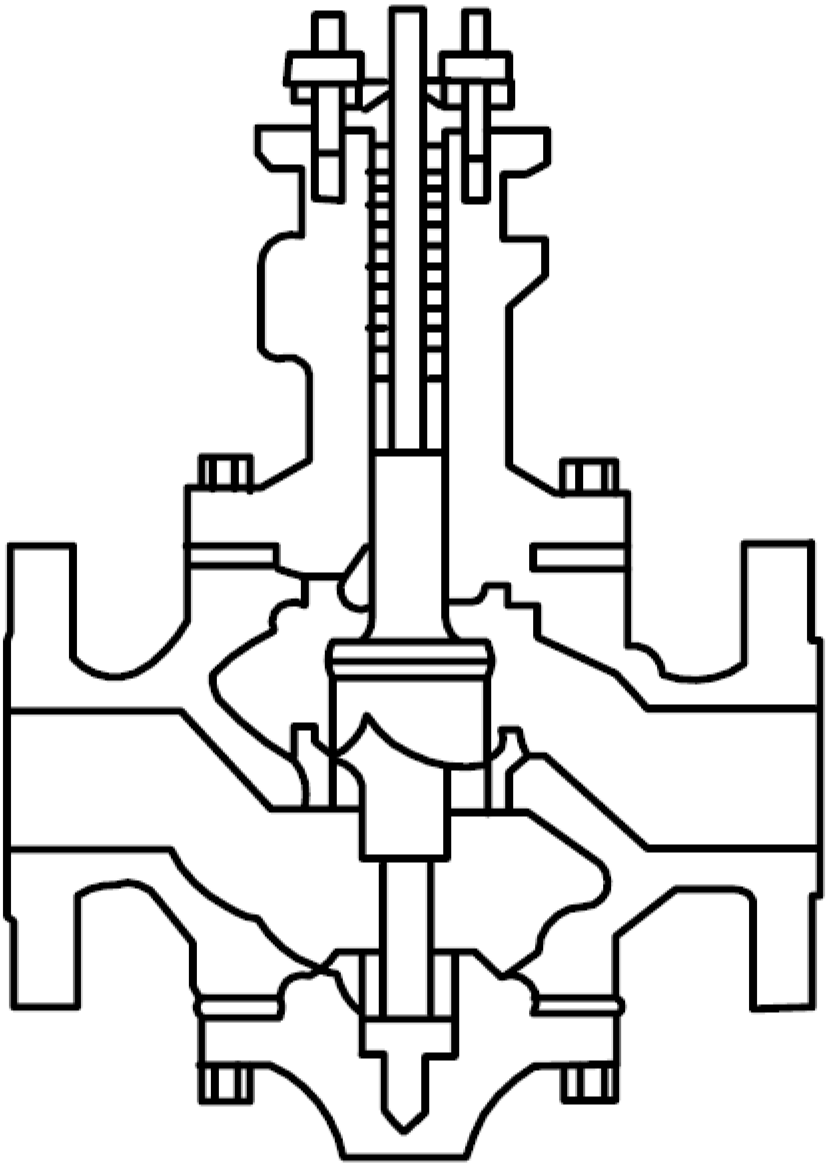
CONTROL VALVES

Control Valves - Theoretical Basis and Process Sizing



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1. Introduction

This document aims to be an introductory guide to control valve sizing, viewed through the eyes of a process engineer. It condenses the knowledge and experiences gained throughout my professional career. I trust that this resource can serve as a valuable support for those navigating the complex world of control valve sizing, offering a practical and targeted approach to the specific challenges that characterize this field.

Before moving on to the actual sizing phase (Chapter 4), it is good to briefly recall some basic concepts that all chemical engineers have studied during their university education.

A control valve is a device used to regulate the flow of a fluid (such as liquids, gases, or vapors) through a hydraulic circuit. Its main function is to regulate the quantity of fluid passing through it to maintain the desired process variable, such as pressure, temperature, or flow, within predefined or desired limits. Control valves can be operated manually or, as in most cases, automatically, through appropriate control signals sent by the control system.

When fine adjustment of the fluid flow through the valve is required, the valve is properly called a control valve or 'modulating' valve. Conversely, when simpler control is needed, such as a simple open or complete shut-off action, the control valve is commonly referred to as an 'on-off' valve.

The control valve regulates the flow through it by increasing or decreasing the passage area of the fluid, acting on a specific internal element called the regulating element or plug. To do this, the valve is equipped with an actuator. This actuator can be pneumatic, hydraulic, or electrically operated and allows the movement of the regulating element. To ensure the correct opening position of the regulating element, it is typical to use a positioner. This element is responsible for correcting the signal from the control system to maintain the partial opening or closing of the valve at the correct value.

2. Basic definitions

Below are briefly presented some definitions, certainly already known to process engineers, but useful as a review and fundamental for a better understanding of the following paragraphs.

2.1. Valve Characteristics

The relationship that describes the variation in the fluid passage area in the valve, as a function of the position of its stem, is defined as the "characteristic" of the valve. In cases where the pressure drop across the control valve can be assumed constant under any condition, this relationship directly expresses the variation in flow as a function of the stem position; in this case, it is referred to as the “inherent” characteristic of the valve. The inherent characteristic over the entire valve opening range constitutes the series of values that a supplier reports in their catalog, and it is generated by assuming a constant pressure drop through the valve as the opening (valve travel) varies.

In real conditions, it is very difficult for the pressure drop through the valve to be considered constant at all times. The pressure drop will tend to vary due to effects both internal and external to the valve itself, such as the variation in head provided by a centrifugal pump as the fluid flow changes. Consequently, the relationship between the flow variation and the valve opening position depends, in real-world contexts, on the characteristics of the entire hydraulic circuit, of which the valve is just one component, and is defined as the installed characteristic of the valve.

Each type of valve has an intrinsic characteristic that distinguishes it. The most common types of characteristics are as follows:

- Equal percentage
- Linear
- Quick opening
- Parabolic

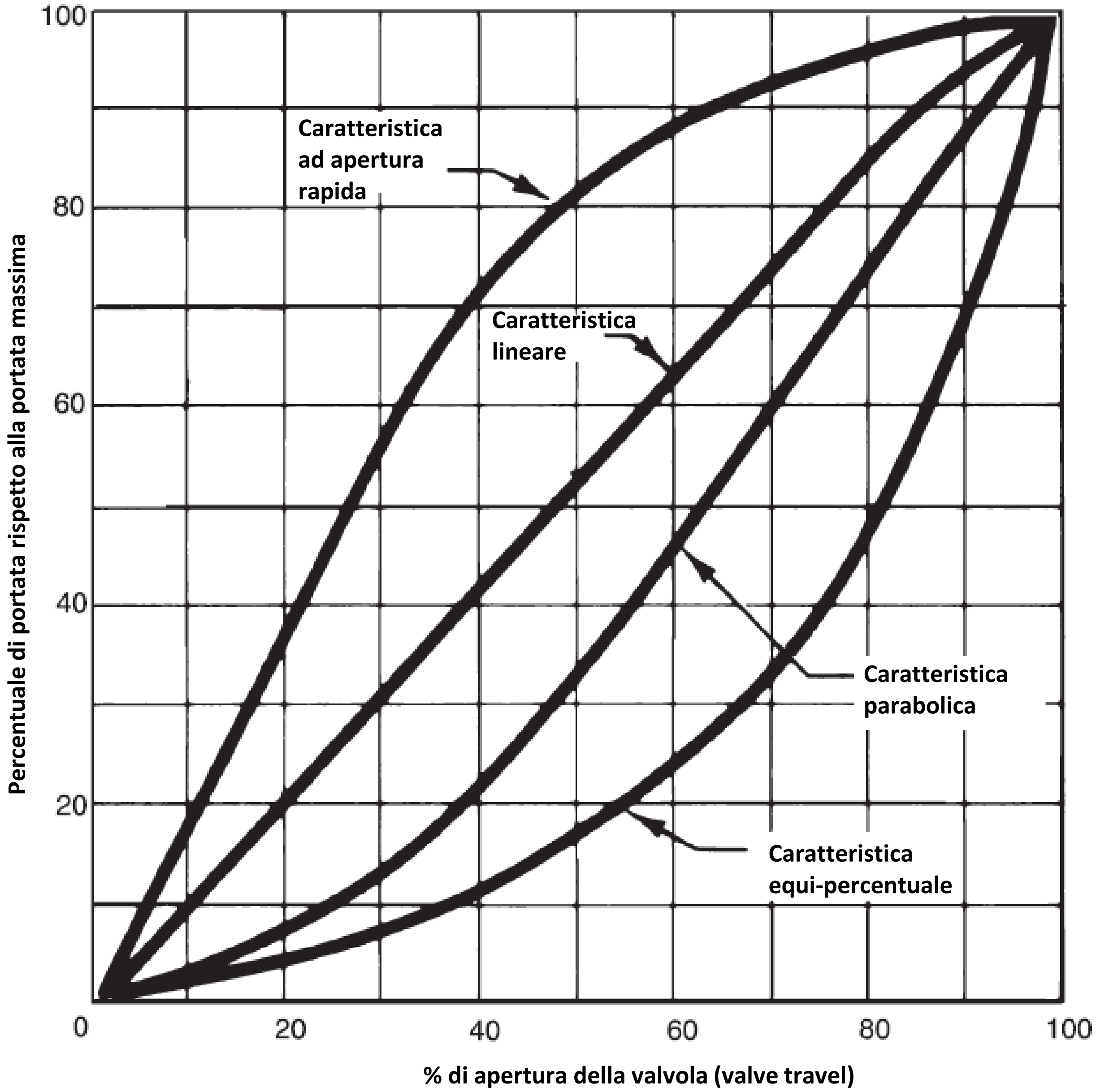


Figure 1: Main characteristics of a control valve

In valves with an equal percentage characteristic, equal increments, in percentage terms, of the fluid flow correspond to equal increments of the valve travel, referenced to the flow passing before the change. When this flow is low, indicating that the valve is nearly closed, the change in terms of flow will be modest. Conversely, with a high passing flow, the change in opening will cause a significant increase in flow.

