FISHER® Fisher Controls

technical monograph 31

Fundamentals of Valve Sizing for Gases

Floyd D. Jury

Fundamentals of Valve Sizing for Gases

Introduction

Improper valve sizing can be both expensive and inconvenient. A valve that's too small will not pass the required flow, and the process will be starved. A valve that is oversize will not only be more expensive, but it can also lead to instability and other problems.

The days of selecting a valve based upon the size of the pipeline are gone forever. Selecting the correct valve size for a given application requires a knowledge of process conditions that the valve will actually see in service. The technique for using this information to size the valve is based upon a combination of theory and experimentation.

Early efforts in the development of valve sizing theory centered around the problem of sizing valves for liquid flow. Daniel Bernoulli was one of the early experimenters who applied the science of fluid flow theory to liquid flow. Subsequent experimental modifications to this theory have produced a useful liquid flow equation.

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

where:

Q_{gpm} = Liquid flow in gpm
C_v = Valve sizing coefficient
ΔP = Valve pressure drop
G = Liquid specific gravity

This equation rapidly became widely accepted for sizing valves on liquid service and most manufacturers of valves began publishing C_v data in their catalogs.

It was inevitable that the valves, which had worked so well on liquids, would sooner or later be used to control the flow of gases, such as air.

It was probably just as inevitable that the good results obtained from the C_v equation would strongly tempt its use to predict the flow of gas.

Modified C_v Equation

In order to use the liquid flow equation for air it was necessary to make two modifications. The first step was to introduce a conversion factor to change flow units from gallons-per-minute to cubic-feet-per-hour. The second step was to relate liquid specific gravity in terms of pressure, which would be more meaningful for gas flow. The result was the C_v equation revised for the flow of air at 60°F.

$$Q_{scfh} = 59.64C_vP_1\sqrt{\Delta P/P_1} \qquad (2)$$

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

$$Q_{scfh} = 59.64C_vP_1\sqrt{\Delta P/P_1}\sqrt{520/GT} \qquad (3)$$

The term 520 represents the product of the specific gravity and temperature of air at standard conditions. The specific gravity is one or unity. In absolute units, the standard temperature is 520°R which corresponds to 60°F. The G and T represent the specific gravity and absolute temperature of any gas.

The apparent simplicity of Equation (3) can obscure the serious problems that develop from indiscriminately using this simple conversion without being aware of its rather strict limitations that result from compressibility effects and critical flow.

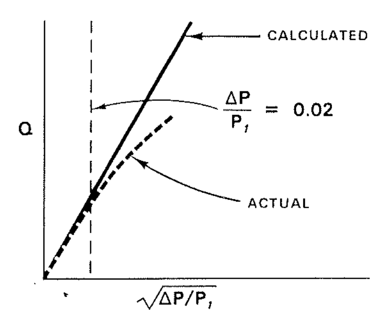


Figure I. Comparison of Equation (3) and an Actual Flow Curve

A plot of this equation shows a straight line relationship where the slope of the curve is a function of the valve sizing coefficient, C_v. The greater the C_v of the valve, the steeper the slope.

An actual flow curve would show good agreement with the theoretical curve at low pressure drops. However, a significant deviation occurs at pressure drop ratios greater than approximately 0.02 because the equation was based upon the assumption of incompressible flow. When the pressure drop ratio exceeds approximately 0.02 the gas can no longer be considered an incompressible fluid.

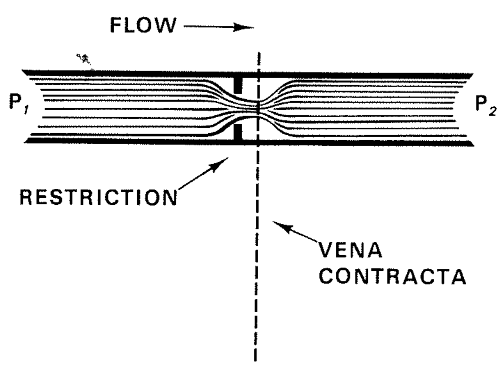


Figure 2. Vena Contracta Illustration

A much more serious limitation on this equation involves the phenomenon of critical flow. To help understand critical flow, a control valve, at any flow opening, can be represented by a simple restriction in the line. As the flow passes through the physical restriction, there is a necking down, or contraction, of the flow stream. The minimum cross-sectional area of the flow stream occurs just a short distance downstream of the physical restriction at a point called the *vena contracta*. In order to maintain a steady flow of fluid through the valve, it is obvious that the velocity must be greatest at the vena contracta where the cross-sectional area is the least.

