**10.450 Process Dynamics, Operations, and Control**
**Lecture Notes - 20**

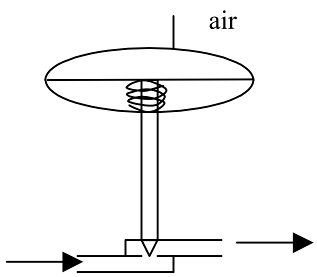
## Lesson 20. Control valves

### 20.0 Context

Controller output is a signal that varies between 0 and 100%. Putting this signal to use requires a final control element, a device that responds to the controller output signal by manipulating the process. In chemical processes, this is most often a valve, so that the controller output changes a flow rate. This control valve contributes a gain and requires time

### 20.1 Construction

Control valves are throttling valves, with an automatic actuator. A common design will use air and spring to move a diaphragm, which is connected to the stem, and thus the valve plug (trim). The air pressure varies between 3 and 15 psig to drive the valve through its full range. Fail-open or fail-close may be accomplished with either the actuator design (spring on top or bottom) or the valve body design (relative position of plug and seat ring). Typical applications: open for cooling water; closed for reactants. The example shows a valve that could be called either "fail-open" or "air-to-close". At 3 psig, or 0 psig if the air pressure fails, the valve will be fully open. At 15 psig, the valve will be fully closed.




### 20.2 Flow and head loss through fully-open valves

Remember your fluid mechanics: for flow going through some obstruction (such as a pipe fitting or a valve), we relate the friction loss to the flow rate by a resistance coefficient, or a loss coefficient. For turbulent flow, the loss coefficient does not vary much with flow rate.

$$\frac{\Delta P}{\rho} = K\frac{v^2}{2} \qquad (20.2.1)$$

where ΔP is the change in static pressure due to friction, ρ is the fluid density, K is the loss coefficient, and v is the cross-sectional average velocity at the entrance or exit.

Control valve capacity (that is, flow when fully open) is designated by a flow coefficient $C_v$.

$$F_{full} = C_v \sqrt{\frac{\Delta P}{\rho / \rho_{ref}}} \tag{20.2.2}$$

where the reference density is that of water at 60°F (999.0 kg $m^{-3}$). Although it is usually stated simply as a number, $C_v$ is actually a dimensional quantity with particular units.

$$C_v (=) \frac{\text{gal} - \text{in}}{\text{min} - \text{lb}_f^{0.5}} \tag{20.2.3}$$

$C_v$ is characteristic of a <u>fully open valve</u>. It's the horizontal flow in gpm of 60°F water under a 1 psid drop (there are no elevation contributions to the pressure drop used in this definition; it's all friction loss). Manufacturers determine $C_v$ experimentally by measuring the flow and pressure drop with the valve fully open, then using (20.2.2).

Of course, the $C_v$ formula (20.2.2) is related to the loss coefficient formula (20.2.1). The **dimensionless** K can be expressed in terms of $C_v$ and the area of the valve nozzles (standard pipe sizes from tables). Thus, this K is based on the average velocity in the pipeline, not the interior of the valve.

$$K = \frac{2}{\rho_r} \left( \frac{A_p}{C_v} \right)^2 \tag{20.2.4}$$

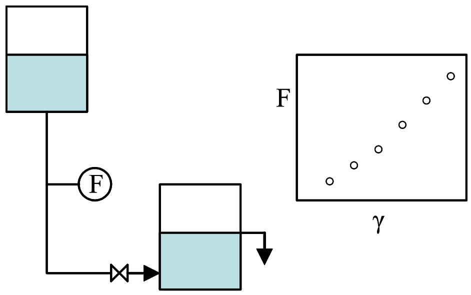
To the extent that K is constant, so will $C_v$ be constant with flow rate.

### 20.3 Inherent characteristics (flow as a function of opening)

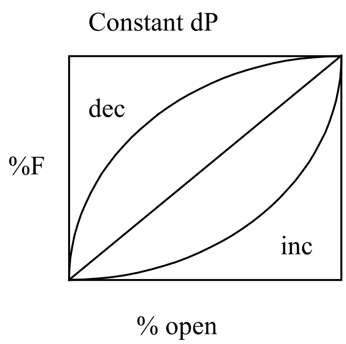
As a valve closes, it admits less flow for a given pressure drop. Thus flow is a function of pressure drop ΔP and γ, the fractional opening of the valve (0 < γ < 1). We put the γ-dependence into a function φ that decreases monotonically from 1, for the fully open valve, to zero for a closed valve.

$$F = C_v \phi(\gamma) \sqrt{\frac{\Delta P}{\rho / \rho_r}} \tag{20.3.1}$$

The function φ(γ) is called the *inherent characteristic* of the valve. Manufacturers determine characteristics experimentally by measuring flow and pressure drop at various valve openings. Ideally, the pressure drop would be kept constant, as if the valve were installed between two tanks and fed between constant liquid levels. However, (20.3.1) can be used with any pair of flow and pressure drop measurements.