Valves with an equal percentage characteristic are primarily used for flow control or when a significant portion of the pressure drop is absorbed by the hydraulic circuit itself. This situation occurs when the valve authority is very low. It is not uncommon to find equal percentage characteristic valves used for downstream flow control of a centrifugal pump. In fact, when the valve authority is low and the valve characteristic is equal percentage, the installed characteristic (valve + hydraulic circuit) tends to assume an almost linear trend in the valve opening range of 20-80%.

A valve with a linear characteristic is characterized by a linear relationship between the valve travel and the flow increment, as suggested by its name. This type of valve is often employed for level control, in specific circumstances such as temperature control achieved by varying the flow of a condensing heating fluid (typically steam). In cases where the pressure drop upstream and downstream of the valve remains nearly constant, a linear control is preferable. It is also used when most of the pressure drop in the circuit is absorbed by the valve itself (high valve authority)."

It is evident that in circuits composed of few fittings, bends, and limited pipe length, the installed characteristic of the valve tends to increasingly approach its intrinsic characteristic. This is immediately noticeable by observing the following figure, which illustrates, solely as an example, how the installed characteristic varies as the "weight" attributed to overall pressure losses due to piping decreases (i.e., as will be seen shortly, as the valve authority of the valve increases), whose intrinsic characteristic is of the equal percentage type.

Although this is an example, it is clear that as the percentage of pressure losses "absorbed" by the valve increases, the installed characteristic gets closer and closer to the inherent characteristic of the valve itself.

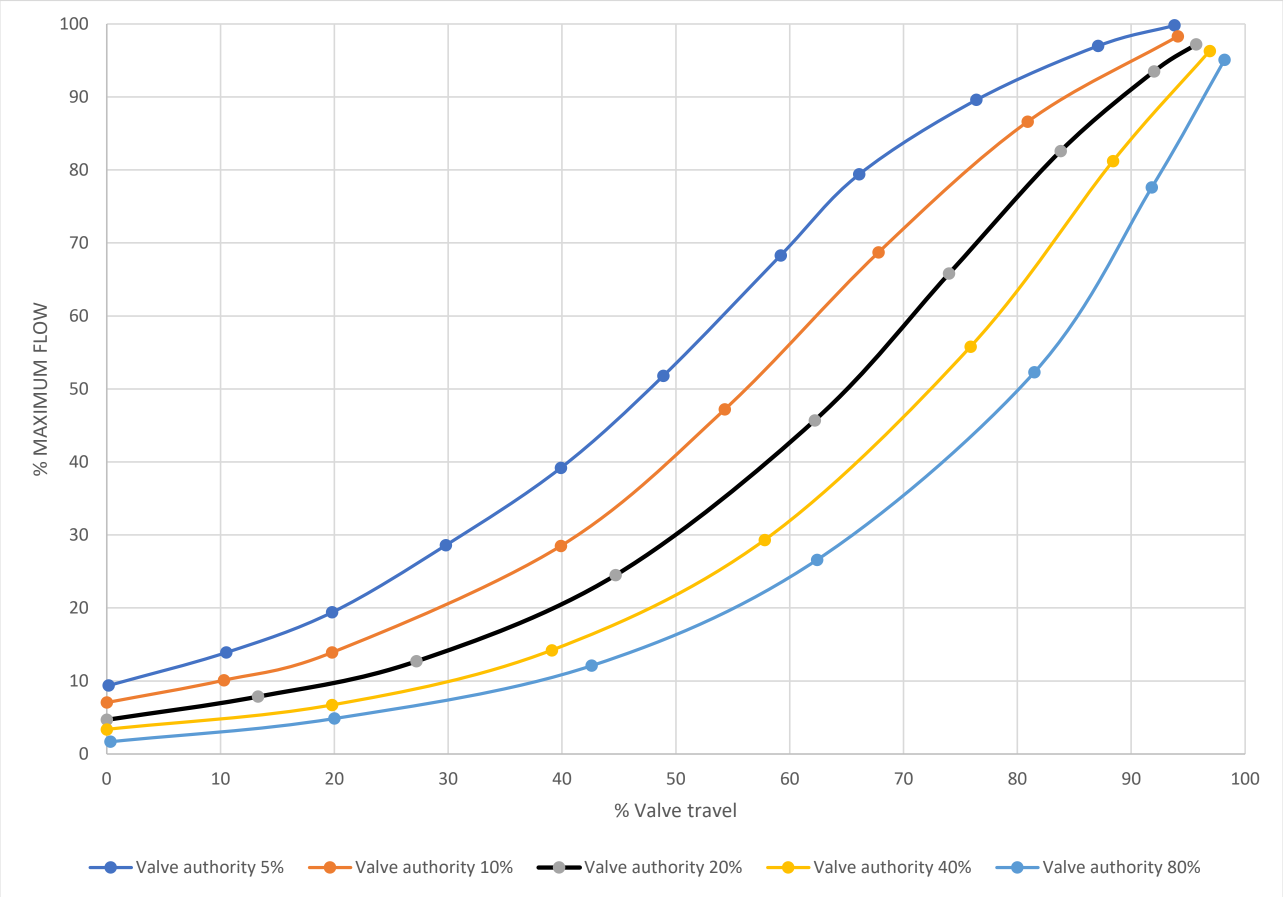


Figure 2: Flow variation as a function of valve opening, with changes in the valve authority of an equal percentage valve

A control valve with a quick opening characteristic provides a rapid increase in flow when the valve travel is low (valve nearly closed), with a growth that remains linear up to approximately 40% of the opening. Subsequent increases in travel progressively reduce the flow increment obtained, to the point that when the valve is almost fully open (valve travel exceeding 80%), the flow increment obtained is nearly negligible. Valves of this type are primarily used for on-off services.

Valves with a parabolic characteristic exhibit performance between those with an equal percentage characteristic and those with a linear characteristic, achieved through a suitably shaped plug.

2.2. The Flow Coefficient (Cv or Kv)

The flow coefficient of a valve is a parameter that expresses the flow capacity of a valve in terms of the fluid flow it can pass through per unit of time, given a specific pressure difference between the valve's inlet and outlet.

The flow coefficient is often referred to as Cv or Kv.

The **Cv** of a valve is defined as the water flow rate expressed in gallons per minute (gpm) at 60°F, passing through a valve with a pressure drop of 1 psi.

On the other hand, the **Kv** of a valve is defined as the water flow rate expressed in cubic meters per hour (m^3/h) at a temperature between 5 and 40°C, passing through a valve with a pressure drop of 1 bar.

In the following text, especially in the equations that reference it, Cv will be used, as it is more commonly employed. Nevertheless, it is straightforward to convert from Cv to Kv using the direct relationship Kv = 0.856 Cv.

<u>Calculating the flow coefficient under various operating conditions (minimum, normal, and maximum flow rates at different pressures) is one of the key aspects to consider in valve sizing.</u>

2.3. Control Valve Authority – Most Common Definition

"Valve authority" is defined as the correlation between the pressure losses that occur through the control valve and those due to the hydraulic circuit (dynamic and concentrated pressure losses). Typically, this correlation is expressed as the ratio of the pressure drop across the valve under design conditions to the total circuit pressure drop (including both dynamic and concentrated pressure losses), which also encompasses the pressure drop across the valve itself. The resulting value is always between 0 and 1 (0-100%). The higher this value, the better the control valve's ability to control, as the valve will have greater "authority" over the overall pressure drop in the circuit. Conversely, higher circuit pressure losses will be incurred.

It is important to highlight that the calculation of authority is always carried out by considering the circuit pressure losses without accounting for <u>elevation differences</u> (static head is not included in the calculation). The calculation relationship is, therefore, as follows:

$$Valve\ authority = \frac{\Delta Pvalve}{\Delta Pvalve + \Delta Pfriction, circuit}$$

Verifying the value of valve authority is crucial for sizing a control valve. While each engineering company may adopt specific internal criteria, in general, it is considered that the "valve authority" should be above 0.2 (20%) under design conditions, with typical values ranging between 20% and 40%. Values below 20% usually do not ensure effective control, as the valve cannot adequately compensate for large variations (its contribution is too small compared to the total circuit losses), while values that are too high can be uneconomical. Of course, there are exceptions to this rule.

