the controllability of the system.

Close-off Pressure

Close-off pressure is how much differential pressure the valve / actuator combination can overcome in order to seat the valve and stop flow completely. As such, this criterion has a direct impact on sizing the valve actuator. The determination of the necessary close-off pressure is a function of the hydraulic design of the system. Once the designer responsible for the design determines this requirement, the control designer can use this information to properly select the actuator. Actuator sizing can become quite involved and is beyond the scope of this course. Fortunately, actuator selection is typically done by the valve manufacturer.

Typically, actuators are either electronic or pneumatic. In some industries, actuators may also be hydraulic or vacuum operated. Most industrial and commercial processes use pneumatic and electronic actuators, so we will focus our discussion on these. Pneumatic actuators are very popular due to their relatively low cost, high power output, and reliability. They are available in a myriad of pressure ranges and are easy to sequence. Recently, electronic actuators have become quite popular. Technological advances have reduced their cost, increased their power output, and improved their reliability. The major difference between pneumatic and electronic actuators is the speed of operation. The effect of speed of operation is discussed under the topic of system time lags and dead time.

Valve Action

Valve action defines whether the valve is full open when the control signal to the actuator is low, or if is full closed when the control signal to the actuator is low. The selection of a normally closed vs. a normally open valve is based on a desired fail-safe condition. Fail-safe refers to that condition in which you wish the valve to be in the case of a failure of the control system. For example, assume an office suite is heated by air flowing over a hot water coil. If the control system fails, it would probably be desirable for the control valve to fail in the open position so as to provide full heat to the space. Normally open is the typical fail-safe condition selected for most heating valves. However, assume the space houses a mainframe computer system and any heating required is accomplished with a reheat coil in a VAV box. Mainframes tend to be somewhat sensitive to high ambient temperatures. In such a case, we may wish the heating valve to fail in a full closed position should the control system fail. Although the space may overcool, this is preferable to overheating in this situation. As one can surmise, the selected fail-safe condition is dependent upon the application. One should also note the selected fail-safe condition does not affect the controllability of the system, although it does impact certain controller settings. The remaining four criteria are, debatably, the most important parameters to properly determine for good controllability.

Valve Coefficient

Valve coefficient or C_v is a measure of the volume flow rate of 25 ^oC water through a valve with a 1 psi pressure differential across the valve. It is determined by the following equation:

$$C_v = \frac{GPM}{\sqrt{\frac{\Delta P}{SG}}}$$

where:

$$GPM = Fluid\ flowrate\ expressed\ as\ gallons\ per\ minute$$
$$\Delta P = Pressure\ drop\ across\ control\ valve$$
$$SG = Specific\ gravity\ of\ fluid$$

For example, suppose you know there is a 15 psi pressure drop across a control valve when the valve is wide open with a flow rate of 150 gpm of water through the valve. The specific gravity of water is one. The valve coefficient can be calculated as:

$$C_v = \frac{150\,gpm}{\sqrt{\frac{15\,psi}{1}}} = 38.72\frac{gpm}{psi^{1/2}}$$

Once we know the valve coefficient, we can then calculate the pressure drop across the valve given a flow rate, or a flow rate given a pressure drop. For example, determine the pressure drop across the above valve if the flow rate increases to 200 gpm.

$$\Delta P = \left(\frac{GPM}{C_v}\right)^2 \times SG = \left(\frac{200}{38.72}\right)^2 \times 1 = 26.68\,psi$$

In practice, once you know the design flow rate and the desired pressure drop, one can calculate the required valve C_v and select a proper valve from manufacturer's literature.

But how does one determine the desired pressure drop? This is accomplished by designing for a specified valve authority.

