# Choked Flow in Control Valves in Liquid Applications

PIPE-FLO® PROFESSIONAL
MODELING

## Choked Flow in Control Valves in Liquid Applications

by Engineered Software, Inc.

When designing and installing a piping system for liquid service in industrial or commercial applications, the location and type of valve selected for process control plays a major role in whether the valve will operate smoothly or experience cavitation or choked flow. These severe operating conditions not only damage the valve and increase maintenance costs, they could also create safety hazards to plant personnel. In addition, they also impact the ability of the process to deliver the liquid at a designed flow rate, pressure, temperature or other key quality parameter.

Cavitation and choked flow conditions are hard to recognize and can occur in any piping system. However, using PIPE-FLO® Professional to model the piping system, a problem such as choked flow can easily be identified and solutions evaluated in the model prior to implementation. High temperature and high pressure drop applications make the valve more susceptible to cavitation and choked flow. Installing the valve at high elevations in the system where the inlet pressure of the valve is low may cause a valve to cavitate when it wouldn't if installed at a lower elevation. The type of valve selected also plays a key role in determining whether the valve will operate with cavitation present or if the choked flow rate is reached.

## Phenomenon of Cavitation and Choked Flow

Cavitation is a condition that occurs when the pressure drop across a valve causes the fluid's static pressure to drop to the vapor pressure and the liquid flashes into vapor bubbles. The area with the smallest flow passage in the valve, or the vena contracta, is the most susceptible location for cavitation to begin, as this is the point of highest velocity and lowest pressure (Bernoulli principle in action). As the flow passage downstream of the vena contracta expands, some pressure recovery occurs as the fluid velocity decreases and pressure increases before it leaves the valve body. If the pressure increases above vapor pressure, the vapor bubbles collapse and implode on internal surfaces of the valve, removing a small piece of material with each implosion. This causes high noise levels, vibration, pipe stress, and pitting of the valve's internal surfaces and even downstream piping, as seen in Figure 1.

**Figure 1.** Severe pitting damage from cavitation resulted in a pinhole leak on the valve body of a V-notch Ball Valve used to regulate the cooling water flow to aluminum casting molds.

The severity of the cavitation damage increases as the pressure drop across the valve increases and more liquid is flashed to vapor at the vena contracta. If the pressure drop across the valve is high enough, the flow passage at the vena contracta becomes fully occupied by vapor and choked flow occurs. The flow rate at choked conditions reaches the maximum flow that can be achieved for the given inlet conditions and cannot be increased regardless of how much the pressure drop across the valve is increased.

## Deviation from Predicted Performance

**Figure 2.** Graph of flow rate versus the square root of the pressure drop across the valve (courtesy of Crane Technical Paper TP-410).

When cavitation occurs in a control valve, the actual flow rate begins to deviate from what is predicted using the flow coefficient equation presented in the ISA standard for sizing control valves S75.01 (IEC 60534-2-1 equivalent). This is because the vapor bubbles occupy more volume as the mass of liquid expands during the phase change, creating an additional resistance to flow. As seen in Figure 2, for a given valve position and flow coefficient (Cv), at the onset of incipient cavitation the valve's performance begins to deviate from the linear relationship defined by the flow coefficient, flow rate, and square root of the pressure drop in Equation 1.

$$Q = C_v N_1 F_P \sqrt{\frac{P_1 - P_2}{SG}}$$

(1)

Where:

- $Q$ = volumetric flow rate
- $C_v$ = valve flow coefficient at the given valve position
- $N_1$ is a numerical constant based on units used in the formula (=1.0 for gpm and psi)
- $F_P$ = piping geometry factor
- $P_1$ = absolute pressure at the valve inlet
- $P_2$ = absolute pressure at the valve outlet
- $SG$ = specific gravity of the liquid

As the pressure drop increases from the onset of cavitation, the deviation from the equation becomes greater until the point the valve is fully choked and the maximum flow rate and pressure drop are reached.

The ISA and IEC standards have equations to calculate the choked flow rate (Equation 2) and the choked pressure drop (Equation 3) at fully choked conditions.

$$Q_{choked} = N_1 F_L C_v \sqrt{\frac{P_1 - F_F P_{vp}}{SG}}$$

(2)

Where:

- $Q_{choked}$ = maximum flow rate at choked flow conditions
- $F_L$ = liquid pressure recovery factor
- $P_{vp}$ = liquid absolute vapor pressure (psia)
- $F_F$ = liquid critical pressure ratio factor

$$dP_{choked} = \left(\frac{F_{LP}}{F_P}\right)^2 \left(P_1 - F_F\ P_{vp}\right)$$

(3)

Where:

- $dP_{choked}$ = choked pressure drop
- $F_{LP}$ = combined liquid pressure recovery factor and piping geometry factor
- $F_F$ = liquid critical pressure ratio factor (see Equation 4 below)
- $P_{vp}$ = absolute vapor pressure of the liquid at inlet temperature

The liquid critical pressure ratio factor (FF) depends only on the properties of the fluid:

$$F_F = 0.96 - 0.28\sqrt{\frac{P_{vp}}{P_c}}$$

(4)

Where:

- $P_c$ = liquid absolute critical pressure (psia)

If the flow rate or pressure drop required for the application is greater than the choked values, then the required flow or pressure drop won't be achieved and the valve will be exposed to these extreme conditions.