Regarding the type of valve to use, as described earlier, linear characteristic valves are usually preferred when high valve authority is required (above 50%) or when, based on calculations, the circuit already exhibits a linear characteristic (typically consisting of short pipes with few bends or fittings). On the other hand, equal percentage valves tend to be preferred for low authority values. There is also a quick method for selection, as outlined shortly (in section 2.5).

2.4. Control Valve Authority – Alternative Definition

The definition of "valve authority" outlined in the previous section is not the only one in use. Some engineering companies prefer an alternative interpretation, although the results are still very similar. In this perspective, "valve authority" is defined as the ratio of pressure losses through the valve to the total circuit pressure drop, without including the specific contribution of pressure losses caused by the valve in the denominator. Others still prefer the first definition for general cases and adopt the second definition in specific contexts, such as sizing a control valve downstream of a centrifugal pump.

What was described in the previous section is still valid, but the numerical value obtained will be different, necessarily larger. The acceptable ranges are also different in this case.

2.5. Quick Method to Determine the Most Suitable Characteristic (VPDD)

In light of the considerations presented in the preceding sections, the following quick method can be formulated to provide an indication of the most suitable intrinsic characteristic for a particular process. It considers the ratio between the pressure losses due to the valve calculated at maximum flow conditions and the pressure losses also due to the valve at minimum flow conditions::

$$vpdd\ (valve\ pressure\ drop\ decay) = \frac{\Delta Pvalve, max\ flow}{\Delta Pvalve, min\ flow}$$

In the event that:

- If this ratio is between 0.6 and 1, it is preferable to opt for a valve with a linear characteristic.
- If the ratio falls between 0.4 and 0.6, it is advisable to choose a valve with a mixed characteristic (parabolic).
- I If the ratio is between 0.2 and 0.4, a valve with an equal percentage characteristic is preferable.

Finally, if the ratio is below 0.2, the valve may not be able to control effectively (the valve's contribution is excessively low compared to the circuit).

2.6. Rangeability

Depending on the type of plug used, the valve has a specific opening range known as "rangeability" or turndown ratio. This "rangeability" is defined as the ratio between the minimum opening value that allows satisfactory control and its maximum, corresponding to the ratio between the Cv values in the two cases. Typical limits of "rangeability" are reported in the following table, differentiated based on the type of valve used:

Valve typer	Max rangeability
Globe	8 (some suppliers also suggest 10)
Butterfly	6
Ball valve	15
Three vay	10

Angle	8
Diaphgram	8 (some suppliers also suggest 10)

It is important to highlight that the rangeability shown in the table is a theoretical value. In reality, this value is lower due to being limited by some factors:

- Control valves are typically specified to operate at 80-85% of the valve's maximum capacity (maximum allowed opening) because the valve needs some margin to regulate the flow effectively.
- The process sizing of the valve rarely aligns with the valve actually selected from the supplier. Typically, the maximum Cv of the selected valve is greater than the calculated one, reducing the valve's actual rangeability.
- Over time, the valve's rangeability decreases due to erosion and corrosion phenomena.

When fine control with a rangeability greater than 10 is required, it is advisable to consider the possibility of using two valves in parallel, sized for different flow rates. The smaller valve, capable of operating at low flows, complements the larger valve that operates at higher flows. This configuration allows for achieving a higher effective rangeability and ensures more precise flow control.

3. Main Types of Valves

Selecting the appropriate valve for each application involves numerous factors, from the valve's shape to the type of actuator, the generated noise, and even economic considerations. Below, we review the most commonly used types, listing their main advantages and disadvantages.

3.1. Globe valves

Globe valves are the most widely used type of valve in chemical plants when precise regulation is the primary goal. Their name originates from the fact that, originally, the regulating element was contained in a body shaped like a globe. Although the body's shape is often no longer that of a globe, the name has persisted.

The regulating element typically has the shape of a disk or a semi-disk. The valve stem moves the disk up or down depending on the desired degree of opening. This configuration, coupled with the specific shape of the seat on which the disk moves, allows globe valves to offer very precise control, especially when configured as double-seated valves. However, they are usually associated with higher pressure drop compared to other types of valves, and the flow coefficient (Cv) is lower than other types.

Globe valves have an inherent linear or equal percentage characteristic.

<u>Advantages</u>

- Very precise control, especially with double-seated valves.

<u>Disadvantages</u>

- High pressure losses
- Low flow coefficient
- Relatively expensive

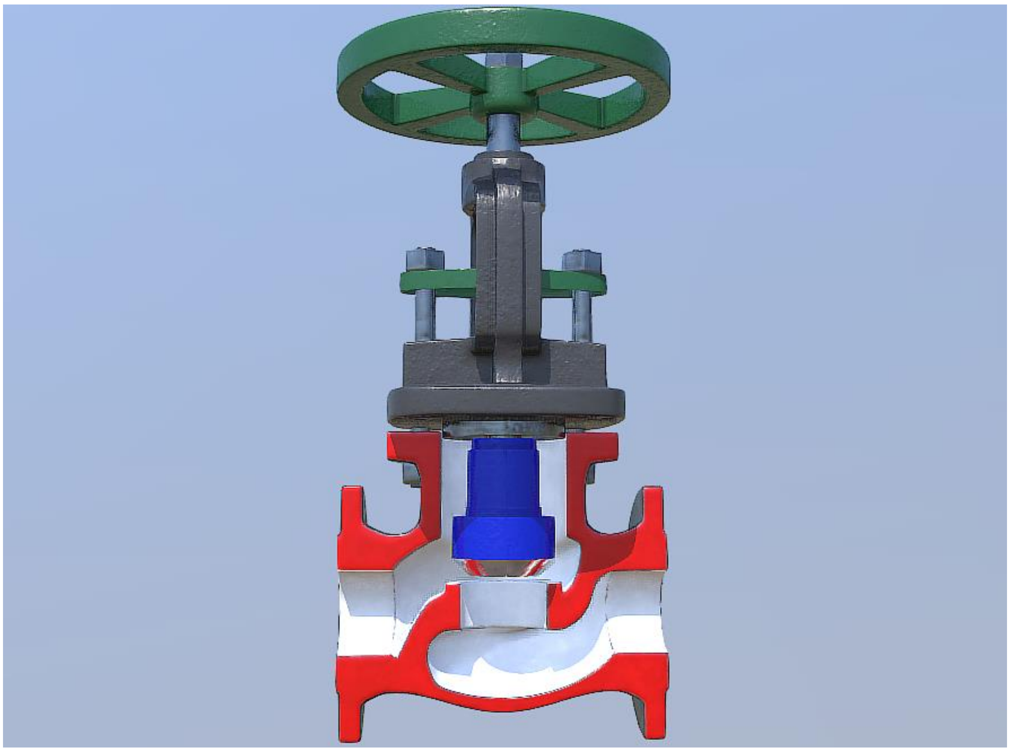


Figure 3: Example of a cutaway view of a globe valve

3.2. Ball valves

Ball valves are quick-opening valves and take their name from the fact that the regulating element is a perforated ball that is rotated into an open or closed position. This type of valve offers minimal resistance to flow when fully open, making it ideal for interception and on-off applications. However, due to their strongly non-linear intrinsic characteristic, ball valves are not recommended for use as modulating valves. Minimal adjustments in the opening angle have a significant impact on flow variation, making it challenging to achieve precise flow control.

<u>Advantages</u>

- Very cost-effective up to 3-4 inches in diameter
- At full opening, they ensure minimal pressure drop and high fluid flow capacity
- Optimal for ensuring tight shut-off

<u>Disadvantages</u>

- Not suitable for modulation
- Not suitable for dirty or solid-containing fluids
- When not fully open, they can lead to cavitation phenomena

