Gas Flow in Control Valves

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The principle difference between the nature of the flow of gas and the flow of liquid through control valves is that liquids are incompressible and gasses are compressible. When the pressure of a liquid changes, the volume and density, ?, remain unchanged, while on the other hand, pressure changes in a gas result in both volume and density change. When observing flow through a control valve vs. pressure drop, both liquid and gas flows can choke, that is, at some pressure drop, flow stops increasing with increasing pressure drop, but for different reasons.

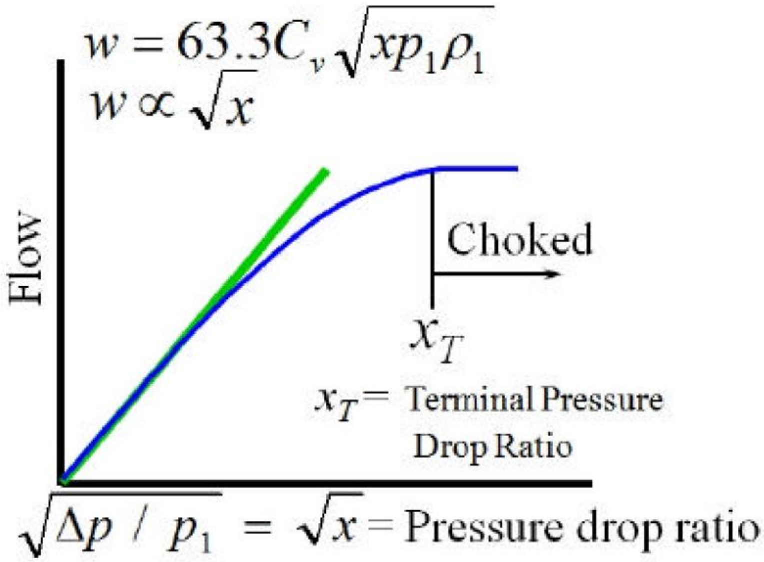


Figure 1. Flow of gas vs. pressure drop ratio through a control valve.

The equation for flow at the top of Figure 1 is almost identical to the equation we would use for liquid in cases where flow was given in pounds per hour. (Note that the subscript, 1, for pressure and density indicate that they are the conditions upstream of the valve.) The only difference is that instead of using the square root of pressure drop (?p) in the equation and for the scale of the horizontal axis of the graph, we use the square root of the "Pressure drop ratio," ?p/p1. We then substitute the single character, x, for ?p/p1 to make the expression simpler. Making this change makes the expression "?p" which would appear in the equivalent liquid equation, equal to "x p1." (?p/p1 X p1 = ?p) This change from the liquid equation is not absolutely necessary, but we will see later that it makes the prediction of gas choked flow much more convenient. The equation at the top of Figure 1 tells us that flow is proportional to the square root of x. Graphing the equation results in the upward sloping green line.

If we were to conduct a flow test, the actual relationship between flow and pressure drop ratio would be as shown by the curved blue line, not the straight one. At low pressure drop ratios the flow follows the straight line, but then it deviates more and more until at last, further increases in pressure drop ratio do not yield any additional flow. At this point we say that flow has become choked. Since for gas flow, we have chosen to call the horizontal axis the "x" axis instead of the delta p axis, we define the pressure drop ratio at which flow becomes fully choked as the Terminal Pressure Drop ***Ratio***, and give it the symbol x_T, T standing for "Terminal."

Let's see what is going on inside the valve to cause this choking of the flow and to give the graph its shape.