The Liquid Pressure Recovery Factor ($F_L$) is an important characteristic of a control valve which roughly indicates how much pressure drop occurs across the valve compared to the pressure drop from the inlet to the vena contracta. Some types of valves, such as ball and butterfly valves, have a low $F_L$ in the range of 0.55 to 0.7. 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 determined by testing by the valve manufacturer and should be provided to the user along with other critical valve data.

**Figure 3.** Pressure profile for various types of valves for a given pressure drop.

## Using PIPE-FLO® Professional to Evaluate Choked Flow

PIPE-FLO® Professional will display a warning when the conditions for choked flow are met. Consider the piping system modeled in PIPE-FLO in Figure 4. Cold water at 60 °F is pumped to a heat exchanger and heated to 180 °F. The flow rate is controlled by a globe valve type of flow control valve located at 30 ft elevation.

With this design, the control valve would operate at about 77% open at 750 gpm with a pressure drop of about 27.7 psi. Since the operating flow rate and dP are below the Choked Flow Rate (813.9 gpm) and Choked dP (32.61 psi) values, the valve will not be choked and this system should operate as designed.

**Figure 4.** Control valve at 30 ft elevation.

## Higher Elevations Increase Susceptibility to Choked Flow

Suppose a last minute design modification was made after all the equipment was purchased and required the heat exchanger and control valve to be located at 45 ft elevation instead of 30 ft. Figure 5 shows that this design change would result in choked flow at the control valve. What caused it to choke?

Because of the higher elevation, the inlet pressure of the control valve is lower (pressure head is converted to elevation head per the Bernoulli Theorum). This reduces the Choked dP and Choked Flow Rate according to Equations 2 and 3. Since the required dP across the control valve (27.49 psi) is greater than the Choked dP (27.44 psi), the valve would operate under choked flow conditions at 750 gpm.

**Figure 5.** Heat exchanger and control valve located at 45 ft elevation. Choked flow is indicated.

## Higher Temperatures Increase Susceptibility to Choked Flow

To evaluate the effect of fluid temperature on choked flow in a control valve, consider the same system in Figure 5 with choked flow at the valve at the higher elevation and higher fluid temperature. If the required fluid temperature was 150 °F instead of 180 °F, as shown in Figure 6, the valve would not be choked and would deliver the fluid to the Hot Water Tank at the designed flow rate of 750 gpm. Why isn't the valve choked even when installed at the higher elevation?

Again the answer can be seen by evaluating the equations above, but it also requires understanding how the fluid properties change with temperature, specifically the vapor pressure of the liquid. Figure 6 shows that the lower temperature liquid results in a higher Choked dP (29.4 psi) and higher Choked Flow Rate (790.4 gpm). Since the actual dP is less than Choked dP, the valve will not be choked with 1 50 °F water flowing through it, but it will be choked with 180 °F water .

**Figure 6.** Colder water does not result in choked flow, even with the valve at the higher elevation.

## Valve Type Influences Susceptibility to Choked Flow

Different types of valves have different values of the Liquid Pressure Recovery Factor ($F_L$) based on the internal flow passages of the valve. The original, non-choked system in Figure 4 was based on selecting a globe valve design which has a higher $F_L$ in the range of 0.9. If a different valve with a lower $F_L$ (around 0.83) is selected as shown in Figure 7, choked flow conditions are flagged in PIPE-FLO. The lower $F_L$ reduces the values of the Choked dP and Choked Flow Rate, causing the valve to be choked at the designed flow rate.

**Figure 7.** A different control valve with a lower $F_L$ selected for the original system (valve at lower elevation with 180°F) results in choked flow.

## Summary

Engineers typically don't design piping systems to operate at choked flow conditions, but unforeseen operating conditions may unexpectedly cause choked flow in a control valve. Choked flow is extremely detrimental to the valve and potentially to downstream piping and equipment, increasing maintenance costs as well as potentially impacting product quality and worker safety.

It's important for the design engineers to understand why choked flow occurs and to recognize potential scenarios that may result in choked flow in control valves. High temperature applications, installing the valve at high elevations, and selecting the wrong type of control valve for the required pressure drop are all scenarios that make the valve more susceptible to cavitation and choked flow.