Ask An Engineer

*Many of our customers have similar questions. Each month we will try to pick the most common question and answer it in the ESI Monthly eNewsletter. If you have a question about piping systems, send your question to natalie@eng-software.com with "**Ask an Engineer**" in the subject line.*

Q. What is Choked Flow and when does it occur?

A. Choked flow is a condition that occurs in a valve when the static pressure of the liquid drops below the vapor pressure, causing the liquid to flash to a vapor. The vapor bubbles occupy more volume than the same mass of liquid, resulting in restriction of the flow through the valve. When fully choked flow occurs, fluid flow through the valve will not increase when the downstream pressure is decreased. Choked flow results in high noise levels, vibration, pipe stress, and severe erosion and pitting of the valve seat and disc. Choked flow may result from an over-sized control valve or if an inappropriate type of valve is specified for a given application.

One important characteristic of a control valve is its liquid pressure recovery factor (F_L), which indicates the pressure recovered from the vena contracta to the valve outlet relative to the overall pressure drop across the valve. Some types of valves, such as ball and butterfly valves, have a low F_L in the range of 0.55 to 0.7, as described in the ISA Standard S75.01. Globe valves, on the other hand, have a high F_L in the range of 0.85 to 0.9. This important piece of control valve data is one that the valve manufacturer should supply along with the valve capacity values.

In the valve sizing process, the maximum flow rate at choked flow is calculated using the following formula:

$$q_{max} = N_1 F_L C_v \sqrt{\frac{P_1 - F_F P_v}{G_f}} \quad \text{(equation 1)}$$

Where:
N_1 is a numerical constant based on units used in the formula (=1.0 for gpm and psi)
F_L = liquid pressure recovery factor
C_v = flow coefficient at the given valve position
P_1 = absolute pressure at the valve inlet (psia)
P_v = liquid absolute vapor pressure (psia)
G_f = liquid specific gravity
F_F = liquid critical pressure ratio factor, given by the equation below

$$F_F = 0.96 - 0.28 \sqrt{\frac{P_v}{P_c}} \quad \text{(equation 2)}$$

Where:
P_c = liquid absolute critical pressure (psia)

Engineered Software, Inc.'s PIPE-FLO® can be used to show how choked flow occurs in a control valve that is oversized or one that has a low F_L value.

Consider the Condensate Tank 1 level control valve shown in Figure 1 below. The system is designed to pass 50 gpm of 160 degF condensate from the tank to a header at 5 psig. Fluid properties are density = 60.94 lb/ft^3, vapor pressure = 4.745 psia, and critical pressure = 3198 psia. The piping is 2" schedule 40 steel pipe. LCV 1 is an un-designed valve installed to calculate the valve sizing information. The calculated differential pressure is 56.58 psig with an inlet pressure of 61.77 psig.

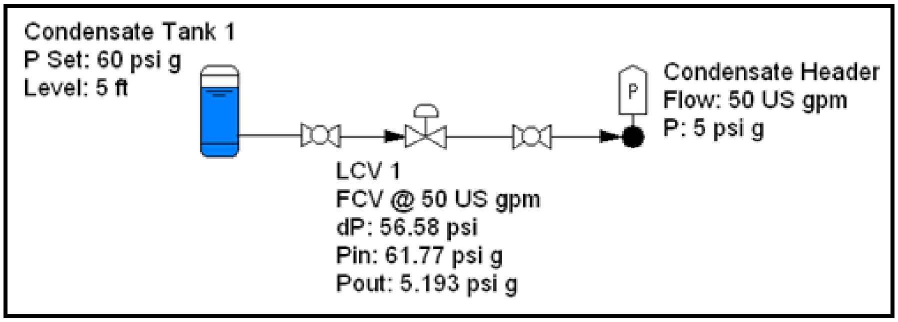

Figure 1. Un-designed flow control valve installed to obtain critical valve sizing data.