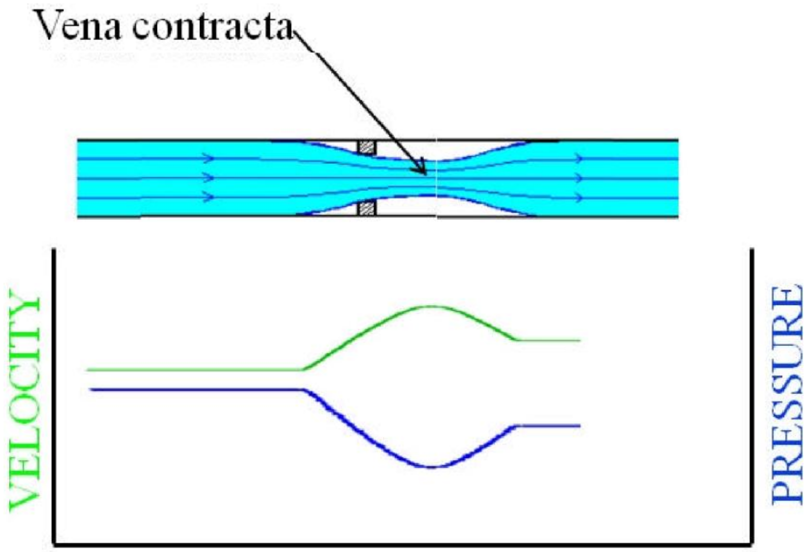


Figure 2. Gas velocity and pressure profile inside a control valve.

At this point, I need to point out that in addition to flow being proportional to the square root of the pressure drop ratio, it is also proportional to the square root of the density at the **vena contracta**. This is true for both liquid and gas, but with liquids (which are incompressible) we don't need to make an issue of the fact, because the density at the vena contracta is exactly the same as the density upstream of the valve. Also, with liquids, the density at the vena contracta does not change as the flow rate changes.

The velocity of the gas flowing through a valve reaches a maximum at the vena contracta. Due to conservation of energy, as a result of the velocity increase, the pressure decreases to a minimum at the vena contracta. When the pressure decreases the gas becomes less dense. Since flow is proportional to the square root of density at the vena contracta, the decrease in density causes the flow to be less than it would be if gas were not compressible, accounting for flow graph starting to round off instead of following the straight line.

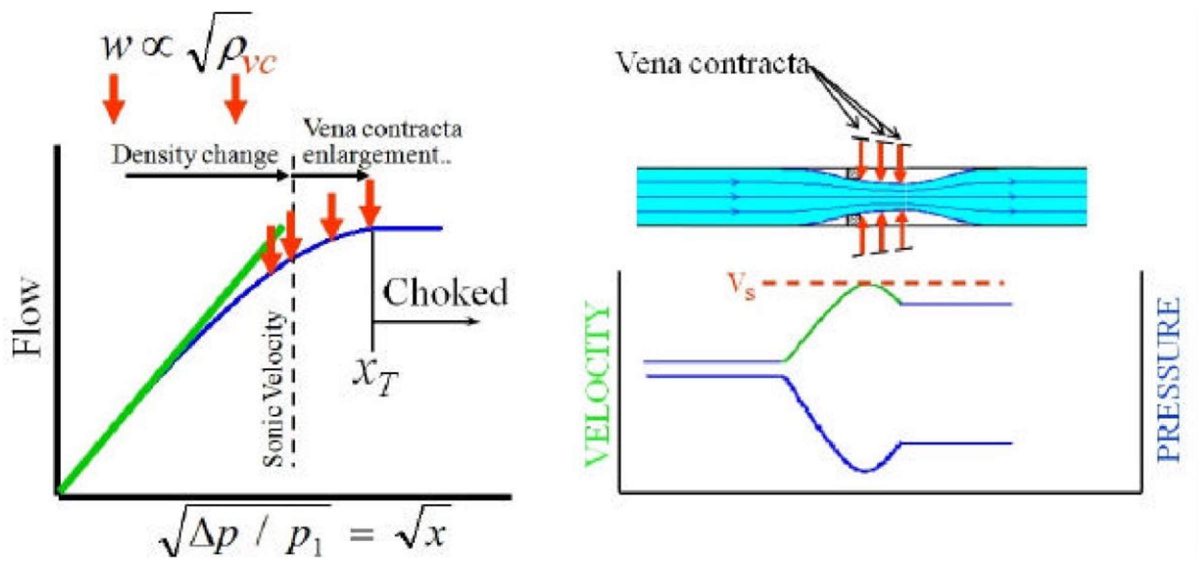


Figure 3. Density change and vena contracta enlargement are responsible for the shape of the flow graph.

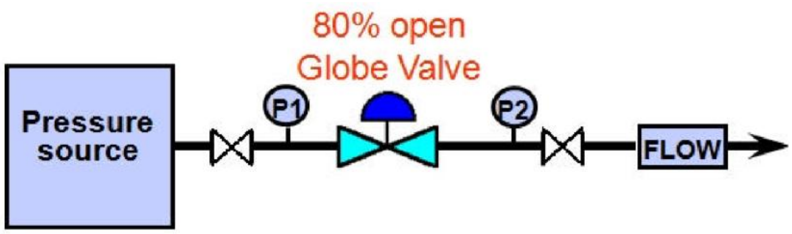
As we continue to increase the pressure drop ratio, the velocity at the vena contracta becomes greater and the pressure becomes less, resulting in an even lower density. Now the flow deviates even more from the straight line that assumes a constant density at the vena contracta as would be the case for a liquid.