Valve Authority

Valve authority is defined as the ratio of the minimum pressure drop across the valve (that which occurs when the valve is wide open) to the maximum pressure drop across the valve (that which occurs at the minimum controllable closed position of the valve) expressed as a percent. In some literature, this is referred to as the Pressure Drop Ratio (PDR). The maximum pressure drop is generally taken to be the pressure drop of the system in which the valve controls. As such, we can mathematically define valve authority as:

$$\beta = \frac{\Delta P_{valve}}{\Delta P_{pipe} + \Delta P_{coil} + \Delta P_{valve}}$$

where:

$$\Delta P_{valve} = Pressure\ drop\ across\ control\ valve$$
$$\Delta P_{pipe} = Pressure\ drop\ of\ piping\ including\ service\ valves, etc.$$
$$\Delta P_{coil} = Pressure\ drop\ of\ the\ coil$$

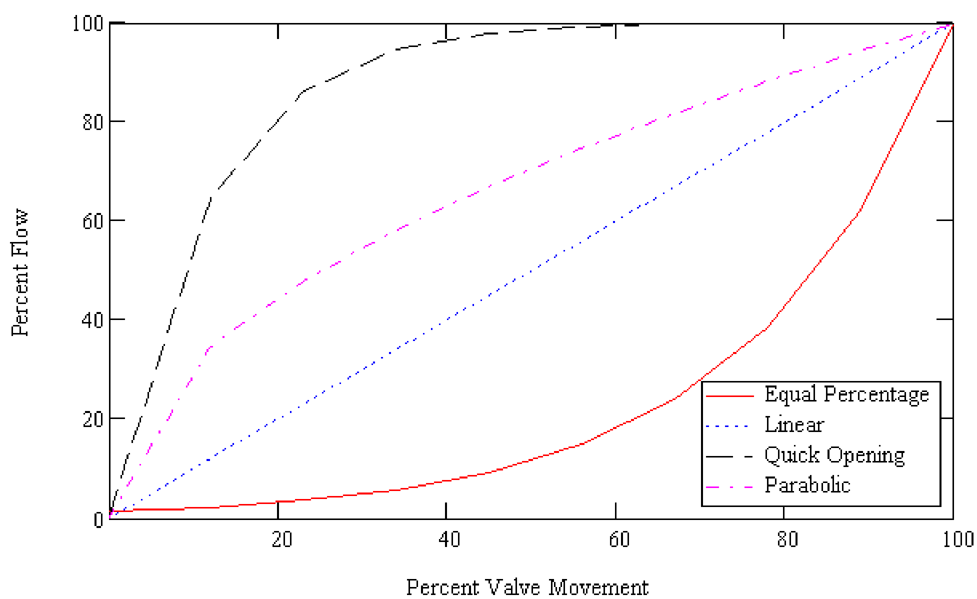
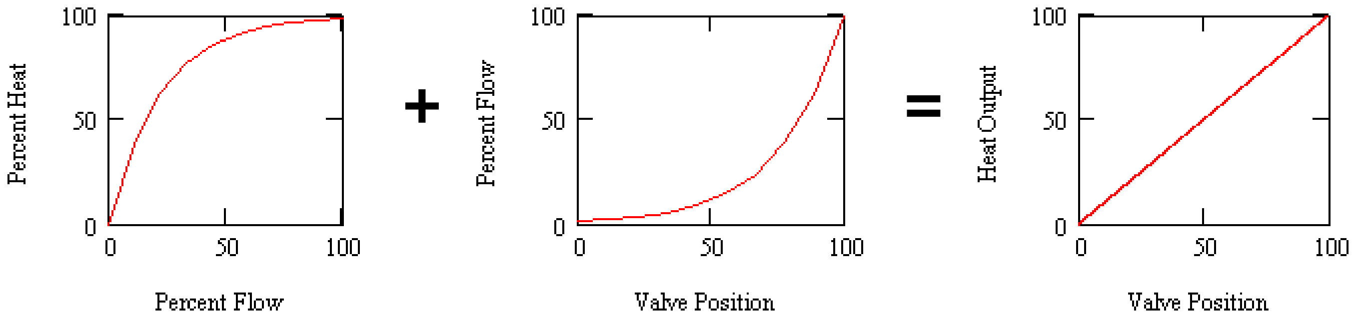


Figure 1 Characteristic curves of some valves

All control valves have an inherent performance characteristic. Figure 1 shows the typical characteristic curve of an equal percentage, parabolic, linear and quick opening valve.