As the ΔP across the valve increases, flow also increases, and the velocity at the vena contracta increases. At some value of ΔP, however, the gas reaches sonic velocity at the vena contracta. Since the gas can't normally travel any faster than this limiting velocity, a choked flow condition is reached known as critical flow.

When critical flow is reached, Equation (3) becomes absolutely worthless for predicting the flow since the flow no longer increases with pressure drop. So far, all we have is an equation that deviates significantly from the actual flow for pressure drop ratios greater than 0.02 and is totally inaccurate once critical flow is reached.

Various 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 approach had a very strong economic appeal to the manufacturers since it meant they would still only have to test their valves on water to obtain a C_v. The modified equation would then take care of predicting the gas flow. As it turned out, three equations were developed all of which did a fairly decent job of predicting gas flow through standard globe type valves at pressure drop ratios less than 0.5.

$$Q = 1360 C_v \sqrt{(P_1 - P_2) P_2 / GT} \quad (4)$$

$$Q = 1364 C_v \sqrt{(P_1 - P_2) P_1 / GT} \quad (5)$$

$$Q = 1360 C_v \sqrt{\Delta P / GT} \sqrt{(P_1 + P_2)/2} \quad (6)$$

For globe type valves, which were in most common use at the time, 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 plotted from any of these three equations is the same as that established by the original C_v equation (Eq. 3). If the pressure drop ratio is equal to 0.5, each of the modified equations will predict a flow which approximates the actual critical flow. At this point, all three of the modified equations reduce to the form of a constant times C_v and the absolute inlet pressure. This indicates that once the critical pressure ratio is reached, the flow through the valve will no longer be dependent upon the pressure drop across the valve. The flow will change only as a function of the inlet pressure.

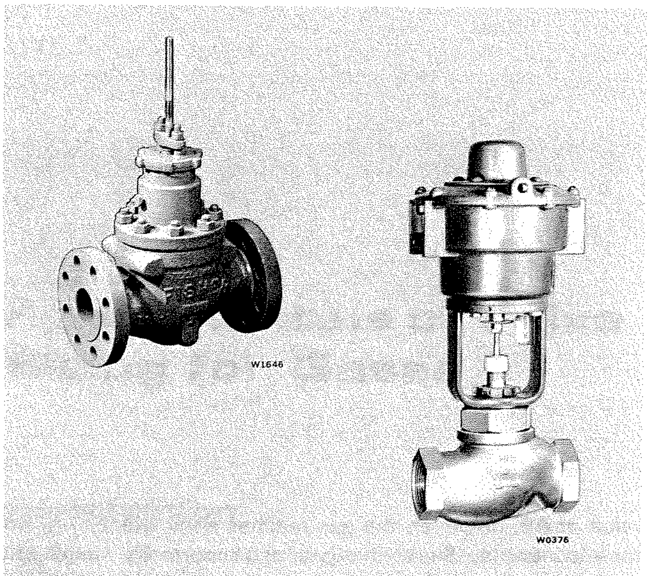


Figure 3. Typical Low Recovery Valves

For a while it looked as though the problem was solved. Low recovery type valves, such as those shown in Figure 3 worked reasonably well with these equations, but then along came various types of high recovery valves such as those shown in Figure 4.

High Recovery Valves

The flow through a high recovery valve is quite streamlined and efficient compared to that in a low recovery type valve. 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 refer to the valve's ability to convert velocity at the vena contracta back into pressure downstream of the valve.