At some point, as the pressure drop ratio is increased and the flow rate increases, the velocity at the vena contracta becomes sonic. Because the vena contracta is downstream of the physical restriction and has a smaller cross sectional area than that of the physical restriction, even though the velocity has reached the maximum velocity that is possible at a restriction, it is still possible for the flow rate to increase. As the pressure drop ratio is increased further, the vena contracta starts backing up toward the physical restriction and the cross sectional area of the vena contracta increases, so even though flow is sonic there is still some increase in flow because the area is larger. Finally, when the vena contracta backs up to the physical restriction, it can get no larger, and since flow is already sonic, no increase in flow is possible, and flow becomes fully choked.

Summarizing how the gas flow graph gets its shape:

At vena contracta velocities below sonic, the deviation of the flow curve from a straight line is caused by the density at the vena contracta decreasing. Once sonic velocity is reached, the velocity, pressure and density at the vena contracta remain constant, but the vena contracta backs up toward the physical restriction, becoming larger and thus allowing flow to increase. When the vena contracta finally reaches its maximum size (and since the velocity is already at the maximum possible) flow chokes.

Now let's see why we plot flow against pressure drop ratio instead of just pressure drop.



P1 (PSIA)	100	200	1000
Δ P Choked	70	140	700
x_T	0.7	0.7	0.7.

$$x_T = \Delta p\ Choked / p_1$$

Figure 4. The rated Terminal Pressure Drop Ratop, x_T, of an 80% open globe valve.

Let's see what would happen if we were to run the three flow tests listed in Figure 4, using a typical GLOBE valve, with the inlet pressure, p_1, at first 100 psia, then at 200 psia, and finally at 1,000 psia.

With p_1 at 100 psia and starting with delta p at zero and gradually increasing it we would find that flow would choke when the pressure drop was 70 psi.

Repeating with p_1 = 200 psia, flow would choke at a pressure drop of 140 psi.

Finally, repeating the test with p_1 = 1000 psia, flow would choke at a pressure drop of 700 psi.

Now, if we calculate the value of xT for each of the tests (since x is delta p divided by p_1, x_T, the choked value of x, is delta p Choked / p1) we see something very interesting. x_T turns out to be 0.7 in each case.

The point here is that for a particular style of control valve at a particular degree of valve travel (in this case an 80% open globe valve) the pressure drop ratio at which flow becomes choked is a constant. Knowing that the terminal pressure drop ratio for this particular model globe valve is 0.7 we can now predict that if the inlet pressure was 300 psi, flow would choke at 210 psi pressure drop (300 X 0.7 = 210).

In order to properly size control valves for gas service, it is necessary to know at what pressure drop flow will choke. Different valve styles have different values of xT , and for each valve type, xT also varies with valve opening.