The equal percentage is typically used to linearize the output of a heat exchanger. The output of a heat exchanger is also logarithmic and tends to have a characteristic opposite that of an equal percentage valve. As such, the heat output of a heat exchanger controlled by an equal percentage valve tends to be nearly linear with valve movement. Refer to Figure 2.



A heating coil may have a characteristic similar to that shown in the graph above left. Ideally, one would control this heat exchanger with an equal percentage valve with a characteristic similar to that shown in the center. When the characteristics of each piece of equipment interact, they will produce a linearized output. This is desirable in the area of control in order to ease the process of tuning or calibrating the control loop

Figure 2 The linearization of a control process through proper selection of equipment

The equal percentage valve is so named because each the flow rate will increase an equal percentage of the previous flow for every equal step change in valve movement. It is mathematically defined as:

$$\Delta flow\ percent = e^{k(1-x)}$$

where:

$$k \equiv a\ constant\ unique\ to\ the\ valve$$
$$x \equiv a\ value\ between\ 0\ and\ 1\ representing\ valve\ position$$
$$0 = closed \qquad 1 = open$$

As an example, suppose k = -3.3648.

Then for x = 0.01 (1%), %flow = 0.03575

For x = 0.02 (2%), %flow = 0.03697

Thus, the change in flow rate for a 1% increase in valve position is:

$$\frac{(0.03697 - 0.03575)}{0.03575} = 0.034(3.4\%)$$

The parabolic valve provides flow variation that varies as the square of pressure drop. From a basic course in fluids, you may remember that the pressure drop across any hydraulic element varies with the following ratio:

$$\frac{PD_1}{PD_2} = \left(\frac{GPM_1}{GPM_2} \right)^2$$

A valve with parabolic trim will vary the flow in a fashion opposite to this relationship. This type of valve allows the flow rate of a fluid flow system to vary linearly with a differential pressure measurement.

The linear valve is rather self-explanatory. The flow through the valve varies linearly with valve stem position. Such valves are useful for controlling steam flow or providing temperature blending of two fluid streams.

A look at the characteristic curve of a quick opening valve shows that such a valve make a poor modulating control valve. However, it is often in on/off control systems.

The inherent characteristic of a control valve is valid only if it is the sole pressure drop in the system. This can only occur if the valve is the only pressure drop within the system it is controlling or if it is installed in such a fashion that the pressure at each valve port is essentially equal. There are few applications when this occurs. Perhaps the most common is a three-way valve installation at the interface of a primary-secondary system where the valve is controlling a blending temperature at the secondary. Otherwise, the control valve will always be some percentage of the total pressure drop in the circuit. As such, the installed characteristic of the valve can be quite different from its inherent characteristic. This is what valve authority measures.

For example, consider the system shown in Figure 3. The piping, including all fittings and service valves, has a calculated pressure drop of 15 ft. w.g. The coil has a pressure drop of 30 ft w.g. and the control valve has a pressure drop of 20 ft. w.g. Calculate the valve authority.

$$\beta = \frac{20}{15+30+20} = 0.307$$

The characteristic of an equal percentage valve with different degrees of authority is shown below. Note that at low values of authority, the equal percentage valve approaches the characteristic of a linear valve. It can also be shown that a linear

