Understanding Valve Characteristics

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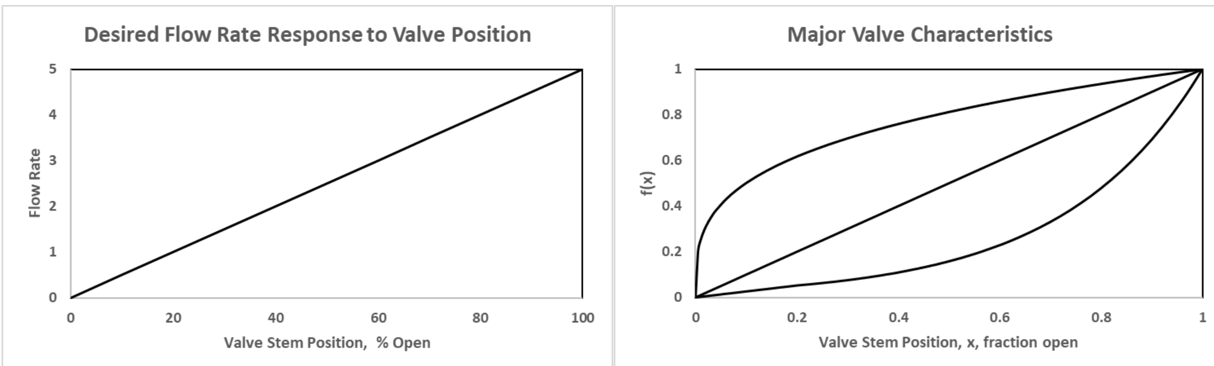
The valve characteristic represents how the flow rate changes with valve position. Desirably, for normal use, as in Figure 1, we want the characteristic to be linear, a constant gain, so that controller tuning at one flow rate is acceptable for all flow rates.



Figures 1 & 2. 1) A linear flow rate response, and 2) three categories of valve characteristics

The idealized valve equation is

$$F = C_v\, f(x) \sqrt{\frac{\Delta P_v}{G\, \xi}} \tag{1}$$

Where F is the volumetric flow rate (gal/min, L/s, SCFM/hr, etc.) and C_v is the valve capacity, the flow rate (same units as F) at full open conditions. ΔP_v is the pressure drop across the valve that is pushing the fluid through it (psi, Pa, etc.), G is the fluid specific gravity, and ξ has a value of 1 with the same units as ΔP_v to make the equation dimensionally correct. Usually ξ is not shown, since its value is unity. Finally, $f(x)$ is the valve characteristic, the fraction of maximum flow as a function of valve stem position, x. Both $f(x)$ and x are dimensionless, and they range from zero to 1. When the stem is closed, $x = 0$, the fraction of maximum flow is also zero, $f(x) = 0$. And when the stem is fully open, $x = 1$, the fraction of maximum flow is also unity, $f(x) = 1$.

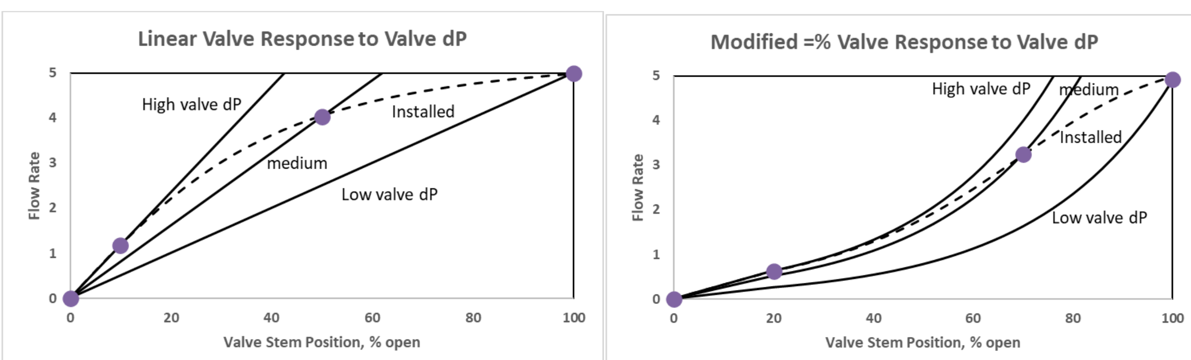
Figure 2 illustrates three valve characteristics. The linear characteristic is the middle line, where $f(x) = x$. The upper curve is called a quick opening characteristic, meaning that small initial openings of the stem permit a very large flow-through. This might be good where emergency flooding/dousing is important. The lower curve represents a modified equal percentage characteristic. Even up to 50% open, the valve is just up to 20% capacity. The ideal equal percent relation has an equal fractional flow increase, $\Delta F/F$, for each incremental stem change, Δx. After a bit of math the relation is

$$f(x) = R^{x-1} \tag{2}$$

R is termed rangeability. Unfortunately, when the stem is closed, $x = 0$, the fraction of maximum flow is not zero, $f(x) = 1/R$. So, an equal percent valve is modified at low stem positions to shut off when $x = 0$.