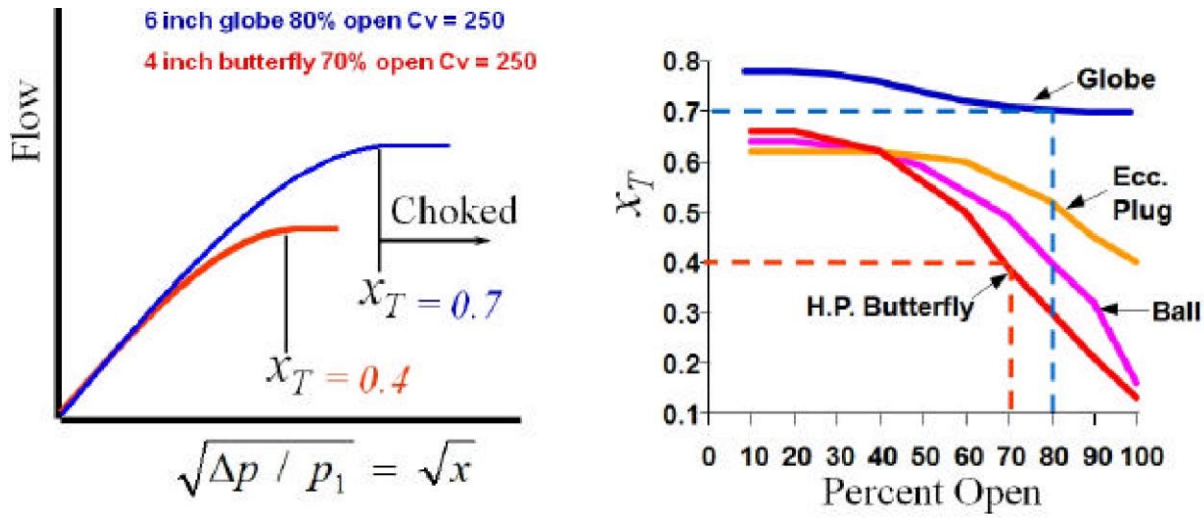


Figure 5. Typical values of xT and how they affect the flow through control valves.

Valve manufacturers test their valves for xT and then publish the results, making it possible to predict the point at which flow will choke and therefore properly size control valves.

The blue line on the left hand graph represents the flow through a globe control valve, where xT is 0.7. (That is, flow will choke when the pressure drop is 70% of p1. As an example, this upper line could represent a 6 inch globe valve at 80% open which would have a Cv of about 250. A 4 inch high performance butterfly valve operating at around 70% open would also have a Cv of about 250. Although both valves have the same flow capacity (CV), the graph of flow through the butterfly valve (red line on the left hand graph) looks quite different than the graph of flow through the globe valve. That is because it has an xT of 0.4, meaning that flow chokes when the pressure drop is 40% of p1. At low pressure drop ratios, the flow is the same through both valves, but as the pressure drop ratio increases, the flow in the butterfly valve starts aiming toward choked flow before the flow in the globe valve does. Understanding this will help you understand why a sizing calculation may show that, with all the flow conditions the same, one style of valve will need a larger Cv than is required of a different style of valve.

Before we conclude by showing how the ISA/IEC control valve sizing equations accurately predict both the shape of the gas flow vs. pressure drop ratio curve and the point at which flow chokes, we need to introduce one more concept, that of the "Ratio of Specific Heats Factor," F? The valve manufacturer's published values of xT are based on choked flow tests using air as the test medium. Many gasses other than air have sonic velocities that differ from that of air, so to compensate for the sonic velocity of those gasses, the published value of xT is multiplied by the Ratio of Specific Heats Factor, F? (F sub gamma), of the gas for which the valve is being sized. The Ratio of Specific Heats Factor is calculated by dividing the Ratio of Specific Heats, ?, by the Ratio of Specific Heats of air, which is 1.4.

F?=? / 1.4

F? of air reduces to 1.0.

Most tables of gas properties include values of the Ratio of Specific Heats.

Note that older versions of the ISA control valve sizing Standard, and some manufacturer's literature, use the symbol "k" for the Ratio of Specific Heats.