To determine the flow coefficient to size the valve, use the following equation from the ISA standard S75.01 for incompressible fluids:

$$C_v = \frac{q}{N_1 F_P \sqrt{\frac{P_1 - P_2}{G_f}}} \quad \text{(equation 3)}$$

F_P is the piping geometry factor that takes into account fittings on the inlet or outlet of the valve. Let's assume the valve will be the same size as the piping, so F_P = 1.0. Specific gravity is 60.94/62.37 = 0.977. The sizing equation becomes:

$$C_v = \frac{50\ gpm}{(1.0)(1.0)\sqrt{\frac{61.77 - 5.193}{0.977}}} = 6.57$$

If we want the valve to control at about 80% open at the calculated C_v value, we have all the information we need to size the valve in PIPE-FLO's control valve calculator, as shown below in Figure 2 and 3. Let's select a linear, single port globe valve, ported plug, flow to open, with a linear characteristic. PIPE-FLO will calculate typical C_v values for each incremental valve position, along with typical F_L and X_t values.

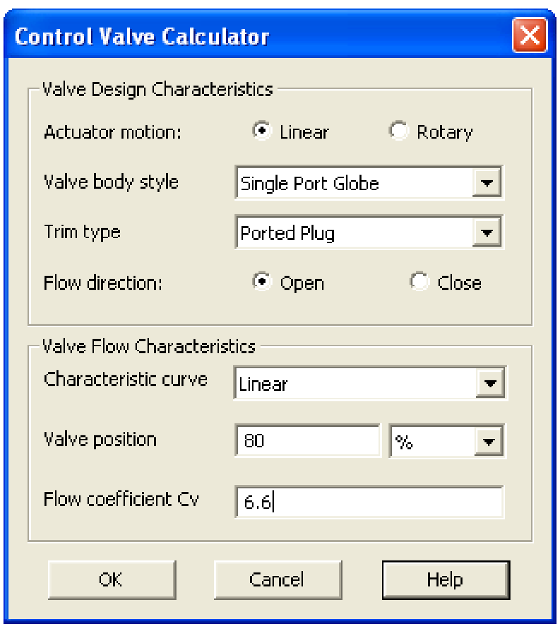

Figure 2. Control Valve Calculator dialog box.

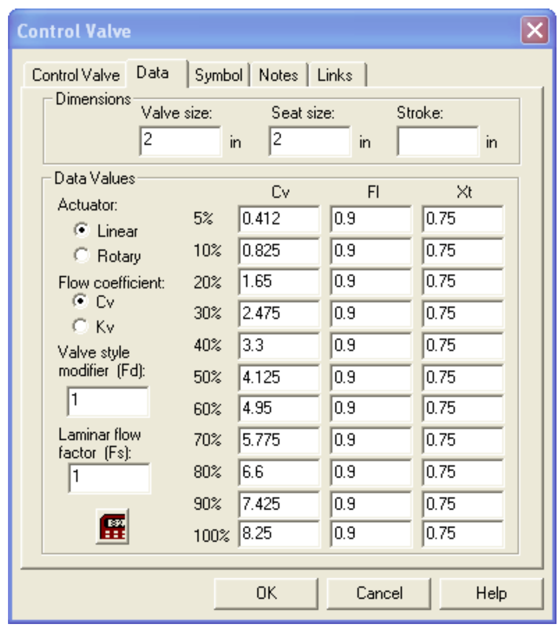

Figure 3. Calculated control valve data.

Figure 4 below shows the system with the control valve designed using the C_v data from the calculator.

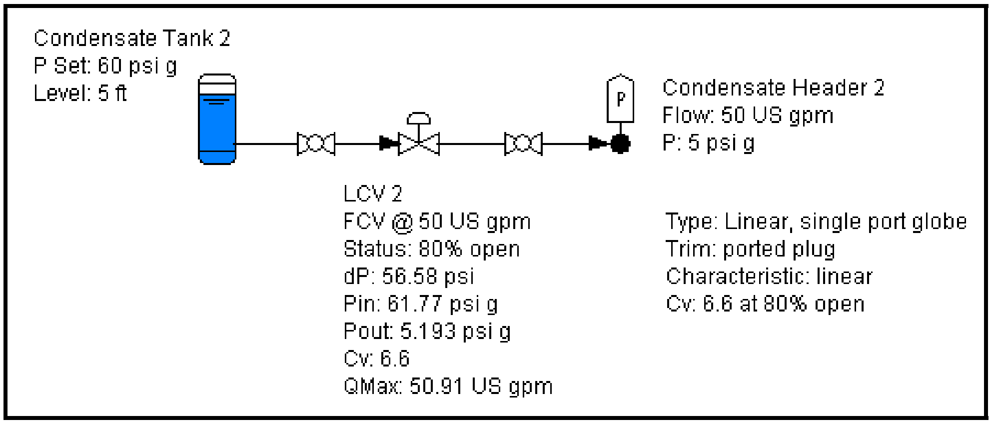

Figure 4. Designed control valve installed showing valve position, C_v and Q_{max}.

