SELECTION, SIZING, AND OPERATION OF CONTROL VALVES FOR GASES AND LIQUIDS

Class # 6110

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Introduction

Proper control valve sizing and selection in today's industrial world is essential to operating at a cost-effective and highly efficient level. A properly selected and utilized control valve will not only last longer than a control valve that is improperly sized, but will also provide quantifiable savings in the form of reduced maintenance costs, reduced process variability, and increased process availability. An undersized valve will not pass the required flow, while a valve that is oversized will be more costly and can cause instability throughout the entire control loop.

In order to properly size a control valve, one must know the process conditions that a given valve will see in service. Proper valve selection is not based on the size of the pipeline, but more importantly, the process conditions and a combination of theory and experimentation used to interpret these conditions.

Basic Control Valve Equation History

The earliest efforts in the development of valve sizing theory centered around the problem of sizing valves for liquid flow. Experimental modifications to early fluid flow theory have produced the following liquid flow equation:

$$Q_{gpm} = C_v \sqrt{(\Delta P / G)} \quad (1)$$

where:
- Q_{gpm} = Liquid Flow in GPM
- C_v = Valve Sizing Coefficient
- ΔP = Pressure Drop Across Valve
- G = Liquid Specific Gravity

This equation has become widely accepted for sizing valves on liquid service, and most valve manufacturers publish C_v data in all their catalogs.

In the years following the origination of this widely accepted equation, a derivation of the formula was developed to assist in predicting the flow of gas.

This paper will begin by explaining control valve selection from a liquid sizing perspective. That knowledge will then be utilized to assist in learning the basics of control valve sizing and selection with regard to a gas medium.

Valve Sizing for Liquids

The procedure by which valves are sized for normal, incompressible flow is straightforward. The simplest case of liquid flow application involves the following equation:

$$C_v = \frac{Q}{\sqrt{\frac{P1 - P2}{G}}} \quad (2)$$

where:
- C_v = Flow coefficient
- Q = Flow rate
- $P1$ = upstream pressure
- $P2$ = downstream pressure
- G = liquid specific gravity

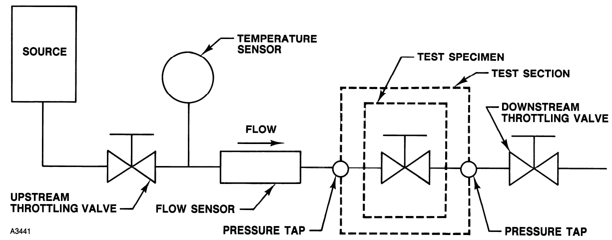

Figure 1. ISA Flow Test Piping Configuration

The flow coefficient is a measured value by which the measuring procedure is governed by the Instrument Society of America (ISA). The basic test system configuration is shown in Figure 1. Specifications, tolerances, and accuracies are given for all components such that coefficients can be calculated to an accuracy of $\pm 5\%$. Fresh water is circulated through the test valve at specified pressure differentials and inlet pressures. The temperature of the water is approximately 68° F. Flow rate, fluid temperature, inlet and differential pressures, valve travel, and barometric pressure are all measured and recorded. This information enables us to calculate the flow coefficient, as well as the pressure recovery coefficient, the piping correction factor, and the Reynolds number factor.

Once a valve has been selected and C_v is known, the flow rate for a given pressure drop, or the pressure drop for a given flow rate, can be predicted by substituting the appropriate quantities into equation 2 and solving for the appropriate term. As we know, many applications fall outside the scope of the basic valve sizing just considered. Rather than develop special flow equations for all of the possible deviations, it is possible (and preferred) to account for different behavior with the use of simple correction factors. These factors, when incorporated, change the form of Equation 2 to the following:

$$Q = \left(N_1 F_p F_r\right) C_v \sqrt{\frac{P1 - P2}{G}} \quad (3)$$

The additional factors will be explained in the following sections.

Choked Flow

As the previous equations illustrate, flow rate through a valve increases with the pressure differential. Simply stated, as the pressure drop across the valve gets larger, more flow is forced through the restriction due to the higher flow velocities. In reality, this relationship only holds true over a limited range. As the pressure drop across the valve is increased, it reaches a point where the increase in flow rate is less than expected. This continues until no additional flow can be passed through the valve regardless of the increase in pressure drop. This condition is known as choked flow. To understand more about what is occurring, it is necessary to return to some of the basics.