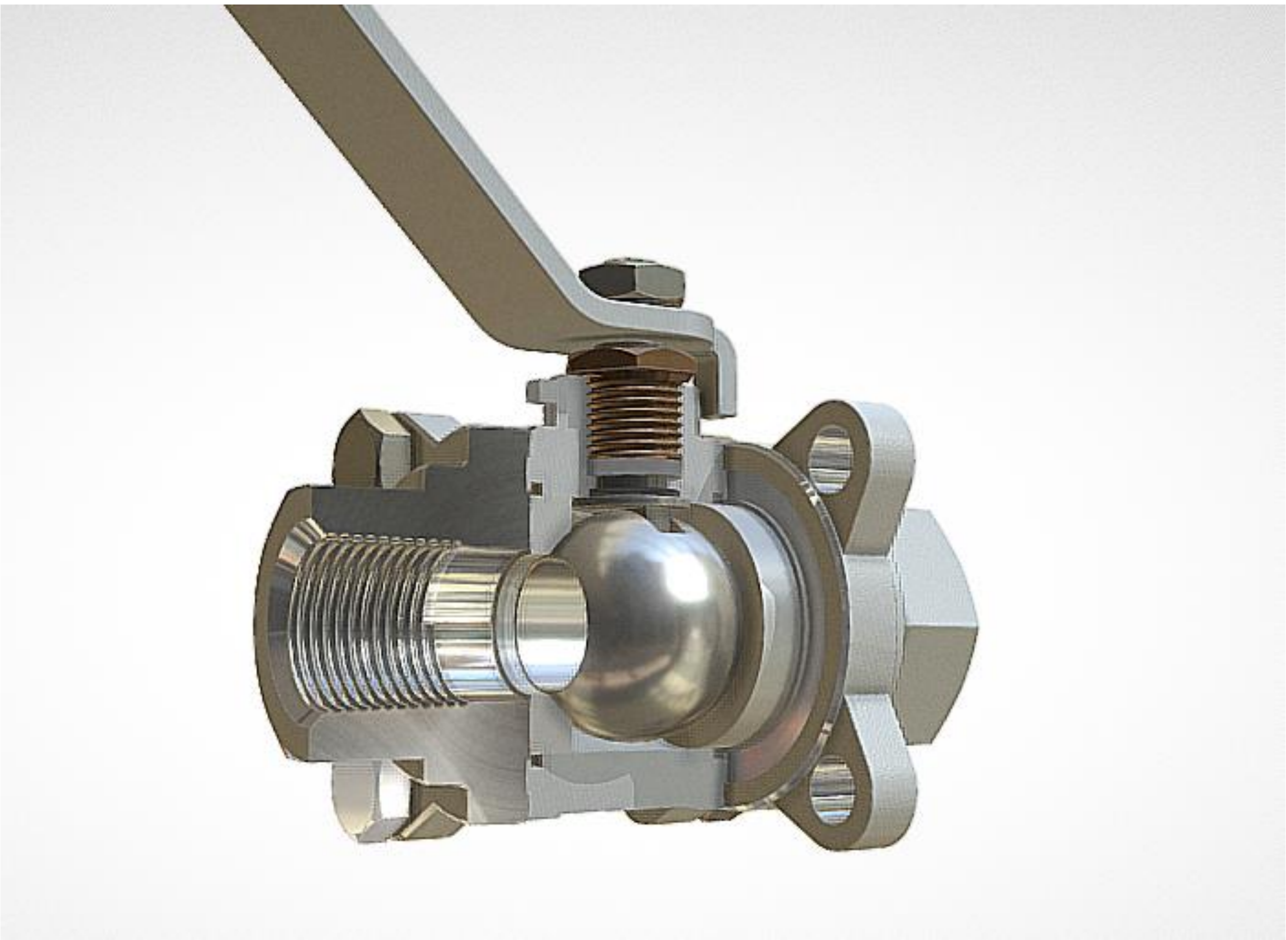


Figure 4: Example of a cutaway view of a ball valve

3.3. Butterfly valves

The butterfly valve is a valve in which the disc, serving as the obturator, rotates around an axis perpendicular to that of the pipe. Like ball valves, they are characterized by low fluid passage resistance. Butterfly valves are used for both interception and regulation, mainly when the dimensions of the pipeline make the economically convenient use of other types (diameters equal to or greater than 4-6 inches).

Butterfly valves are often used when dealing with clean fluids or systems that use tower water, air conditioning systems, and in large-diameter pipelines..

<u>Advantages</u>

- More cost-effective than other types beyond 4-6 inches in diameter
- Can be used for both interception and regulation
- Low pressure drop

<u>Disadvantages</u>

- Generally not suitable for providing a tight seal

Figure 5: Example of a butterfly valve

3.4. Gate valves

A gate valve is a valve whose obturator has the shape of a gate or knife. Due to the specific shape of the obturator, they do not allow fine regulation and are primarily used as on-off or interception valves, especially for infrequent uses, particularly in steam lines. They are also particularly suitable when dealing with abrasive fluids, those containing solids, or when a tight seal is required.

Advantages

- Possibility of a tight seal
- Low pressure drop

Disadvantages

- Not suitable for modulation

Figure 6: Example of a gate valve

3.5. Diaphgram valves

Diaphragm valves use a flexible membrane, known as the diaphragm, as plug. The diaphragm can be raised or lowered to regulate the fluid flow. These valves are employed when dealing with fluids containing solids or particles, or when a tight seal is required to prevent liquid leakage.

Although they are less commonly used in the Oil & Gas sector, they are widespread in chemical plants where working with slurries and highly corrosive or hazardous fluids, such as acids, is common.

Advantages

- Possibility of a tight seal
- Low pressure drop
- Can be used for modulation

Disadvantages

- Relatively expensive
- The diaphragm may be prone to breakage or wear
- Limited to lower pressures and temperatures compared to other types

3.6. Needle valves

The needle valve, commonly known as a "needle valve," is a type of valve designed for precise control of the flow of liquids or gases. The name comes from its characteristic needle-like shape, featuring a sharp cone or piston at the end of a stem. This type of valve is particularly suitable for applications that require accurate flow control, such as in laboratories, specific sectors of the chemical industry, medical applications, and gas analysis systems.

However, they are prone to clogging with fluids containing solid particles, have higher pressure losses than other types, and are limited to low flow rates.

The operation of a needle valve is relatively simple: by rotating the actuator or lifting the stem, the needle-like end is lifted from the fluid passage, opening the valve and allowing the fluid to flow through the cone or piston. Conversely, by rotating or lowering the actuator or stem, the cone or piston lowers, gradually closing the valve and reducing the fluid flow.

<u>Advantages</u>

- Precise flow control

<u>Disadvantages</u>

- Relatively expensive
- Not suitable for fluids containing solids
- Limited to low flow rates compared to other types of valves

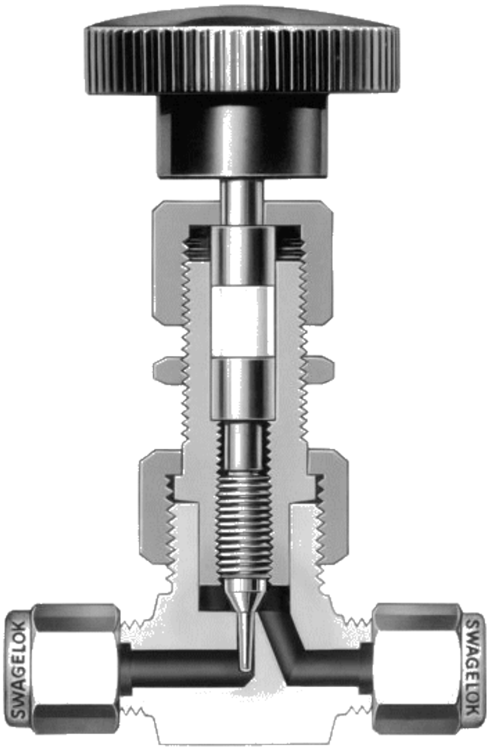


Figure 7: Cutaway view of a needle valve

3.7. Plug valves

Plug valves are a particular type of valve with a conical or cylindrical body inside that is rotated to regulate the flow. The plug in this type of valve has one or more cavities running along it, allowing the fluid to flow through when the valve is open. They are characterized by a moderate flow control capacity, but still higher than ball valves, and find application in various fields, particularly being widely used for fluids containing solids.

Advantages

- Suitable for fluids containing solids
- Suitable for aggressive or corrosive fluids

Disadvantages

- More expensive than other types of valves, such as ball valves
- Require actuators with greater force due to the higher friction developed

Figure 8: Cutavay view of a plug valve

3.8. Other Elements: Positioner

In the description provided so far, it has been implicitly assumed that a control valve always responds to a change with a corresponding correction. In reality, there are several factors that cause the valve not to behave so ideally. For example, the friction generated during the movement of the valve stem causes hysteresis phenomena, distorting the valve's control capacity by a measure ranging from 2 to 5%. This means that if we assume the typical control signal for the valve is pneumatic, with a value ranging from 3 to 15 psig, the error due to friction alone can reach 0.5 psi.

Another phenomenon that reduces the control capacity of the valve is represented by the forces generated by the fluid in motion inside the valve, which counteract the opening or closing action of the valve itself. Some types of valves, such as butterfly valves, are particularly affected by this.

To address these issues, positioners have been devised. The function of a positioner is theoretically quite simple: the device ensures that the valve responds proportionally to the received control signal, canceling out the effects of hysteresis or resistance to movement described earlier by sending the correct amount of air pressure to the actuator.

All modern control valves are equipped with positioners.

There are essentially three possible configurations:

- Pneumatic Positioner: A pneumatic signal (3-15 psig) is sent to the positioner, which translates it into the correct amount of air to be sent to the valve to achieve the desired opening.
- Analog I/P (current to pneumatic): The positioner functions like the pneumatic type but receives an analog electrical signal (4-20 mA) that is converted into pneumatic.
- Digital: The positioner behaves like the analog I/P type but receives a digital signal instead of an analog one. In this case, the signal travels through specific network protocols, the most common of which are the HART protocol and FieldBus, and the signal is managed by a dedicated microprocessor.