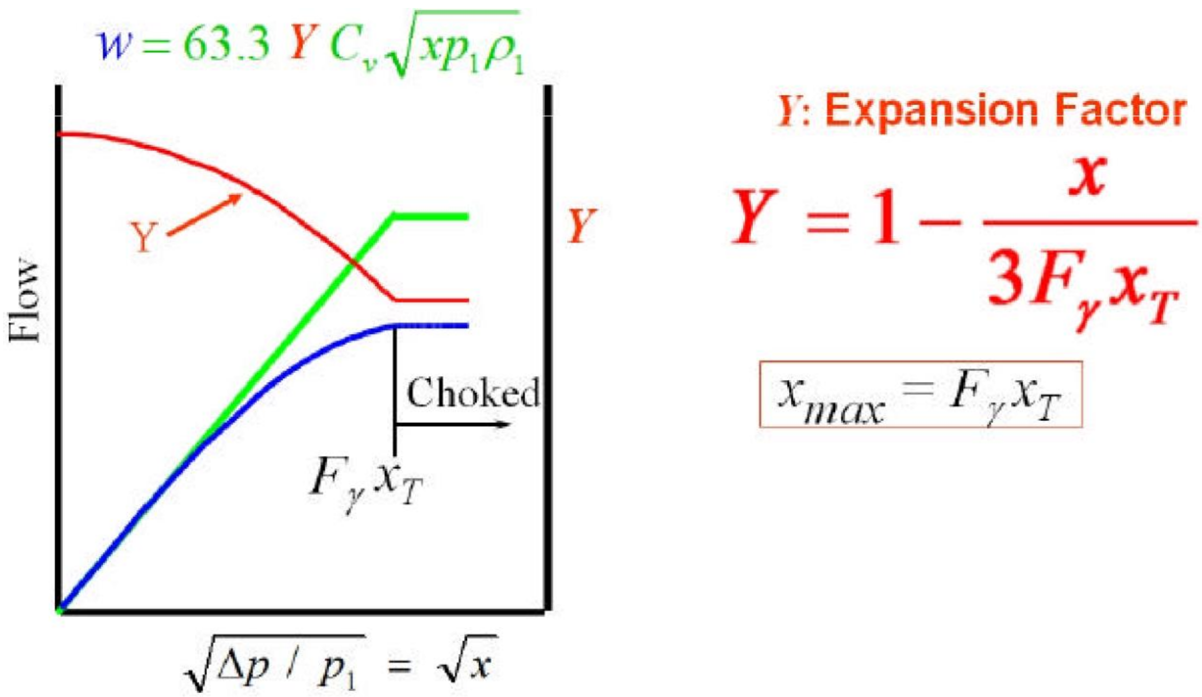


Figure 6. The ISA/IEC gas flow equation including the "Expansion Factor," Y, which compensates for density change at the vena contracta and vena contracta enlargement.

The equation at the top left of Figure 6 is the ISA/IEC gas equation with mass flow in pounds per hour as the dependent variable.

Because it is not easy to determine what the density of the gas is at the vena contracta (which varies with valve style, valve opening and flow rate), the ISA/IEC control valve gas equation uses the (easy to determine) upstream density (rho sub 1). Recall that earlier, when we discussed why the actual flow graph has the shape it does, we said that the first part of the curved portion is the result of changes in density at the vena contracta, but the second portion (when flow at the vena contracta is sonic and density remains constant) is due to enlargement of the vena contracta as it backs up to the physical restriction. So, even if we could determine the density at the vena contracta, that wouldn't be enough to give the flow graph its correct shape. To accurately size control valves for gas service, and give the flow graph is correct shape, an *Expansion Factor (symbol Y)* is added to the equation we started with earlier, to correct the calculated flow (and the graph) for both changes in density at the vena contracta and for vena contracta enlargement. The equation shown here for Y is based on experimental observation of what actually happens.

Y is a function of x, the pressure drop ratio. When plotted on a square root scale, the graph of Y looks like the red line labeled "Y" in Figure 6.

Multiplying the straight green line (the flow graph if there was no density change and choking) by Y results in the actual flow graph (blue line). It is important to limit the value of x used in sizing or flow calculations to the choked value (F? xT), otherwise Y would decrease below 0.67 and the predicted flow, after reaching a maximum value at x = F? xT would then decrease, which we know is not the case.

Figure 7 summarizes the ISA/IEC gas sizing equations. The two most commonly used forms are shown.

$$C_V = \frac{W}{63.3Y\sqrt{xp_1\rho_1}}$$

$$C_V = \frac{Q}{1360p_1Y}\sqrt{\frac{G_gT_1Z}{x}}$$

where:

$$Y = 1 - \frac{x}{3F_\gamma x_T} \qquad F_\gamma = \gamma / 1.4$$

and

$$x(max) = F_\gamma x_T$$

Figure 7. Summary of the most common forms of the ISA/IEC control valve gas sizing equations.

The top equation is the one we have been using so far, but rearranged to solve for C_v instead of W. This form is appropriate for gasses and vapors (including steam) where flow is in mass flow units (pounds per hour) and where the upstream density is known. The second equation, which is simply the first equation, with appropriate unit conversions for flow in volumetric units (scfh) and with the density calculated from the specific gravity, absolute temperature, absolute pressure and compressibility factor.

For many years the ISA equations were published with flow as the dependent variable. (Which is the form we used in our discussion of gas flow, since it was our purpose to understand how the flow of gas behaves as it goes through a control valve.) Because the most common use of the ISA/IEC "Flow Equations for Sizing Control Valves," ANSI/ISA S75.01, is for sizing control valves (calculating the required Cv) the current version of the Standard presents the equations with Cv as the dependent variable as shown above.