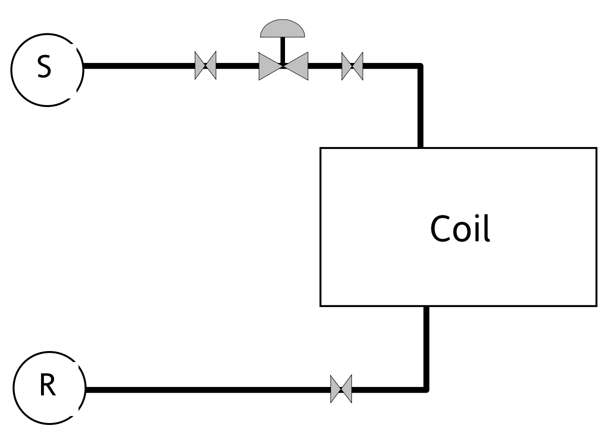


Figure 3 Coil and associated subcircuit

valve approaches the performance characteristic of a quick opening valve when installed with a low degree of authority. This curve also implies that systems should be designed with a high valve authority.

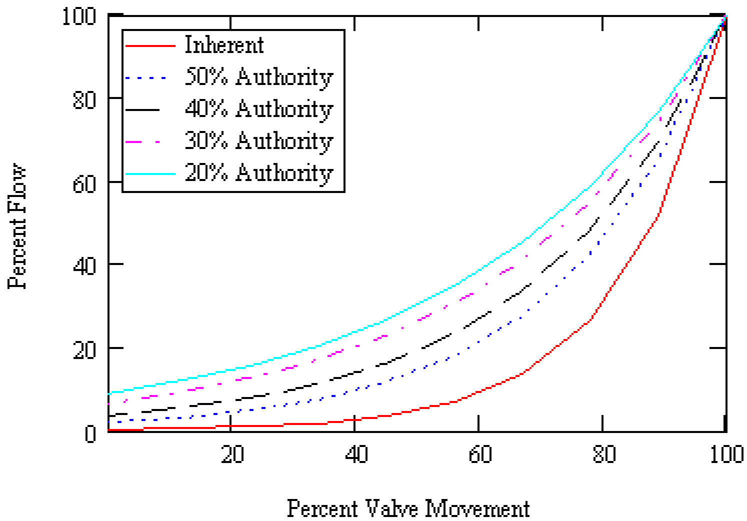


Figure 4 An equal percentage valve with varying degrees of authority

The obvious question then becomes, '*What value of authority should I use?*'. Unfortunately, this is a question not easily answered. The selection of an authority value is a compromise between controllability and the life-cycle cost of the system. A high value of authority improves controllability, but at the expense of high pump head. This means we need a larger, more expensive pump which not only drives up first cost, but also operating cost. As such, a designer must make a judgment call based upon the needs and desires of the client and the criticality of the process being designed as to whether one should select a higher or lower value of authority.

For example, suppose you are selecting a valve for a critical industrial process. Further assume that although the client wishes as low an operating cost as possible, accurate and precise control is more important. In such a case, valve authority as high as 50% may be justified. However, if we have a comfort heating process, one may be able to tolerate a certain level of reduced controllability for purposes of reducing the size and operating cost of the installed pumping system. In such a case, a value of authority around 30% may be appropriate.

Depending on who you talk to, 'proper' value of authority may range from a low of 10% to a high of 50%. However, most people agree valve authority should be above 0.23 (23%) for acceptable controllability. On the other hand, one well known manufacturer of valves and pumps recommends an authority of not less than 33%. In the end, the proper selection of authority is often a judgment call based on one's experience with fluid flow systems. For purposes of this module, authority should range between 30% and 50%.

Valve Rangeability

Another aspect of controllability relates to valve rangeability. Rangeability is a measure of the minimum controllable flow the valve is able to handle. Mathematically, it is defined as:

$$R = \left(\frac{Q_{\max}}{Q_{\min}} \right) \times \beta^{1/2}$$

where:

$$R = valve\ rangeability$$
$$Q_{\min} = minimun\ controllable\ \ flow\ rate$$
$$Q_{\max} = design\ \ flow\ rate$$
$$\beta = installed\ \ valve\ authority$$

The minimum controllable flow rate through a valve is a function of the valve design. It is directly affected by all sources of friction within the valve assembly. In an ideal valve, any change in signal applied to the actuator, even an infinitely small change, will force the valve stem to move, even if that movement is infinitely small. However, friction represents a force that must be overcome by the actuator. When the actuator exerts sufficient force to overcome friction, the valve stem will move some finite amount. When this occurs when the valve is full closed, this finite movement results in a certain minimum flow rate.