Let's confirm the Q_{max} calculated value using equation 1 and 2 above.

$$F_F = 0.96 - 0.28\sqrt{\frac{P_v}{P_c}} = 0.96 - 0.28\sqrt{\frac{4.745\ psia}{3198\ psia}} = 0.949$$

$$q_{max} = N_1 F_L C_v \sqrt{\frac{P_1 - F_F P_v}{G_f}} = (1.0)(0.9)(6.6)\sqrt{\frac{(61.77+14.7)-(0.949)(4.745)}{0.977}} = 50.9\ gpm$$

Since the set point of the control valve is less than the flow rate at which choked flow occurs, the valve is operating as designed. Let's compare this case with one in which a valve is installed off the shelf without regard to properly sizing the valve for the application. In this scenario, a valve with a C_v =50 at 80% open is installed in the system. As shown below in Figure 5, because the valve is grossly over-sized, it is only open to 11% in order to control to the design flow rate of 50 gpm.

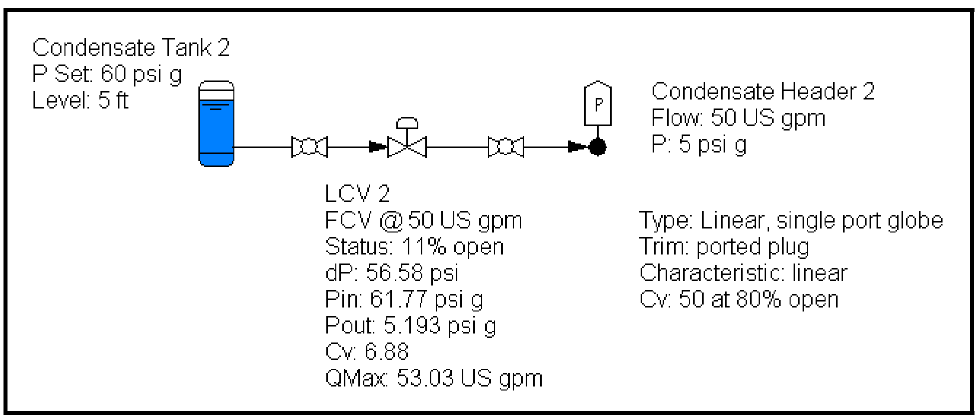

Figure 5. Over-sized control valve installed, controlling at 11% open at 50 gpm.

But if the flow rate is reduced to 40 gpm as shown in Figure 6, choking occurs because the valve is less than 8% open (corresponding to a C_v = 5), resulting in the maximum flow rate calculation of 38.6 gpm.

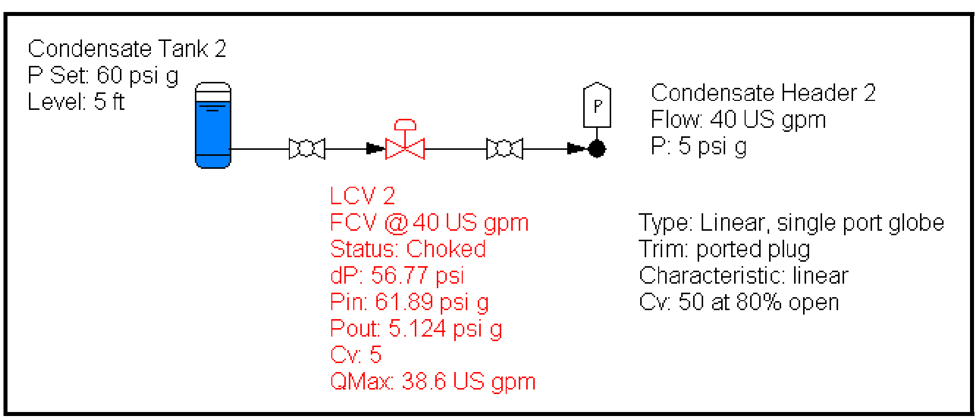

Figure 6. Over-sized control valve throttle to 40 gpm resulting in choked flow.