Recall that as a liquid passes through a restriction, the velocity increases to a maximum and the pressure decreases to a minimum. As the flow exits, velocity is restored to its previous value, while the pressure never completely recovers, thus creating a pressure differential across the valve. If the pressure differential is sufficiently large, the pressure may, at some point, decrease to less than the vapor pressure of the liquid. When this occurs, the liquid partially vaporizes and is no longer incompressible.

It is necessary to account for choked flow during the sizing process to insure against undersizing a valve. In other words, it is necessary to know the maximum flow rate that a valve can handle under a given set of conditions. In order to compensate for this problem, a method that combines the control valve pressure recovery characteristics with the thermodynamic properties of the fluid was developed to predict the maximum usable pressure differential. This will be the pressure differential at which choked flow occurs.

The pressure recovery coefficient is defined as follows:

$$K_m = \frac{P_1 - P_2}{P_1 - P_{vc}} \qquad (4)$$

where P_{vc} = pressure at the vena contracta

Under choked flow conditions, it is established that:

$$P_{vc} = r_c P_v \qquad (5)$$

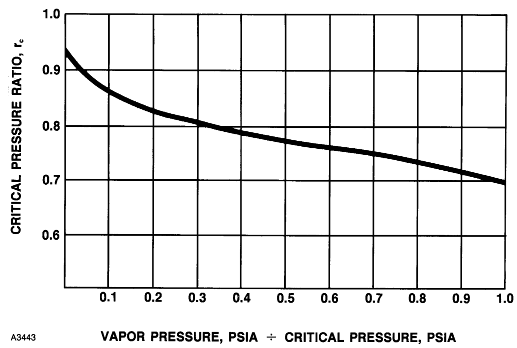

Figure 2. Generalized r_c Curve

The vapor pressure P_v, is determined at the inlet temperature, since the temperature of the liquid does not change appreciably between the inlet and the *vena contracta*. The term r_c is known as the critical pressure ratio and is another thermodynamic property of the fluid. Data for a variety of fluids can be generalized according to Figure 2 or the following equation without compromising overall accuracy:

$$r_c = F_f = .96 - .28\sqrt{\frac{P_{vc}}{P_c}} \qquad (6)$$

The value of K_m is determined individually by test for each valve style and accounts for the pressure recovery characteristics of the valve. By rearranging equation 4, the pressure differential at which the flow chokes is called the allowable pressure differential:

$$\left(P1 - P2\right)_{allowable} = K_m\left(P1 - r_c P_v\right) \qquad (7)$$

When this allowable pressure drop is used in equation 1, the choked flow rate for the valve will result. If the flow rate is less than the required service flow rate, the valve is undersized. A larger valve must be selected and the process of calculating the new coefficients begins.

<u>Cavitation</u>

Cavitation is a phenomenon that is closely related to choked flow. Simply stated, cavitation is the formation and collapse of cavities in the flow stream. If left unchecked, cavitation can cause noise, vibration, and severe material damage to control valves.

As discussed earlier, it is possible for the pressure across the *vena contracta* to drop to a point below the vapor pressure of the liquid, thus causing vapor to form within the valve. If the outlet pressure of the valve rises to a point greater than the vapor pressure of the liquid, we have a phase change from vapor back to liquid. As the gas "bubbles" revert back to the liquid phase, they implode, thus causing high velocity micro-jets to attack the material surfaces with which it comes in contact. This is known as cavitation.

In order to investigate the possibility of cavitation, two conditions must be considered:

1) The service pressure differential is approximately equal to the allowable pressure differential.

2) The outlet pressure is greater than the vapor pressure of the liquid.

If both of these conditions are met, the possibility of cavitation exists. Sizing a valve in this region is not recommended and special purpose trims should be considered. Refer to specific product literature for more information.

Flashing

Flashing shares some common traits with cavitation and choked flow. The process begins with the vaporization of the liquid as it passes through the *vena contracta*. This is very similar to the way cavitation begins. However, unlike cavitation, flashing occurs when the pressure of the liquid/vapor mixture never recovers to a point above the vapor pressure of the liquid.

Flashing is a concern for several reasons. Not only does it have the ability to choke the flow, but the liquid-vapor mixture is highly erosive and can cause material damage throughout the valve. If the downstream pressure is less than the vapor pressure, the standard sizing procedure should be augmented to include a check for choked flow and a valve suitable for flashing service should be considered.