Figure 9: A ditigal positione on a control valve

4. Process sizing

Nearly all engineering companies have developed internal criteria for sizing a control valve based on the sector in which they operate. For a preliminary sizing, the following general steps can be followed:

1. Determination of process conditions
2. Cv calculation
3. Critical flow check
4. Valve characteristic
5. Selection of the valve from supplier catalog
6. Final verification of correct selection or iteration of the method

4.1. Determination of the process conditions

This step is of crucial importance as the process engineer must carefully consider the operating conditions. The calculation relationships for the flow coefficient (Cv) and, consequently, valve sizing vary depending on the state and type of fluid. It is essential to take into account various variables, such as the fluid phase (liquid, vapor), the presence of mixed phases or flashing liquids, and possible mixtures of specific fluids.

Starting the sizing of a valve on boiling liquid without considering, for example, the partial vaporization caused by valve pressure losses can lead to serious problems. Therefore, it is essential to have a clear understanding of fluid conditions before and after passing through the valve.

It is also necessary to check, during the calculations in the following steps, if cavitation problems can arise with critical flow conditions.

Among the process conditions to be determined is, of course, the calculation of circuit pressures, of which the control valve is a part. Therefore, it is necessary to determine the expected pressures both before and after the control valve and calculate pressure drops along the entire hydraulic circuit.

The calculation differs if there is a machine in the considered circuit, such as a pump or a compressor.

Describing in detail the calculation of hydraulic circuit pressure losses goes beyond the scope of this document. However, at the end of the chapter, I have added an example illustrating how to size a control valve, including an estimation of expected pressure losses in the circuit.

4.2. Calcolo del Cv nelle varie condizioni attese

After defining the process conditions and estimating the pressure drop of the circuit, the next step is to estimate the Cv of the valve. As mentioned earlier, there are various formulas for calculating the flow coefficient. Below are the most common calculation methods for various cases. These formulas are found in various manuals, such as the Control Valve Handbook.

1. Single-phase liquid

$$C_V = \frac{q}{N_1 F_p}\sqrt{\frac{G_f}{p_1 - p_2}} \quad \text{oppure} \quad C_V = \frac{W}{N_6 F_p \sqrt{\gamma_1 (p_1 - p_2)}}$$

Where:

q = volumetric flow rate (gpm or m³/h)

w = mass flow rate (lb/h or kg/h)

p_1 = absolute pressure at the valve inlet (psia or kPa)

p_2 = absolute pressure after the valve (psia or kPa)

Gf = specific gravity of the fluid relative to water (ratio of fluid density to water density at 60°F)

γ_1 = specific weight of the fluid at the valve inlet (lb/ft^3 or kg/m^3)

N_1 = 1 if using imperial units, 0.0865 if using metric units

N_6 = 63.3 if using imperial units, 2.73 if using metric units

Fp = piping geometry factor, for preliminary calculations or if there are no reductions, it can be assumed to be 1.

2. Single phase gas/vapor

The following relationships for Cv calculation are equivalent to each other:

$$C_V = \frac{w}{N_6 F_p Y \sqrt{X \gamma_1 P_1}}$$

$$C_V = \frac{q}{N_7 F_p P_1 Y} \sqrt{\frac{G_G T Z}{X}}$$

$$C_V = \frac{w}{N_8 F_p P_1 Y} \sqrt{\frac{T Z}{X M}}$$

$$C_V = \frac{q}{N_9 F_p P_1 Y} \sqrt{\frac{M T Z}{X}}$$

With $x = \frac{p_1 - p_2}{p_1}$

And $Y = 1 - \frac{x}{2.142 k X_C}$, gas expansion factor.

And where

q = volumetric flow rate (scfh or m^3/h)

w = mass flow rate (lb/h or kg/h)

p_1 = absolute pressure at the valve inlet (psia or kPa)

p_2 = absolute pressure after the valve (psia or kPa)

Gg = gas specific gravity (ratio of fluid density to that of air, both calculated under standard conditions, also equal to the ratio of the molecular weights of the gas and air)

γ_1 = specific weight of the fluid at the valve inlet (lb/ft^3 or kg/m^3)

N_6 = 63.3 if using imperial units, 2.73 if using metric units

N_7 = 1360 if using imperial units, 4.17 if using metric units

N_8 = 19.3 if using imperial units, 0.948 if using metric units

N_9 = 7320 if using imperial units, 22.5 if using metric units

Fp = piping geometry factor, for preliminary calculations or if there are no reductions, it can be assumed to be 1.

T = Absolute temperature of the gas, expressed in Rankine if using imperial units, Kelvin if using metric units

Z = compressibility factor, for preliminary calculations and at low pressure, it can be assumed to be 1.

M = molecular weight of the fluid

k = Cp/Cv, ratio of specific heats for the gas

Xc = Critical pressure drop factor, determined experimentally based on the type of valve used, its characteristic, and size.

In Table 1, provided at the end of this paragraph, I have included values of Xc that can be used for a preliminary estimation of sizing based on the expected valve size in inches.

It should be noted that this table represents experimental values averaged from various suppliers of different types of valves and, as such, is only valid for preliminary estimation. Once a preliminary design is obtained, it is always necessary to collaborate with the supplier for design confirmation.

	Globe				Ball (full bore)		Butterfly	
	Equal percentage		Linear					
Valve size (inch)	Typical Cv (100% opening)	Xc	Typical Cv (100% opening)	Xc	Typical Cv (100% opening)	Xc	Typical Cv (90° opening)	Xc
1	10	0.7	25	0.7	35	0.4	-	-
1.5	30	0.7	40	0.7	80	0.3	-	-
2	60	0.7	90	0.7	130	0.4	80	0.44
3	130	0.7	175	0.7	320	0.3	250	0.4
4	200	0.7	250	0.75	600	0.22	500	0.3
6	400	0.7	450	0.75	1100	0.2	1250	0.3
8	800	0.7	850	0.75	1800	0.2	2150	0.2
10	-	-	1200	0.75	3000	0.2	3600	0.2
12	-	-	1500	0.75	-	-	5400	0.2
16	-	-	-	-	-	-	8600	0.2

Table 1: Cv and Xc for various valve types

3. Flashing liquid

The following relationships for Cv calculation are equivalent to each other:

$$C_V = \frac{w}{N_6 F_L \sqrt{(P_1 - F_F P_V)\gamma}}$$

$$C_V = \frac{q}{N_1 F_L}\sqrt{\frac{G_F}{\sqrt{(P_1 - F_F P_V)}}}$$

Where:

q = volumetric flow rate (gpm or m³/h)

w = mass flow rate (lb/h or kg/h)

p_1 = absolute pressure at the valve inlet (psia or kPa)

G_F = liquid specific gravity (ratio of liquid density to water density, the latter calculated at 60°F)

γ_1 = specific weight of the fluid at the valve inlet (lb/ft³ or kg/m³)

F_F = Liquid critical pressure ratio, determinable from the graph in Figure 10 that follows

P_v = Vapor pressure of the liquid under the considered conditions (psia or kPa)

N_1 = 1 if using imperial units, 0.0865 if using metric units

N_6 = 63.3 if using imperial units, 2.73 if using metric units

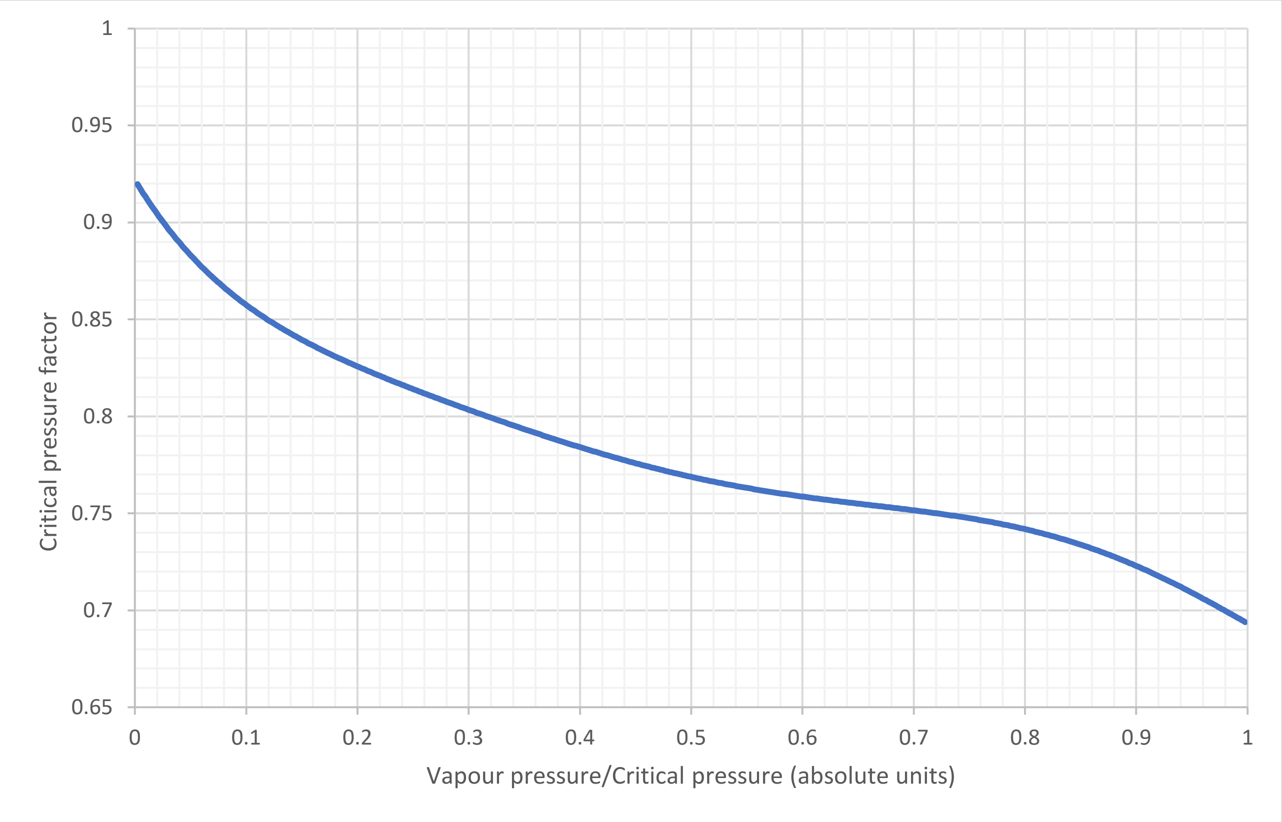


Figure 10: Determination of the Liquid Critical Pressure Factor.