There are 3 ideal types that real valves approximate:




Linear – for liquid level control

$$\varphi(\gamma) = \left(\frac{F}{F_{full}}\right)_{\text{constant } \Delta P} = \gamma \tag{20.3.2}$$

Increasing-sensitivity (equal percentage) – for pressure and flow control

$$\varphi(\gamma) = \left(\frac{F}{F_{full}}\right)_{\text{constant } \Delta P} = R^{-(1-\gamma)} \tag{20.3.3}$$

where R is the maximum rangeability; that is, the ratio between the fully open flow rate and some minimum flow. R is often 30 to 50. Notice that this is not the practical rangeability, because the valve should usually operate between about 10 and 80% open. Notice also that (20.3.3) predicts that the minimum flow occurs when the valve is fully closed, so it's not to be believed for small openings.

Decreasing-sensitivity (quick-opening) – for shut off and fast flow

Equal-percentage is most commonly used.

Inherent characteristics can be expressed in terms of the loss coefficient through (20.2.4). This allows the valve to be described with its associated piping in a mechanical energy balance. For a linear valve,

$$K_{(linear)} = \frac{2}{\rho_r}\left(\frac{A_p}{C_v}\right)^2 \gamma^{-2} = K_{fullyopen}\gamma^{-2} \tag{20.3.4}$$

where $A_p$ is the flow area of the valve nozzles. Similarly, for an equal percentage valve,

$$K_{(eq\%)} = \frac{2}{\rho_r}\left(\frac{A_p}{C_v}\right)^2 R^{2(1-\gamma)} = K_{fully-open}R^{2(1-\gamma)} \tag{20.3.5}$$

In general, for manufacturer's data that express fractional flow as some function of opening,

$$K = \frac{2}{\rho_r}\left(\frac{A_p}{C_v}\right)^2 \phi^{-2}(\gamma) = K_{fully-open}\phi^{-2}(\gamma) \tag{20.3.6}$$

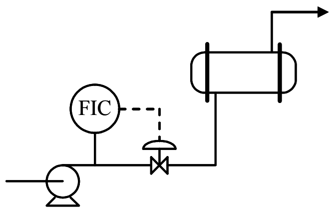
In (20.3.4-6) we are representing K as a function of valve opening $\gamma$; i.e., the loss coefficient at any particular valve condition. $C_v$, however, is the published capacity of the valve, a constant in the equations.

## 20.4 Installed characteristics

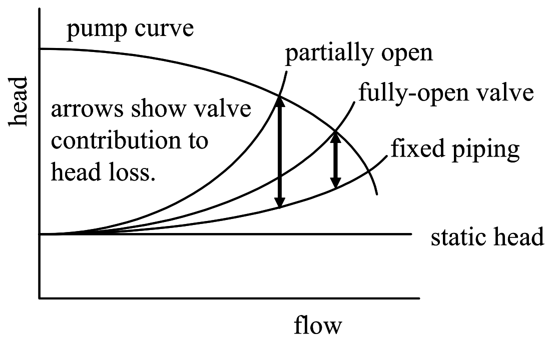
We have defined the *inherent characteristic* as the function $\phi(\gamma)$, a property of the valve. To make use of a valve, we install it in piping, and we want to know the dependence of flow on valve opening. This *installed characteristic* is given by

$$\left(\frac{F}{F_{full}}\right) = \phi(\gamma)\sqrt{\frac{\Delta P|_{\gamma}}{\Delta P|_{\gamma=1}}} \tag{20.4.1}$$

In general, installed characteristics differ from inherent characteristics. This does <u>not</u> represent some alteration in the valve – $\phi(\gamma)$ has not changed. Rather this behavior is the result of the pressure drop across the valve varying as the valve is opened. Consider a control valve in series with a pump and other equipment.




Imagine the valve being fully open, accounting for some portion of the total pressure drop in the piping. Now close the control valve to an intermediate opening. Its loss coefficient K is now increased, but the flow resistance of the rest of the piping has not changed. Thus the valve is now responsible for a greater fraction of the total piping pressure drop. This effect is exacerbated when the supply head decreases with increasing flow, as with a centrifugal pump.




Therefore, at the intermediate valve opening, there is a greater pressure drop across the valve than when fully open. Naturally, this drives a greater flow than would be observed had the pressure drop remained unchanged. The result is an approach of the equal-percentage inherent characteristic toward a linear installed characteristic.

The installed characteristic is determined by the properties of the valve (the inherent characteristic) and the piping system that surrounds it. Suppose that the manipulated variable is a stream that circulates through equipment in a piping loop, driven by a pump. From the mechanical energy balance on the loop, the pump head TDH is expended on fixed friction loss in the piping and equipment and variable friction loss in the valve.