Viscous Flow

To this point, we have only presented sizing procedures for a fully developed, turbulent flow. Turbulent and laminar flow are flow regimes that characterize the behavior of flow. In laminar flow, all fluid particles move parallel to one another in an orderly fashion and with no mixing of the fluid. Conversely, in turbulent flow, the velocity direction and magnitude is random. Significant fluid mixing occurs in turbulent flow. There is no distinct line between these two regimes, so a third was developed.

The physical quantities that govern this third flow regime are viscous and inertial forces, the ratio of what is known as the Reynolds number. When the viscous forces dominate, the Reynolds number is over 2000 and the flow is laminar. If the inertial forces dominate, the Reynolds number is over 3000 and the flow is turbulent. For equivalent flow rates, the pressure differential across a restriction will be different for each of these flow regimes.

To compensate for this effect, a correction factor was developed to be incorporated into valve sizing. The required C_v can be determined from the following equation:

$$C_{vrequired} = F_r C_{vrated} \quad (8)$$

The factor F_r is a function of the Reynolds number and can be determined from a nomograph not included in this paper.

To predict the flow rate or resulting pressure differential, the required flow coefficient is used in place of the rated flow coefficient in the appropriate equation.

When a valve is installed in the field, it is almost always going to be installed in a piping configuration different than that of the test configuration. Elbows, reducers, couplers, and other fittings may be used in the field. To correct this situation, two correction factors are used. These factors are F_p, which is used in incompressible flow situations, and $F_{lp,}$ which is used in the choked flow range. In order to determine these values, the loss coefficients of all devices must be known. In the absence of test data or knowledge of loss coefficients, loss coefficients may be estimated from information contained in resources outside the scope of this paper.

The factors F_p and F_{lp} would appear in the following flow equations:

For incompressible flow, $$Q = F_p C_v \sqrt{\frac{P1 - P2}{G}} \quad (9)$$

For choked flow, $$Q_{max} = F_l C_v \sqrt{\frac{P1 - F_f P_v}{G}} \quad (10)$$

Gas Sizing

In order to use the liquid flow equation for air, it was necessary to make two modifications.

1) Introduce a conversion factor to change flow units from gallons-per-minute to cubic-feet-per-hour.

2) Relate liquid specific gravity in terms of pressure, which is more meaningful for gas flow.

The result is the C_v equation revised for the flow of air at 60°F.

$$Q_{scfh} = 59.64 C_v P_1 \sqrt{\frac{\Delta P}{P_1}} \quad (11)$$

Generalizing this equation to handle any gas at any temperature requires only a simple modification factor based upon Charles' Law:

$$Q_{scfh} = 59.64 C_v P_1 \sqrt{\frac{\Delta P}{P_1}} \sqrt{\frac{520}{GT}} \quad (12)$$

The term 520 represents the product of the specific gravity and temperature of air at standard conditions. The specific gravity is one or unity. It is essential to be aware of the limitations that result from compressibility effects and critical flow with regard to equation 12.

An actual flow curve would show good agreement with the theoretical flow curve at low flow pressure drops. However, a significant deviation occurs at pressure drop ratios greater than approximately .02 because the equation was based upon the assumption of incompressible fluid. When the pressure drop ratio exceeds .02, the gas can no longer be considered an incompressible flow.

A much more serious limitation on this equation involves the choked flow condition, which was explained earlier. When critical flow is reached, equation 12 becomes useless for predicting the flow since the flow no longer increases with pressure drop.

In order to compensate for this problem, valve manufacturers modified the C_v equation even further in an attempt to predict the behavior of gases at both critical and subcritical flow conditions. This was economically beneficial to valve manufacturers as they could continue to test their valves on water only. The modified equation would then predict the gas flow. As it turned out, three equations were developed, all of which did a decent job predicting the gas flow through a standard globe valve at pressure drop ratios of less than 0.5.

$$Q = 1360 C_v \sqrt{\frac{(P1 - P2)P2}{GT}} \quad (13)$$

$$Q = 1364 C_v \sqrt{\frac{(P1 - P2)P1}{GT}} \qquad (14)$$

$$Q = 1360 C_v \sqrt{\frac{\Delta P}{GT}} \sqrt{\frac{(P1 + P2)}{2}} \qquad (15)$$

For globe valves, critical flow is reached at a pressure drop ratio of about 0.5. In the low-pressure drop region, the slope of the flow curve established by any of these equations is equal to that established by the original C_v equation. When the pressure drop ratio is equal to 0.5, each of the equations reduces to a form of a constant times $C_{v.}$ This indicates that once critical flow is reached, the flow will change only as a function of the inlet pressure. Low recovery valves work rather well in equations such as this. High recovery valves introduce new problems altogether.