For example, suppose a valve has an installed authority of 35%. The design flow rate is 350 gpm. For good low-flow control, we wish a minimum flow rate of not more than 2 gpm. We can calculate the required rangeability as:

$$R = \left(\frac{350}{2} \right) \times 0.35^{1/2} = 123$$

This means the valve must have a manufacturer's rangeability rating of 123:1 or greater. A typical commercial valve generally has a rangeability of about 50:1. Industrial valves can have a rangeability as high as 200:1. This is part of the reason why industrial valves are so much more costly than a commercial valve.

Valve Cavitation

A final criteria is valve cavitation. As the fluid passes through the restricted opening of the valve, the local static pressure drops. If it drops below the vapor pressure of the fluid, the fluid flashes to vapor; in other words, it boils thus forming gas bubbles. As the fluid continues through the valve, the static pressure begins to rise. As this pressure rises above the vapor pressure of the fluid, the bubbles begin to collapse. This collapse releases a significant amount of energy in the form of a shock wave moving at mach one. The energy released is sufficient to chip away at the material making up the valve plug and valve seat thus seriously damaging the valve.

Valve cavitation often sounds like gravel flowing through the valve. Valve cavitation tends to occur most frequently when flowing hot fluids. However, it is possible for cavitation to occur in cold fluids as well. Cold water cavitation is far worse than hot water cavitation. This is due to the fact that the ratio of the specific volumes of the fluid in liquid form to the liquid in a gaseous state is significantly higher when the fluid is cold than when the fluid is hot. For example, consider the value of specific volume of water at 60 ^{o}F vs. water at 240 ^{o}F.

Temp	***Specific Volume (Fluid)***	***Specific Volume (Gas)***
60 ^{o}F	0.01604	1206.32
240 ^{o}F	0.01692	16.314

Table 1 Specific Volume of Water vs. Steam

Note the ratio of specific volume at 60 ^{o}F is 1206.32 / 0.01604 = 75,200. This same ratio for 240 ^{o}F water is 16.314 /0.01692 = 964. This means that as a bubble in cold water collapses, it releases 78 times more energy than when a bubble collapses in hot water. Fortunately, cold water cavitation occurs far less frequently than hot water cavitation. However, when it does, it will be significantly more destructive.

Engineers responsible for the design of a valve take great care to reduce the cavitation potential as much as possible. The cavitation potential of a valve is specified by a value known as the recovery coefficient. Mathematically, it is calculated as:

$$K_c = \frac{P_u - P_d}{P_u - P_{vp}}$$

where:

K_c = Valve recovery coefficient (unitless)

P_u = Pressure at a point 3 pipe diameters upstream of valve

P_d = Pressure at a point 12 pipe diameters downstream of valve

P_{vp} = Vapor pressure of fluid at operating temperature

All pressures must be expressed as absolute pressure. Also note the numerator represents the pressure drop across the valve.

As an example, consider a valve used to modulate the flow of 280 ^{o}F process water. The inlet pressure to the valve is 50 psig. What is the minimum downstream pressure allowed for incipient cavitation if the valve has a recovery coefficient of 0.45?

From a steam table, we can determine the vapor pressure of water to at 280 ^{o}F to be 49.226 psia. Let's assume an ambient barometric pressure of 14.7 psia. Then:

$$0.45 = \frac{64.7 - P_d}{64.7 - 49.2}$$

Solving for P_d, we fine the minimum allowable downstream pressure is 57.7 psia (43 psig). If we know the installed valve C_v, we can predict the potential for valve cavitation.