To obtain the value of the critical pressure factor, referring to the graph in Figure 10, you need to divide the vapor pressure of the fluid calculated at the design temperature by the critical pressure of the fluid. By plotting the obtained value on the graph, you can derive the corresponding value of the critical pressure factor.

It is important to note that Cv calculation should be performed for all process conditions in which the valve is expected to operate, not just limited to calculating the case of operating or maximum flow. While very experienced engineers in a particular process may be able to size a control valve based solely on the operating or maximum flow, with the addition of a certain safety margin, there is still a risk. The valve may not be able to operate satisfactorily under other anticipated conditions.

Generally, Cv calculation is carried out under the following conditions:

1. Normal Operating Flow: This is the expected flow rate during the normal system operation, often determined through a material balance. Pressures upstream and downstream of the valve are specifically calculated for this condition.
2. Minimum Flow: Typically corresponds to 50-60% of the normal operating flow, and pressures upstream and downstream of the valve are recalculated considering the reduced flow. This case is important to ensure that the valve can handle even minimal flows.
3. Maximum Operating Flow (Design Flow): This is the maximum flow expected for the system, and circuit pressures are recalculated accordingly. Usually, to avoid excessive overdesign, this flow is assumed to be 10-15% higher than the normal operating flow.

In other words, at least the following three Cv values are determined: Cv at minimum flow, Cv at normal operating flow, and Cv at maximum operating flow. While there may be other specific cases, typically these three cases listed above are sufficient. In some engineering companies, it is not uncommon for the nominal flow to already coincide with the maximum.

Next, the **Cv max** is determined, also known as **Cv at full valve opening conditions or Cv at the system limit**. It is generally assumed that the Cv calculated at maximum flow is about 80-85% of Cv max, providing sufficient margin for effective control.

It is then necessary to verify whether the valve is still capable of operating correctly under minimum and normal operating flow conditions. While for normal operating flow conditions, it is sufficient to ensure that the calculated Cv falls around 60-70% of Cv max to avoid excessive over-sizing, the estimation of Cv in the case of minimum flow is used to determine the valve's rangeability, as described in section 2.4.

$$Control\ valve\ rangeability = \frac{C_V\ Max}{C_V \min flow}$$

If the calculated value falls within the acceptable rangeability for the chosen valve type, you can proceed to select the valve from the supplier's catalog. Otherwise, it is advisable to review the calculation or consider a different type of valve.

Minimum Pressure Drop

The minimum pressure drop across the valve (P1-P2), calculated under design conditions, is another aspect not to be overlooked. Typically, the following minimum values are assumed:

- 0.7 bar for liquids
- 0.2 bar for gases and vapors

4.2.1. Calculation of the piping geometry factor Fp

For absolutely preliminary calculations, the piping factor, which accounts for the effect of any reductions or bends immediately before or after the valve, can be initially assumed to be 1. However, if the calculations reveal that the valve will have a smaller size than the line (requiring appropriate reductions), or if there is already knowledge of bends or reductions in the line, it is necessary to iterate the calculation procedure considering the piping factor Fp in the determination of Cv.

The equation for calculating the coefficient Fp is as follows:

$$F_P = \left[1 + \frac{\sum K}{N_2}\left(\frac{Cvmax}{d^2}\right)^2\right]^{-1/2}$$

Where

N2 = 890 if using imperial units, 0.00214 if using metric units

Cvmax = The Cv calculated previously under maximum valve opening conditions

d = Valve diameter, expressed in inches if using imperial units or mm if using metric units

$\sum K$= Sum of velocity heads of all fittings immediately before and after the control valve. In most cases, the terms to consider are only the inlet and outlet reductions, calculable with the following expressions:

$K_1 = 0.5\left(1 - \frac{d^2}{D^2}\right)^2$, for the reduction before the valve, and

$K_2 = 1\left(1 - \frac{d^2}{D^2}\right)^2$, for the reduction after the valve.

In the above expressions, the term D represents the internal diameter of the line.

4.2.2. Critical flow check

For liquids, another aspect to check is that the control valve is not in critical flow conditions or "choked," meaning that the pressure losses do not limit the fluid flow. To determine the maximum acceptable pressure drop, the following expressions are used:

For valves that do not have fittings immediately before or after:

$$DP_{max} = {F_L}^2(P_1 - F_F P_V)$$

While for valves with fittings:

$$DP_{max} = \left(\frac{F_{LP}}{F_F}\right)^2 (P_1 - F_F P_V)$$

Where

P_1 = Upstream pressure of the control valve (absolute psia or kPa)

P_2 = Downstream pressure of the control valve (absolute psia or kPa)

P_v = Vapor pressure calculated at the fluid temperature at the valve inlet

F_F = Liquid critical pressure factor, discussed earlier. It can be determined from the graph in Figure 10 or calculated with the following relation: $F_F = 0.96 - 0.28\left(\frac{P_V}{P_C}\right)^{0.5}$

Where Pc is the critical pressure of the fluid.

Finally, Fl represents the recovery factor of the control valve. This parameter is experimental and is provided by the valve supplier. In its absence, it can be approximated with the values indicated in the following table:

Valve type	Flow direction	Fl
Globe, single seat	Flow to open	0.9
Globe, single seat	Flow to close	0.8
Globe, double seat	Flow to open	0.9
Globe, double seat	Flow to close	0.8
Butterfly	Any	0.67

4.3. Valve type selection

As seen, the "rangeability" depends on the intrinsic characteristic of the valve, as the selection is guided by the need to linearize control over as wide a range as possible in the valve's stroke, as described in Chapter 2 and its subsections.

As highlighted in the preceding paragraphs, generally for flow control applications where the control valve contributes a non-preponderant percentage of the total circuit pressure drop (low authority), a control valve with an equal percentage characteristic is preferable. This is because the variation in the circuit pressure drop tends to be nonlinear. While this situation reflects the majority of cases encountered, there may be exceptions for which other valve types could be more suitable.

For level control in a tank, a control valve with an intrinsic linear characteristic is generally preferred. This is because the control valve tends to absorb a significant portion of the circuit pressure drop, and the variation in the pressure drop is often linear.

Regarding pressure or temperature control, the situation is more complex as it heavily depends on the nature of the control, the type of fluid being used, and the process unit. For instance, varying the temperature of an outlet fluid from a heat exchanger by adjusting the flow, with one case involving hot water and another involving condensing steam, has different effects on the choice of valve type. This is due to various parameters coming into play, including the heat exchanger surface area and the heat transfer coefficient.

4.4. Selection of the valve from the supplier catalog

After completing this initial iteration of the calculation, the next step is to select, from the catalogs of qualified suppliers, the valve that most closely matches the calculated parameters in terms of type and Cv. It is essential to bear in mind that the Cv from the catalog must be greater than the calculated Cv.

Since there are no valves available in the market with precisely the same calculated Cv Max, it follows that the chosen valve will have parameters necessarily different from those assumed. Importantly, the selected valve will have a Cv greater than the one calculated by us.

4.5. Calculation check

After selecting the valve from the catalog, it is necessary to perform an additional verification by recalculating the valve's rangeability. The Cv provided by the valve supplier is used instead of the previously assumed Cv max. This ensures that the valve chosen from the catalog can operate correctly. This step is crucial because the catalog-selected valve is necessarily larger than the one estimated by the calculation. If the Cv of the supplier's valve is too large, the valve may have too wide a range for proper control, even if the selected type seemed appropriate based on the preliminary estimate.

From the supplier's catalog, all valve parameters that were initially estimated, such as Xc (critical pressure drop factor), Fp (piping geometry factor), are also determined. These values are then substituted into the preliminary calculations. If there is a significant difference between the two sets of values, the process is iterated until convergence, possibly selecting a new valve from the catalog if a different size valve appears more suitable during the iterations.

