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Choked Flow in Control Valves in Compressible Applications in PIPE-FLO Professional

Using PIPE-FLO® Professional to Evaluate Compressible Choked Flow in Control Valves

PIPE-FLO Professional uses equations from recognized industrial standards for control valves, making it an excellent tool to evaluate cavitation and choked flow in compressible and incompressible fluid flow through control valves in a piping system. PIPE-FLO Professional 2009 used the ***ANSI/ISA-75.01.01-2007 Flow Equations for Sizing Control Valves***, while PIPE-FLO Professional v12 (and above) implemented updated equations based on the ***IEC 60534-2-1 (2011) Industrial Process Control Valves – Flow Capacity – Sizing Equations for Fluid Flow under Installed Conditions*** standard (the ANSI/ISA international equivalent standard).

PIPE-FLO Professional v12 also implements additional calculations and a new methodology for predicting and performing calculations around the choked flow condition. These changes result in lower calculated choked flow rates in v12 than v2009, resulting in choked flow warnings in v12 where they were not indicated in v2009. Customers are encouraged to evaluate models built in earlier versions of PIPE-FLO Professional to determine if this change impacts their systems.

One key to successfully modeling compressible fluid flow in PIPE-FLO Professional is to define the pipe's fluid zone pressure as close as possible to the calculated inlet or average pressures at the device. For control valves, the compressible flow equations from the ANSI/ISA and IEC standards accounts for the compressibility effects of the gas flow by calculating an Expansion Factor (Y) for the valve.

$$W_{\text{compressible}} = 63.3 Y C_v \sqrt{x P_1 \rho_1}$$

$$Y = 1 - \frac{x}{3 F_\gamma x_{\text{TP}}}$$

$$x = \frac{P_{1\ \text{static abs}} - P_{2\ \text{static abs}}}{P_{1\ \text{static absolute}}} = \frac{dP}{P_{1\ \text{static abs}}}$$

Background on Control Valve Performance and Choked Flow for Gas Applications

The hydraulic performance of a control valve is characterized by its Flow Coefficient (Cv), which defines the amount of pressure drop across a valve at a given flow rate, or conversely the flow rate at a given pressure drop. The performance of a control valve at a fixed position (fixed Cv) is shown in Figure 1 for a control valve with Cv = 218.4 and xTP = 0.8575 for air at 100 psia inlet static pressure and 60 degF. The dimensionless Pressure Drop Ratio (x) is used on the vertical axis, which can only vary from 0.0 to 1.0. The Expansion Factor (Y) is shown as the green line and uses the upper horizontal axis with x and takes into account the adiabatic expansion of the air across the valve. The incompressible flow rate (in lb/sec) is the blue line and compressible flow rate (in lb/sec) is the red line. Note: the flow equation results in units of lb/hr, which is divided by 3600 to obtain units of lb/sec.

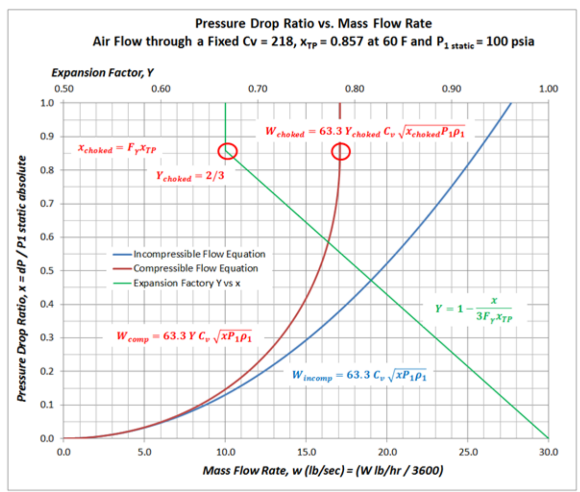

Figure 1. Mass Flow Rate (w) and Expansion Factor (Y) vs Pressure Drop Ratio (x) for Cv = 218.4

The incompressible equation in Figure 1 displays a 2nd order relationship between flow rate and pressure drop across the valve. Multiplying the Expansion Factor Y curve by the Incompressible Flow Equation curve = Compressible Flow Equation curve!

For compressible gas applications, choked flow occurs in a control valve when the gas velocity at the vena contracta approaches the local speed of sound and the Mach Number approaches 1.0. The ANSI/ISA and IEC standards state that choked flow conditions occur when Y=2/3 and the flow rate no longer increases with increasing dP (increasing x). The pressure drop across the valve cannot exceed the choked pressure drop, even if the exit pressure should result in a greater dP and x. When the actual pressure drop is greater than the choked pressure drop, the excess pressure drop must occur at the exit plane in the form of normal shock waves, resulting in a "back pressure" being felt at the outlet of the control valve.

From Figure 1, the choked flow conditions occur at Ychoked = 2/3, x choked = 0.859, w choked = 17.1 lb/sec, dPchoked = 85.9 psi.