Unlike the flow through low-recovery valves, the flow through high recovery valves is quite streamlined and efficient. If two valves have equal flow areas and are passing the same flow, the high recovery valve will exhibit much less pressure drop than the low recovery valve. High and low recovery refers to the valve's ability to convert velocity at the *vena contracta* back to pressure downstream of the valve. As we learned earlier, the low recovery valves generally exhibit critical flow at a pressure drop ratio of .5. The high recovery valves generally reach critical flow at pressure drop ratios of .15. Since the flow predicted by the critical flow equation depends directly upon C_v, and the high recovery valve exhibits critical flow at pressure drop ratios as low as .15, the modified C_v equations grossly over-predict the critical flow through the high recovery valve.

It should be realized that in order for both valves to have the same C_v , the high recovery valve would be much smaller than the low recovery valve. The geometry of the valve greatly influences liquid flow, whereas the critical flow of gas depends essentially on the flow area of the valve. Thus, a smaller high recovery valve will pass less critical gas flow, but its greater streamlines flow geometry allows it to pass as much liquid flow as the larger low recovery valve.

Because of the problems in using the C_v equation to predict gas flow in both high and low recovery valves, valves were finally tested using air as well as liquid. From these tests, a gas sizing coefficient C_g was defined in 1951 to relate critical flow to the absolute inlet pressure. Since C_g is experimentally determined for each style and size of valve, it can be used to accurately predict the critical flow for both high and low recovery valves. The following equation is the defining equation for C_g :

$$Q_{critical} = C_g P_1 \qquad (16)$$

The C_g value is determined by testing the valve with 60° F air under critical flow conditions. To make the equation applicable for any gas at any temperature, the same correction factor can be used that was applied previously to the to the original C_v equation:

$$Q_{critical} = C_g P_1 \sqrt{\frac{520}{GT}} \qquad (17)$$

Now, there were two equations for gas sizing. One was applied to low pressure drops, while the other was good for predicting critical flow.

In an attempt to put the pieces together, Fisher Controls International began development of the Universal Gas Sizing Equation.

Universal Gas Sizing Equation

In 1963, Fisher Controls International developed and introduced the Universal Gas Sizing Equation. This equation is universal in the sense that it accurately predicts the flow for either high or low recovery valves for any gas and under any service conditions. This equation introduces a new factor, C1. The following is the Universal Gas Sizing Equation:

$$Q_{scfh} = \sqrt{\frac{520}{GT}} C_g P_1 \sin\left[\left(\frac{59.64}{C1}\right)\sqrt{\frac{\Delta P}{P1}}\right] rad \quad (18)$$

C_1 is defined as the ratio of C_g to C_v. It provides an index that tells us something about the physical flow geometry of the valve. Its numerical value tells us whether the valve is high recovery, low recovery, or somewhere in between. Generally, C_1 ranges in value from about 16 to 37.

At first glance, the Universal Gas Sizing Equation may appear to be quite scary. However, taking a closer look at a few things may ease some of the pain.

First, consider the extreme where the valve pressure drop is quite small. This means that the angle of the sine function will also be quite small in radians. Under this condition, the equation reduces to the original C_v equation.

The other extreme of the Universal Gas Sizing Equation is the condition of choked flow. At the critical pressure drop ratio, the sine function becomes unity and the equation reduces to the critical flow equation.

Some people find it more convenient to deal with degrees rather than radians. This is not a problem as a simple conversion will allow for the formula to accept degrees rather than radians. The constant, 59.64 in the equation is simply changed to 3417.

The Universal Gas Sizing Equation, as we have seen, is already based upon the assumption of perfect gas laws. In cases where the perfect gas assumption is not acceptable, the following more general form of the equation is used:

$$Q_{lb/hr} = 1.06\sqrt{d_1 p_1} C_g \sin\left[\left(\frac{3417}{C_1}\right)\sqrt{\frac{\Delta P}{P1}}\right] \deg \quad (19)$$

where d_1 is the inlet gas density

Equation 19 is known as the density form of the Universal Sizing Equation. It is the most general form and can be used for perfect and non-perfect gas applications.

Conclusion

The proper selection and sizing of control valves for gas and liquid applications are essential to a profitable and cost-effective operation. Many factors must be considered when sizing and selecting a valve and any one of these factors could cause problems if ignored or misrepresented. However, there are technical information, sizing catalogs, nomographs, and software that make valve sizing a simple and accurate procedure.