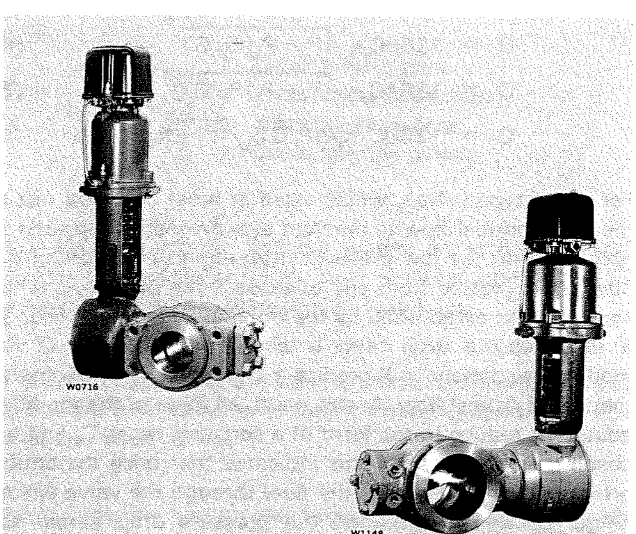


Figure 4. Typical High Recovery Valves

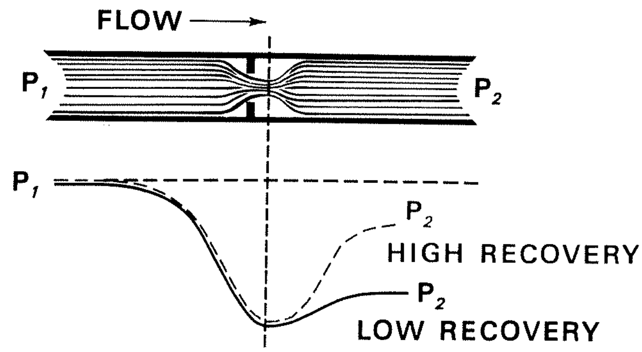


Figure 5. Comparison of Pressure Profiles for High and Low Recovery Valves

The pressure profiles for two valves having the same pressure drop and flow rate are shown in Figure 5. If critical flow is imminent, it is obvious that the pressure drop ratio for the high recovery valve will be much less than for the low recovery valve. While it's true that low recovery valves, such as the globe style valves, exhibit critical flow at a pressure drop ratio of 0.5, the more efficient high recovery valves can exhibit critical flow at pressure drop ratios as low as 0.15.

Now, let's consider the case of a high recovery valve and a low recovery valve that both have the same C_v. Since the initial slop of the flow curve is related to C_v, this portion of the curve will be the same for both valves.

Since the flow predicted by the critical flow equation depends directly upon C_v the equation will predict the same critical flow for both valves. We have already seen, however, that the high recovery valve will exhibit critical flow at pressure drop ratios as low as 0.15. In other words, the modified C_v equations grossly over-predict the critical flow through the high recovery valve.

This point is important enough to warrant repeating. A high recovery valve with the *same* C_v and tested under similar conditions as a low recovery valve will have much less critical gas flow capacity. Thus, if the modified C_v equations,

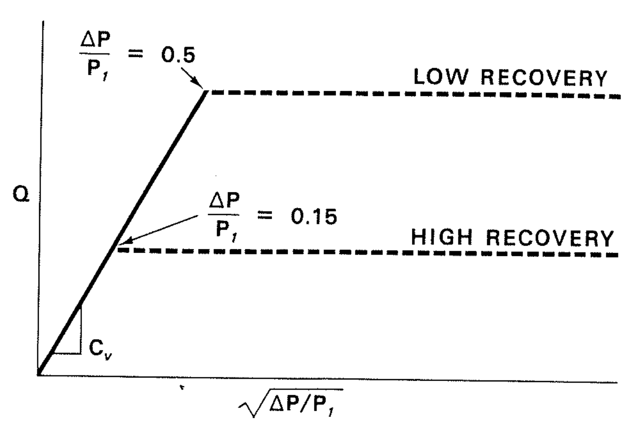


Figure 6. Critical Flow for High and Low Recovery Valves with Equal C_v

intended for *low* recovery valves, are used to size a high recovery valve, the critical flow capacity of the valve can be over-estimated by as much as 300 percent.

This may sound like a strange circumstance, but it should be realized that 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 only upon the flow area of the valve. Thus, a smaller high recovery valve will pass less critical gas flow, but its greater streamlined flow geometry allows it to pass as much liquid flow as the larger low recovery valve.

C_g, A Gas Sizing Coefficient

Because of the problems in using C_v to predict critical flow in both high and low recovery valves, Fisher Controls Company began testing all valves on air as well as water. 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. Equation (7) shows the defining equation for C_g.

$$Q_{critical} = C_g P_1 \quad (7)$$

C_g 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 original C_v equation.

$$Q_{critical} = C_g P_1 \sqrt{520/GT} \quad (8)$$

Fisher now found itself with two gas sizing equations. One equation (Eq. 3) applied only to quite low pressure drop ratios while the other (Eq. 8) was good only for predicting critical flow. What about the transition region?

In an attempt to put the pieces of this puzzle together, the Fisher research department conducted thousands of tests on every different style of valve available including both high and low recovery valves as well as some intermediate ones.

When the results of these tests were normalized with respect to critical flow and then plotted, a very useful fact became apparent. It was noted that all of the test points in the sloping portion of the flow curve could be quite closely approximated by the first quarter cycle of a standard sine curve.