PIPE-FLO Professional 2009 Results

PIPE-FLO 2009 uses equations from the ANSI/ISA-75.01.01-2007 standard to determine the pressure drop and flow rate using the flow coefficient relationship and total inlet pressure. Choked flow conditions were flagged, but there was increased uncertainty in the calculated results when near the choked flow condition. Figure 2 shows the calculated results for the conditions shown in Figure 1 for a control valve with Cv = 218.4 with air at 60 deg F and 100 psia inlet static pressure (107.8 psia total pressure). The valve discharges to a total pressure of 14.7 psia. The inlet and outlet pipes are 4" NPS Sched 40 with a very short length so that P1 and P2 essentially defines the inlet and outlet total pressures of the control valve. Note that there are two fluid zones, one at 100 psia for the inlet pipe and the other at 14.7 psia for the outlet pipe.

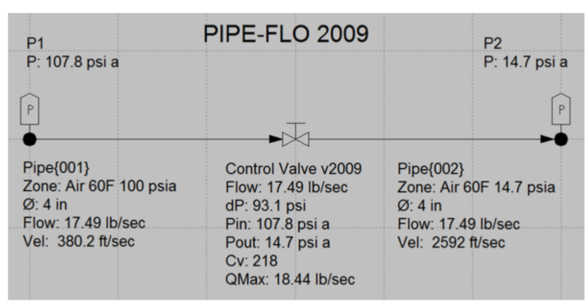

Figure 2. Control valve results in PIPE-FLO 2009

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In PF 2009, the choked flow rate was labeled as Qmax, equal to 18.44 lb/sec in Figure 2. Since the calculated flow rate is 17.49 lb/sec (less than Qmax), choked flow was not indicated. This value of Qmax is 7.8% greater than the choked flow rate in Figure 1, but the calculated flow rate is only 2.3% greater than the Figure 1 choked flow rate.

The calculated air velocity at the outlet is 2582 ft/sec, which is above the sonic velocity of air (around 1100 ft/sec), indicating that there is inaccuracy that needs to be further evaluated.

The calculated dP across the valve is 93.1 psi, which is established by the entered values at P1 and P2, but this is greater than the dP choked from Figure 1, so there is inaccuracy in this value. The calculated Qmax and dP would put this point to the right of the red curve in Figure 1.

PIPE-FLO Professional v12.0 and v12.1 Results

In PIPE-FLO Professional v12, updated equations based on the ***IEC 60534-2-1 (2011) Industrial Process Control Valves – Flow Capacity – Sizing Equations for Fluid Flow under Installed Conditions*** (the ANSI/ISA equivalent) were implemented, as well as new calculations and a different methodology to evaluate performance around the choked flow condition. The IEC standard shifts focus from the choked flow rate to the choked pressure drop, so PFv12.0 added the calculations for Choked dP, but did not calculate Qmax. Additional control valve parameters were also calculated (xT, xTP, Y). Figure 3 shows the results calculated in v12.1 for the same conditions modeled in Figures 1 and 2 above.

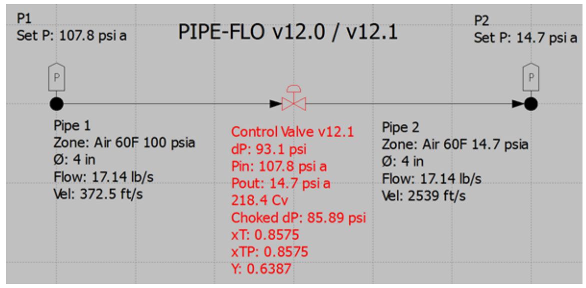

Figure 3. Control valve results in PIPE-FLO v12.1

Since the calculated dP (93.1 psi) is greater than the Choked dP (85.89 psi), a warning (Message ID 157 Choked flow through the device) is generated indicating choked flow conditions. (Also note the calculated Y < 2/3, also indicating choked flow). Because of the choked flow conditions, the calculated flow rate in v12.1 is 2% less than the v2009 flow rate.

The choked condition creates another inaccuracy in the results which shows up in the calculated outlet pressure of the valve. The outlet pressure of the valve is set by the entered value at P2. But the choked condition limits the dP across the valve to the Choked dP value, so the outlet total pressure should be (107.8 - 85.89) = 21.91 psia, not 14.7 psia. The rest of the pressure drop would occur beyond the end of the pipe. The inaccuracy in the calculated velocity in Pipe 2 is also an indication of the uncertainty in the calculated results that needs further evaluation. Improvements have been made to further this evaluation in v14.

PIPE-FLO Professional v14 Results

Additional calculations were added with the development of PIPE-FLO v14.0, including the static pressures at the inlet and outlet of pipes and the choked flow rate for the control valves (which was Qmax in v2009). The absolute ***static*** inlet pressure is now used for P1 in the control valve equations, as opposed to the absolute ***total*** inlet pressure that was used in v12.1 and v2009. This change was made to conform to the IEC and ANSI/ISA standards, and result in lower choked flow rates, especially at high inlet velocities.