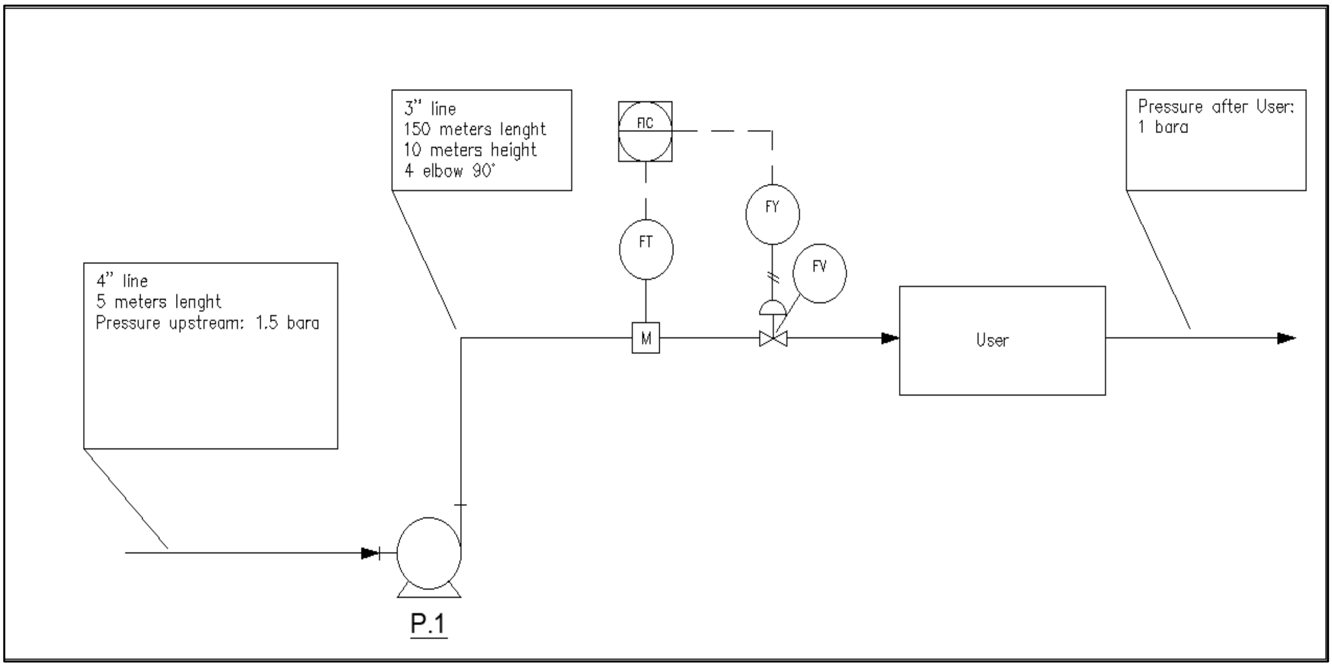
5. Example

Si riporta di seguito un esempio di calcolo, che illustra una situazione tipica: dimensionamento di una valvola di controllo di portata a valle di una pompa centrifuga.

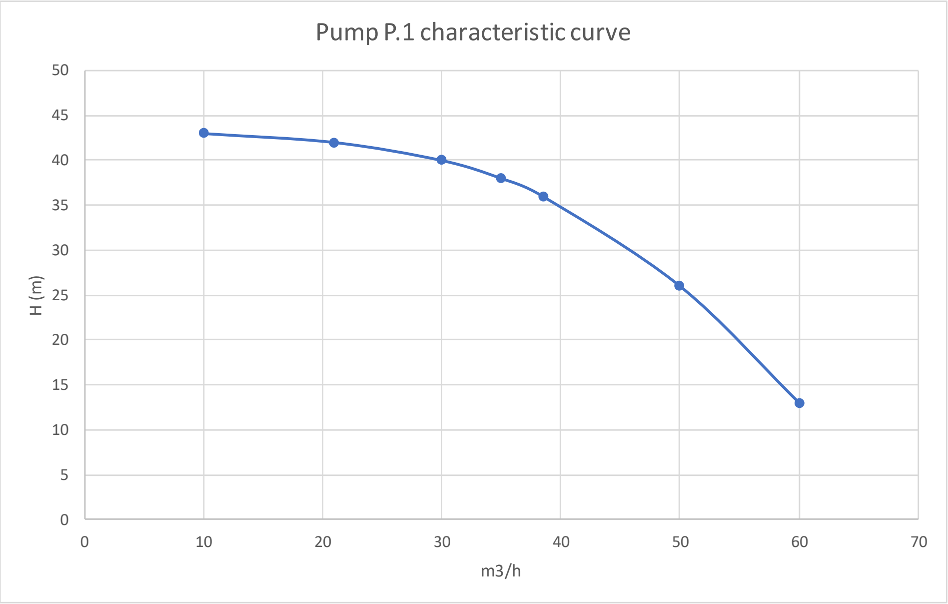
5.1. Example Calculation: Non-boiling Liquid

In the following figure, the circuit illustrated consists of a centrifugal pump, a flow meter, a control valve regulated by the flow meter, and downstream equipment whose pressure drop varies based on the fluid flow (one can imagine it to be, for example, a heat exchanger). The goal is to maintain a constant flow rate of 35 m3/h at the downstream equipment. The centrifugal pump pumps water at 30°C from a tank (not shown here) with a constant liquid level. The downstream equipment is located 10 meters above the pump's suction level. After the equipment, the liquid flows directly into an empty atmospheric tank, not shown here. Our circuit terminates immediately after the downstream equipment.

For simplicity, I have not drawn block valves, check valves, reductions, recycle lines, or other elements that impact the determination of the circuit's concentrated pressure losses. However, for the purpose of this example, we can consider them negligible. The flow meter's pressure losses are also assumed to be fixed at 0.05 bar, and the water density is taken as 1000 kg/m3. The diameters of the lines shown in the drawing, as an additional approximation, are internal.

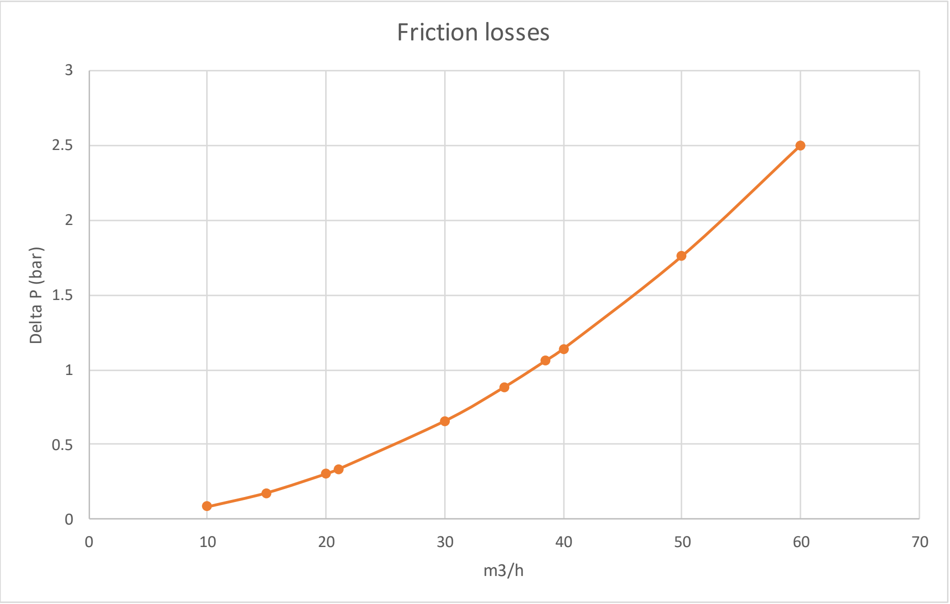


As for the centrifugal pump, let's assume for the purpose of this example that it has the following performance curve:



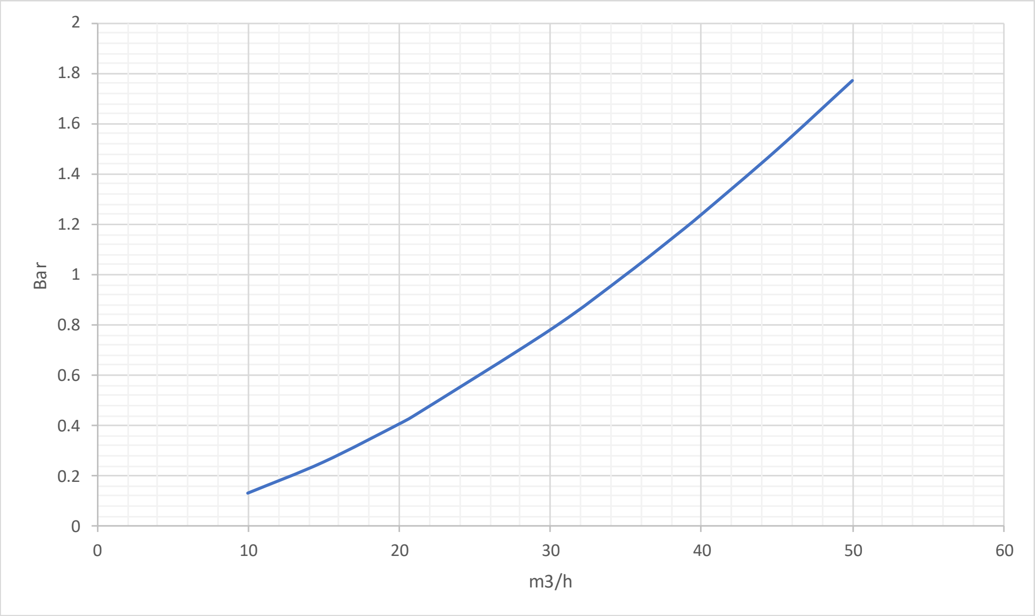
Q m3/h	H m
10	43
21	42
30	40
35	38
38.5	36
50	26
60	13