Universal Gas Sizing Equation

Based on this test program, Fisher Controls Company developed, in 1963, a 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 incorporates both the basic C_v equation and the C_g critical flow equation into a single, dual-coefficient equation where the new factor, C_1, is introduced.

$$Q_{scfh} = \sqrt{520/GT}\; C_g P_1 \text{SIN}\left[(59.64/C_1)\sqrt{\Delta P/P_1}\right]_{Rad.} \quad (9)$$

where:

$$C_1 = C_g/C_v$$

C_1 is defined as the ratio of the gas sizing coefficient and the liquid sizing coefficient. It provides an index which tells us something about the physical flow geometry of the valve. In other words, its numerical value tells us whether the valve is high or low recovery or someplace in between. A simple illustration will help clarify the relationship between C_1 and the valve recovery characteristics.

Example:

High Recovery Valve	Low Recovery Valve
$C_g = 4680$	$C_g = 4680$
$C_v = 254$	$C_v = 135$
$C_1 = C_g/C_v$	$C_1 = C_g/C_v$
$= 4680/254$	$= 4680/135$
$= 18.4$	$= 34.7$

Assume two valves with identical flow areas. One is a high recovery valve, and one is low recovery. Since C_g is determined under critical flow conditions it is relatively independent of the recovery characteristics of the valve. The critical flow is primarily a function of the valve area only. Thus both valves will have the same C_g. Flow geometry, however, has a significant influence upon liquid flow. The greater efficiency and better streamlining of the high recovery valve will allow it to pass nearly twice as much liquid flow even with the same port area. Correspondingly the C_v will be nearly twice as large as the low recovery valve.

This example not only shows how C_1 can vary with valve recovery characterisitics, but it also illustrates the typical range of C_1 values. In general, C_1 values can range from about 16 to 37.

Note that C_v, which appears in the denominator, is the factor which varies primarily with the valve's recovery characteristics. This example illustrates the general principle that high recovery valves have low C_1 values, while low recovery valves have high C_1 values.

In order to accurately predict the gas flow for any style valve, two sizing coefficients are needed. C_g helps to predict the flow based upon the physical size or flow area, while C_1 accounts for differences in valve recovery characteristics. The Universal Gas Sizing Equation (Eq. 9) incorporates both of these coefficients. This equation may appear somewhat complex upon first encounter, but a look at the two extremes of the equation can clear up some of the mystery.

First, consider the extreme where the valve pressure drop ratio is quite small ($\Delta P/P_1 < 0.02$). This means that the angle of the sine function will also be quite small in radians. From basic trigonometry recall that, for small angles, the sine of the angle can be approximated by the angle itself in radians. Under this assumption of a small pressure drop ratio, the universal gas sizing equation simply reduces to the original C_v equation (Eq. 3). We already know that this equation fits the flow data in the incompressible flow region where the pressure drop ratio is less than 0.02.

The other extreme of the Universal Sizing Gas Equation is in the region of critical flow. Critical flow is first established at the point where the sine function reaches its maximum value at the end of the first quarter cycle. At this point the sine function is equal to one and the angle is equal to $\pi/2$ radians. The pressure drop ratio at this point is known as the *critical* pressure drop ratio.

At the critical pressure drop ratio, where the sine function becomes unity, the Universal Gas Sizing Equation simply reduces to the critical flow equation (Eq. 8). This Universal Gas Sizing Equation was originally developed to predict the critical flow for any valve style based upon the experimentally determined gas sizing coefficient, C_g.

In summary, the Universal Gas Sizing Equation takes the basic C_v equation at one extreme and the critical flow equation at the other extreme and blends the two together with a sinusoidal function that fits the experimental data. All of this in one universal equation!

Some individuals find it more convenient to deal with sine angles in degrees rather than in radians. This is easily accommodated by a simple conversion constant. The new constant in the angle becomes 3417 rather than 59.64. Now, the sine angle will be 90 degrees at the critical pressure drop ratio rather than $\pi/2$ radians.

$$Q_{scfh} = \sqrt{520/GT}\, C_g P_1 \mathrm{SIN}\left[(3417/C_1)\sqrt{\Delta P/P_1}\right]_{Deg.} \qquad (10)$$

As the pressure drop across the valve increases, the sine angle increases from zero up to 90 degrees. If the angle is allowed to increase beyond 90 degrees, the equation would predict a decrease in flow. Since this is not a realistic situation, the angle must be restricted to 90 degrees maximum.