Why have such a valve? Consider a linear valve characteristic $f(x) = x$, the middle line in Figure 2. Note that the valve model of Equation (1) indicates that the flow rate through the valve depends on the pressure drop across the valve. For a linear characteristic, the valve equation is $F = C_v\, x \sqrt{\frac{\Delta P_v}{G\, \xi}}$. Whether the ΔP_v is high, medium, or low, the flow rate is linearly related to the stem position., as indicated in Figure 3 by the solid lines for a high, medium, and low ΔP_v.

The issue is that when a valve is installed in a line, the ΔP_v does not remain constant. The pressure drop across the valve changes as the valve changes the flow rate. When the valve is closed, the valve blocks the flow, and it must hold back the entire driving pressure that wants to make the fluid flow, perhaps a combination of pump, gravity, and up- and down-stream pressures, ΔP_{system}. In this fully closed, $x = 0$ case, the pressure drop across the valve is high, $\Delta P_v = \Delta P_{system}$. At an intermediate stem position, perhaps 50%, the flow rate through the piping system is medium, and the pressure drop due to friction losses in the piping system, ΔP_{pipe}, is also medium. This means that the pressure drop across the valve is medium, $\Delta P_v = \Delta P_{system} - \Delta P_{pipe}$. By contrast, when the valve is fully open, and the flow rate is large, the friction loss pressure drop through the piping system is high, leaving a low ΔP_v. The large dots on the linear relations in Figure 3 represent which ΔP_v is associated with the valve stem position. The dashed line is the locus of how the flow rate trends with valve position. Even though the isolated (inherent, when ΔP_v is kept constant) valve characteristic is linear, when installed, because ΔP_v depends on the flow rate, which depends on x, the linear valve has quick-opening nature. This means that a controller tuned for the higher flow rates (low process gain, small changes in flow rate for a given change in controller output) will be too aggressive for the low flow (high process gain) conditions. As illustrated in Figure 3, the process gain (flow rate response to controller output) has about an 18:1 ratio.



Figures 3 & 4. The installed characteristic of 3) a linear valve, and 4) and equal-percent valve.

The installed characteristic (flow rate response to valve stem position) is not the same as the inherent characteristic (where some magic might keep ΔP_v a constant).

The same process flow attributes affect an equal-% valve. Here, the ideal valve model is $F = C_v\ R^{x-1} \sqrt{\frac{\Delta P_v}{G\ \xi}}$. In Figure 4, the solid lines, again, are the plots of flow rate through an =% valve when ΔP_v is a constant at high, medium, and low values. The dashed line is the installed characteristic. Notice now, for the installed characteristic, that the process gain is nearly the same at all flow regions. With the =% valve, the gain ratio is reduced from 18 to about 3.

These illustrations represent an ideal model for pressure losses in the piping system and valve characteristics with an =% rangeability of 40. Valve manufacturers don't have to use Equation (2) for a valve model, and they may offer products with alternate C_v and R values. So, get details from your valve vendor. Although ideally represented here, the concepts are the same for real valves installed in real flow systems.

You can explore the impact of C_v and R values for an FCV (Flow Control Valve) in your particular piping system. Ideally, if the system pressure drop driving flow, ΔP_{system}, is a constant, and the friction losses through the piping system are modeled as being proportional to the square of the flow rate, $\Delta P_{piping\ losses} = k\ G\ F^2$, and the valve model is inverted to determine the $\Delta P_{valve} = \frac{G\xi\ F^2}{[C_v\ f(x)]^2}$, then the installed valve characteristic can be modeled by substituting relations in the pressure balance, $\Delta P_{system} = \Delta P_{pipe} + \Delta P_{valve}$ and solving for flow rate. The installed flow rate model is:

$$F = C_v\ f(x) \sqrt{\frac{\Delta P_{system}}{G\xi + kG[C_v\ f(x)]^2}} \tag{3}$$

Use $f(x) = x$ for a linear valve and $f(x) = R^{x-1}$ for an ideal =% valve. Adjust the value of C_v to get your desired fully-open flow rate, and R to get a close-enough-to-linear installed characteristic. Of course, if you want to include nonidealities like how the outlet pressure of a centrifugal pump changes with flow rate, you can.

There are many aspects of FCV selection. Hopefully, this article will help you understand one of them. I think that technical bulletins and monographs from valve manufacturers provide excellent and comprehensive tutorials.

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Russ Rhinehart started his career in the process industry. After 13 years and rising to engineering supervision, he transferred to a 31-year academic career. Now "retired", he enjoys coaching professionals through books, articles, short courses, and postings on his web site www.r3eda.com.