These additional results give more insight into evaluating choked flow conditions in control valves and adjusting the model accordingly. Figure 4 shows the calculated results for PIPE-FLO v14.1 for the same conditions modeled in Figure 1, 2 and 3 above, with the additional calculated results displayed.

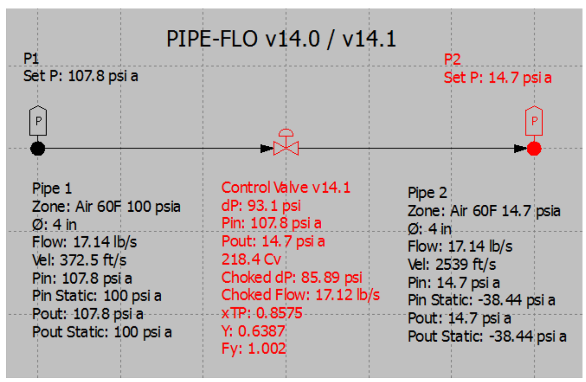

Figure 4. Control valve results in PIPE-FLO v14.0

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Choked flow conditions are still indicated with a calculated dP > Choked dP (93.1 > 85.89 psi) and the calculated Expansion Factor Y = 0.6387 < 2/3 (same results as v12.1). The calculated flow rate = 17.14 lb/sec, which is 0.12% greater than the choked flow rate (17.12 lb/sec), also indicating choked flow conditions.

The new calculated results for static and total pressure at the inlet and outlet of pipes allow the adjustment of the Pressure Boundaries which use the entered Total Pressure value for calculations. In order to obtain 100 psia static pressure at the inlet of the control valve, the total pressure must be 107.8 psia for the calculated flow rate (the dynamic pressure is 7.8 psi).

As with v12.1 in Figure 3, the calculated outlet pressure of the control valve is inaccurate due to the choked flow conditions. Since Choked dP = 85.89 psi and P1 total = 107.8 psia, the actual valve outlet total pressure cannot go below 21.91 psia, even though a lower pressure exists downstream. The outlet pressure shown in the results is calculated from the user-entered total pressure P2 and the dP across the outlet pipe, Pipe 2, which is essentially dP = 0 psi due to the very short length of pipe entered.

A new warning implemented in PIPE-FLO v14.0 indicates that the static pressure at P2 is below absolute 0 psia, indicating the model is depicting a physical impossibility. In other words, the user-entered conditions cannot be achieved due to choked flow conditions. The calculated velocity is also indicating a physical impossibility since it is above sonic velocity, or Mach 1.

Although the calculated results and warnings are indicating a problem with how the system is modeled, the results can be interpreted to help adjust the boundary conditions to eliminate the inaccuracy.

Adjusting Your PIPE-FLO Professional Model for Choked Flow Conditions

The PIPE-FLO model can be adjusted to account for the choked flow conditions created in the control valve, as shown in Figure 5. By increasing the total pressure specified at P2 and assigning Pipe 2 a fluid zone with a pressure close to that value, the results can be corrected. This is an iterative process to find the correct outlet total pressure, P2, and the appropriate fluid zone pressure.

Figure 5 shows a set of results with P2 = 27.8 psia total and a fluid zone pressure of 28 psia assigned to Pipe 2. The calculated flow rate (17.09 lb /sec) is very close but just below the choked flow value (17.12 lb/sec) so the choked flow condition is not flagged (also, the calculated dP is less than the choked dP). These results indicate the valve is just at the verge of the fully choked condition.

The calculated velocity in Pipe 2 is closer to sonic velocity so there is greater accuracy for this calculation. Further iterations of P2 and reassigning fluid zones may be needed to narrow down the solution.

The outlet pressure of the control valve now shows the true amount of back pressure that would be created by the choked flow condition in the valve.

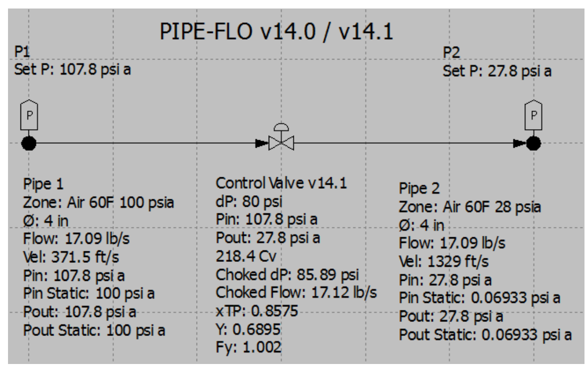

Figure 5. Control valve results with P2 adjusted for choked flow conditions in v14.1.

Summary

Evaluating choked flow conditions in PIPE-FLO Professional has improved with each update of the software. New calculations and tools have been added to improve the accuracy of the calculations and help the user evaluate the calculated results and adjust the model to more accurately depict the real-world performance of the control valve in a piping system.

For additional reading on choked flow in control valves, refer to this article by **Jon Monsen** at **Valin Corporation**: ***Gas Flow in Control Valves***.