The mathematical development of the Universal Gas Sizing Equation shown in Equation (10) is based upon the use of the perfect gas laws. The expression $\sqrt{520/GT}$ is derived from the equation of state for a perfect gas. While it is true that no perfect gases, as such, exist in nature, there are a multitude of applications where the perfect gas assumption is a useful approximation.

For those special applications where the perfect gas assumption is not adequate, a more general form of the Universal Gas Sizing Equation has been developed.

$$Q_{lb/hr} = 1.06\sqrt{d_1 P_1}\, C_g \mathrm{SIN}\left[(3417/C_1)\sqrt{\Delta P/P_1}\right]_{Deg.} \qquad (11)$$

where:

$Q_{lb/hr}$ = Gas, Steam, or Vapor flow (lbs/hr.)

d_1 = Inlet gas density (lbs/ft^3)

Equation (11) is known as the density form of the Universal Gas Sizing Equation. It is the most general form and can be used for both perfect and non-perfect gas applications. Steam is the most common application where Equation (11) is used. The steam density can be easily found from published steam tables.

Because steam service applications are so common, a special form of the Universal Equation was developed. If the pressure stays below 1000 psig, Equation (12) can be used which simplifies the calculation.

$$Q_{lb/hr.} = \left[C_s P_1/(1+0.00065T_{sh})\right] \mathrm{SIN}\left[(3417/C_1)\sqrt{\Delta P/P_1}\right]_{Deg.} \quad (12)$$

where:

C_s = Steam sizing coefficient
T_{sh} = Degrees of superheat (°F)

Equation (11) is more general and can be used in all cases where Equation (12) is valid; however, Equation (11) requires a knowledge of the steam density (d_1). For steam below 1000 psig, a constant relationship exists between the gas sizing coefficient (C_g) and the steam sizing coefficient (C_s).

$$C_s = C_g/20 \quad (13)$$

Density changes that occur as the steam becomes superheated are compensated for by the superheat correction factor that appears in the denominator of Equation (12). Use of Equation (12) eliminates the need for steam tables to look up the density of superheated steam.

At pressures greater than 1000 psig, the steam begins to deviate significantly from the constant relationship defined in Equation (13) and the superheat correction is no longer valid. At greater pressures, Equation (11) must be used for accurate results.

Conclusion

The Universal Gas Sizing Equation can be used to determine the flow of gas through any style of valve. Absolute units of temperature and pressure must be used in this equation. When the critical pressure drop ratio causes the sine angle to be 90 degrees, the equation will predict the value of the critical flow. For service conditions that would result in an angle of greater than 90 degrees, the equation must be limited to 90 degrees in order to accurately determine the critical flow that exists.

The most common use of the Universal Gas Sizing Equation is to determine the proper valve size for a given set of service conditions. The first step is to calculate the required C_g by using the Universal Gas Sizing Equation. The second step is to select a valve from the catalog with a C_g which equals or exceeds the calculated value. Care should be exercised to make certain that the assumed C_1 value for the C_g calculation matches the C_1 for the final valve selection from the catalog.

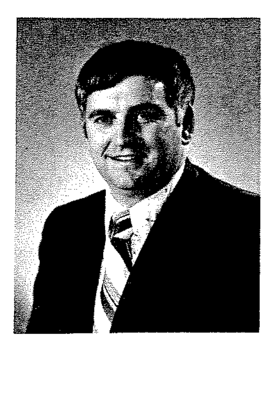
It should be apparent by now that accurate valve sizing for gases requires use of the dual coefficients C_g and C_1. A single coefficient is not sufficient to describe both the capacity and the recovery characteristics of the valve.

This paper has dealt exclusively with the problem of sizing valves for gas flow. Liquid flow requires a different set of considerations which are discussed in another paper.*

The proper selection and sizing of a control valve for gas service is a highly technical problem with many factors to be considered. Fisher Controls Company provides technical information, test data, sizing catalogs, nomographs, sizing sliderules, and even computer programs that remove the guesswork and make valve sizing a simple and accurate procedure.

Meet the Author . . .

Floyd Jury, Director of Education — MSME, N.C. State College, 1963; BSME, University of Alabama, 1961. Previous associations: Bell Telephone Laboratories, Guilford College, Thiokol Chemical Corp., WOI-TV Television Studios



*TM-30, "Fundamentals of Valve Sizing for Liquids", Floyd D. Jury, Fisher Controls Company, 1974.