The choked flow warning in PIPE-FLO indicates that these results are invalid because the head loss in the inlet and outlet pipes is calculated based on 40 gpm. The flow rate of 40 gpm cannot be achieved because of the choked condition. The actual flow rate will be limited to Q_{max}, which can be shown in PIPE-FLO by placing the valve in a manual position to obtain the calculated Q_{max}, as shown in Figure 7. This is an iterative process to adjust the valve position to obtain the desired flow rate.

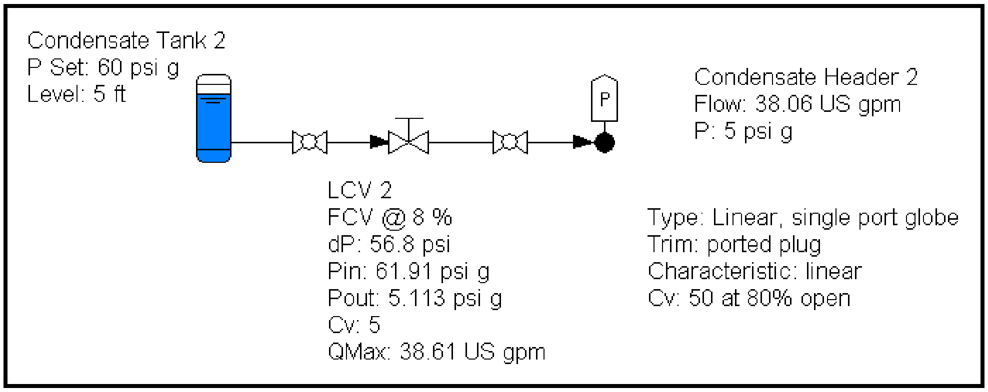

Figure 7. Over-sized control valve manually set to obtain the Qmax shown in Figure 6.

Now let's look at a scenario in which a ball valve is selected with a C_v = 6.6 at 80% open, as shown in Figure 8 below. The valve is properly sized, but is the wrong type for the application.

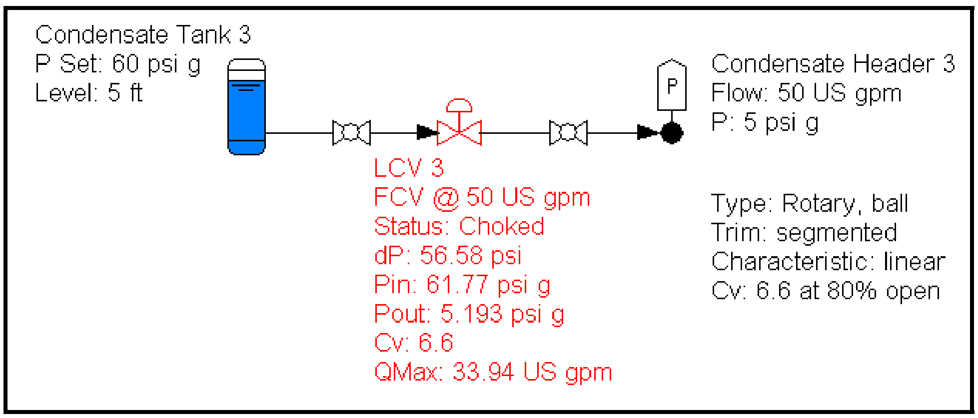

Figure 8. Properly sized ball valve results in choked flow due to inherent low F_L of a ball valve.

Choking occurs at the set flow rate of 50 gpm because the ball valve has a low F_L value. In this case, F_L = 0.6 for the ball valve, and the impact can be seen by confirming the Q_{max} calculation for this scenario using equation 1 and 2.

$$F_F = 0.96 - 0.28\sqrt{\frac{P_v}{P_c}} = 0.96 - 0.28\sqrt{\frac{4.745\ psia}{3198\ psia}} = 0.949$$

$$q_{max} = N_1 F_L C_V \sqrt{\frac{P_1 - F_F P_v}{G_f}} = (1.0)(0.6)(6.6)\sqrt{\frac{(61.77+14.7)-(0.949)(4.745)}{0.977}} = 33.9\ gpm$$

Again, the choked flow warning in this scenario indicates that the results are invalid because the flow rate of 50 gpm cannot be achieved due to the choked condition.

Conclusion

These scenarios show the importance of properly sizing a control valve and for selecting the appropriate type of control valve based on the unique operating conditions of a piping system.