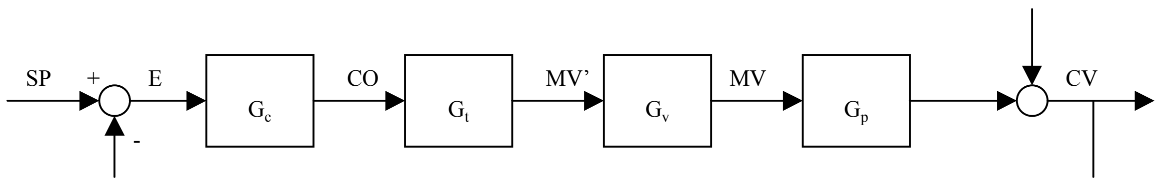
$$TDH(F) = \left[\sum K_{piping} + K_{cv}(\gamma)\right]\frac{1}{2g}\left(\frac{F}{A_p}\right)^2 \tag{20.4.2}$$

TDH(F) is the pump curve; $K_{cv}$ is the inherent characteristic, expressed as a loss coefficient by (20.3.6). Velocity has been expressed as the flow rate

F divided by an appropriate pipe area. From (20.4.2), combined with the pump curve, the installed characteristic ($F/F_{full}$ vs. $\gamma$) can be found.

**20.5 Using the valve in a control system: valve gain**

Installed characteristics become important in designing control systems, because the dependence of F on $\gamma$ should not show sensitive regions that would make control difficult. Consider this portion of the control loop:




The controller output CO is converted by the transducer into a signal MV' that varies between 3 and 15 psig. The valve transfer function $G_v$ relates the air pressure in the control actuator to the flow that passes through the valve. Leaving aside questions of transient response, let us look only at the gain.

Suppose the simplest case, that the installed characteristics (20.4.1) are linear. Then

$$F = F_{full}\gamma = F_{full}\frac{MV'-3}{15-3} \tag{20.5.1}$$

where MV' has units of psi. In deviation variables, this becomes

$$F^* = \frac{F_{full}}{12\text{psi}}MV'^* \tag{20.5.2}$$

or

$$G_v(s) = \frac{F^*(s)}{MV'^*(s)} = \frac{F_{full}}{12\text{psi}}f(s) \tag{20.5.3}$$

where f(s) represents dynamic characteristics of the valve. Thus the gain, i.e., the impact the controller can have on manipulated flow, increases with $F_{full}$, as would be supplied by a larger valve.

Suppose that the installed characteristic is some arbitrary nonlinear function $\psi(\gamma)$. Then the characteristic would be linearized around the reference condition for control design.

$$F^* = F_{full}\left(\frac{\partial \psi}{\partial \gamma}\right)_s \left(\frac{\partial \gamma}{\partial MV'}\right)_s MV'^* = \frac{F_{full}}{12\text{psi}}\left(\frac{\partial \psi}{\partial \gamma}\right)_s MV'^* \qquad (20.5.3)$$

The control engineer must examine the degree of nonlinearity, represented by the magnitude of the partial derivative. If it shows significant variation (say, a factor of 2) over the domain of $\gamma$, then the valve gain, and thus the loop gain, will vary with operating condition. Thus a control system designed to be stable at one reference condition $\gamma_s$ might be unstable at another condition.

## 20.6 Using the valve in a control system: valve dynamics

Most often it is sufficient to describe the valve by a first-order transfer function. The gain relates the flow capacity to the 12 psi range of driving pressure. The characteristic time increases with the size of the valve.

## 20.7 Specifying a valve

At the minimum you must specify a size and a type. In general, select the type on process grounds: for example, if the stream is clean, use a globe valve. If it contains solids, you may want to go to a ball valve. If you need lower pressure drop, use a butterfly valve.

To select the size, you need first to specify normal, maximum, and minimum flows that your process requires. For example, if you are supplying heating oil to a reboiler, set the normal flow for the design heat duty and the extreme flows to handle the upsets you realistically expect. You will also need to decide how much pressure drop you can reasonably expend on the valve. With the valve fully open, for example, the pressure drop across the valve should be about half that across the rest of the piping in the flow loop.

Knowing a flow rate and the pressure drop, you will know the product $C_v\phi(\gamma)$ by (20.3.1). You must now make some decision about the valve characteristic. For initial estimates, you might presume a linear characteristic and see if your operation will take place between 10 and 80% of stem travel for the expected min to max flows. If you need much greater rangeability, you may have to use multiple valves, as described by Shinskey (1996). The end result is a valve $C_v$ that can handle the maximum required flow at somewhat less than fully open

Now select a valve from a catalog that meets the required $C_v$. The next step is to calculate the installed characteristics for the catalog $C_v$ and inherent characteristics, combined with your piping system. From this, determine whether the selected valve has reasonably constant gain (slope of the installed characteristic) between min and max flows.

Try to satisfy these conditions – some may well be in conflict, so that judgement is in order.

- Slope of installed characteristics should vary less than 50% over the range of use
- Max expected flow < 80% open (as installed)
- Min expected flow > 10% open (as installed)
- Valve loss at max flow should be about half of the balance-of-piping head loss.
- Calculate rangeability from the useful range of the installed characteristics (= 80%/10%), not the full range (= 100%/5%).