Regarding the pressure losses due to the hydraulic circuit (excluding the concentrated loss due to the flow meter), they have already been calculated using the Darcy-Weisbach formula based on the flow variation and are presented in the following graph:



Q m3/h	DeltaP bar
10	0.0835
15	0.177
20	0.304
21	0.334
30	0.657
35	0.883
38.5	1.06
40	1.14
50	1.76
60	2.5

Finally, for the downstream equipment, it is assumed that the pressure drop varies nonlinearly with the flow rate but less prominently than the pressure drop in the piping:



Q m3/h	DeltaP bar
10	0.135
21	0.41
35	1
38.5	1.165
50	1.77

We want to size the control valve under normal operating conditions, under the expected maximum conditions (our design flow rate, set to be 10% higher than the normal operating flow rate), and under the minimum conditions with a flow rate of 21 m^3/h (60% of the normal operating flow rate).

Given the process conditions (temperature, pressures involved, fluid conditions) stated in the example text, dealing with a non-boiling single-phase liquid, the relationships to be used for calculating Cv are those indicated in point 1 of paragraph 4.2, presented here for simplicity (refer to paragraph 4.2 for the meaning of the terms):

$$C_V = \frac{q}{N_1 F_p}\sqrt{\frac{G_f}{p_1 - p_2}} \quad \text{or} \quad C_V = \frac{W}{N_6 F_p \sqrt{\gamma_1 (p_1 - p_2)}}$$

Calculation of Cv under normal operating flow conditions:

q= 35 m^3/h

N1 = 0.0865

Fp = 1

Gf = 1

P1 = Before the valve, we have a pump that, with a flow rate of 35 m^3/h, will provide 38 meters of head (373 kPa = (38 meters x 9.81 x 1000 kg/m^3)/1000). To this, we add 5 meters for the head before the pump (Upstream pump pressure = 1.5 bara, neglecting the 5 meters of suction line), and subtract 98.1 kPa for the head to overcome after the pump ((10 meters x 9.81 x 1000 kg/m^3)/1000), 5 kPa for the flow transmitter loss, and friction losses due to the line (150 meters with 4 elbow curves of 90°).

For the latter, we will use the Darcy-Weisbach equation, the calculation of which I do not show here, but it is easy to derive that for a line of 150 meters, 3'' internal diameter, 4 curves, where water flows at 35 m^3/h (approximately 2.1 m/s), the calculated friction losses are approximately 88 kPa. Alternatively, reference can be made to the graph inserted at the beginning of the example.

As for the calculation of the piping factor Fp, for this initial iteration, it is assumed to be 1.

So, P1 is equal to: 373+50−98.1−5−88=231.9 kPag.

P2 = (after the valve) is the pressure drop due to the downstream equipment, which, for a flow rate of 35 m^3/h, is 1 bar (100 kPa). Therefore, P2=100 kPagP2=100kPag.

P1-P2 = 131.9 kPa.

The calculated Cv is therefore:

Cv = 35.2

Calculation of Cv under maximum flow conditions:

The flow rate is increased by 10% (38.5 m^3/h).

q= 38.5 m^3/h

N1 = 0.0865

Fp = 1

Gf = 1

P1 = Before the valve, we have a pump that, with a flow rate of 38.5 m^3/h, will provide a lower head compared to the normal operating case, equal to 36 meters of head (353 kPa = (36 meters x 9.81 x 1000 kg/m^3)/1000). To this, we add again the 5 meters for the head before the pump and subtract 98.1 kPa for the head to overcome, 5 kPa for the flow transmitter loss, and again the friction losses due to the line (150 meters with 4 elbow curves of 90°).

These last losses have increased since the fluid flow in the pipe is now more than 10% higher. Applying the Darcy-Weisbach equation again, they are approximately 106 kPa.

P1 is therefore equal to: 353+50-98.1-5-106 = 193.9 kPag

P2 = After the valve, we only have the pressure drop due to the downstream equipment, which for 38.5 m^3/h is equal to 1.16 bar (116 kPa). Therefore, P2 = 116 kPag.

P1-P2 = 77.9 kPa.

The minimum pressure drop through the valve for liquids, below which it should not fall, is 0.7 bar (70 kPa), so the calculated value is acceptable.

The calculated Cv is therefore:

Cv = 50.4

Calculation of Cv under minimum flow conditions:

The flow rate is 60% of the normal operating flow: 21 m^3/h.

q= 21 m^3/h

N1 = 0.0865

Fp = 1

Gf = 1

P1 = Before the valve, we have a pump that, with a flow rate of 21 m^3/h, will provide a higher head compared to the normal operating case, equal to 42 meters of head (412 kPa = (42 meters x 9.81 x 1000 kg/m^3)/1000). To this, we add again the 5 meters for the head before the pump and subtract 98.1 kPa for the head to overcome, 5 kPa for the flow transmitter loss, and again the friction losses due to the line (150 meters with 4 elbow curves of 90°).

These last losses have decreased significantly since the fluid flow in the pipe is now half of the normal operating case. Applying the Darcy-Weisbach equation again, they are approximately 33 kPa.

P1 is therefore equal to: 412+50-98.1-5-33 = 325.9 kPag

P2 = After the valve, we only have the pressure drop due to the downstream equipment, which for 21 m^3/h is equal to 0.44 bar (44 kPa). Therefore, P2 = 44 kPag.

P1-P2 = 281.9 kPa.

Cv = 14.45

Calculation of Cv max (Cv at maximum valve opening), authority, and rangeability

$$C_V\ Max = \frac{C_V\ (maximum\ flow)}{0.8} = 63$$

L The valve authority, under maximum operating flow conditions, is equal to

$$Authority = \frac{77.9}{77.9 + 115 + 106 + 5} = 25.6\%$$

While under normal flow conditions:

$$Authority = \frac{131.9}{131.9 + 100 + 88 + 5} = 40.6\%$$

This falls within the expected range of values to ensure good control without excessive overdesign.

The rangeability of the control valve, based on the calculated values, is equal to:

$$Control\ valve\ rangeability = \frac{C_V\ Max}{C_V \min flow} = \frac{63}{14.45} = 4.35$$

This is not a high value but certainly falls within the recommended limits for various common types of valves.

Selection from the catalog

For the example in question, the preferable valve is likely a globe valve with an equal percentage characteristic.

We want to verify that this is indeed the case by applying the relationship in paragraph 2.5:

$$vpdd\ (valve\ pressure\ drop\ decay) = \frac{\Delta Pvalve,\ max\ flow}{\Delta Pvalve, min\ flow} = \frac{77.9}{281.9} = 0.279$$

The calculation confirms that an equal percentage globe valve is the best choice.

The following catalog, taken from a supplier of equal percentage globe valves, displays the various available options.

Travel %	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
F_L	**0.94**	**0.94**	**0.94**	**0.94**	**0.93**	**0.92**	**0.92**	**0.91**	**0.91**	**0.90**
Valve Size	**Rated C_V**									
inch										
1	0.4	0.6	0.85	120	2.3	4.3	6.8	9.0	10.7	12
15	13	17	2.5	3.6	6.8	12.5	20.0	27	31	35
2	17	2.3	3.3	4.7	8.9	16.5	26.1	35	412	46
3	3.0	4.0	5.8	8.2	15.6	28.9	45.7	613	72.1	80.5

The 3'' valve is the only one that surpasses the calculated maximum CVCV. Since the valve has the same size as the line, it will not require reductions. The initial assumption of considering the FpFp coefficient as 1 is therefore correct, and the calculation does not need iteration.

In the three flow cases we are considering, the valve will be open approximately at 65% (normal operating flow), 73% (design flow), and about 48% under minimum flow conditions, which are acceptable values.

However, checks for rangeability and the absence of critical flow conditions must now be carried out. Regarding rangeability:

$$Control\ valve\ rangeability = \frac{C_V\ da\ catalogo}{C_V \min flow} = \frac{80.5}{14.45} = 5.57$$

Well within the limits for this type of valve.

To verify the absence of critical flow conditions, the relationship from paragraph 4.2.2 needs to be used, as shown here:

$$DP_{max} = {F_L}^2(P_1 - F_F P_V)$$

The vapor pressure of water at 30°C is approximately 0.04 bar (4 kPa), while the critical pressure value for water is 220 bar. From the graph in figure 10, it can be assumed that the critical liquid factor F_F is approximately 0.92. The value of F_L is obtained from the catalog in the various analyzed cases..

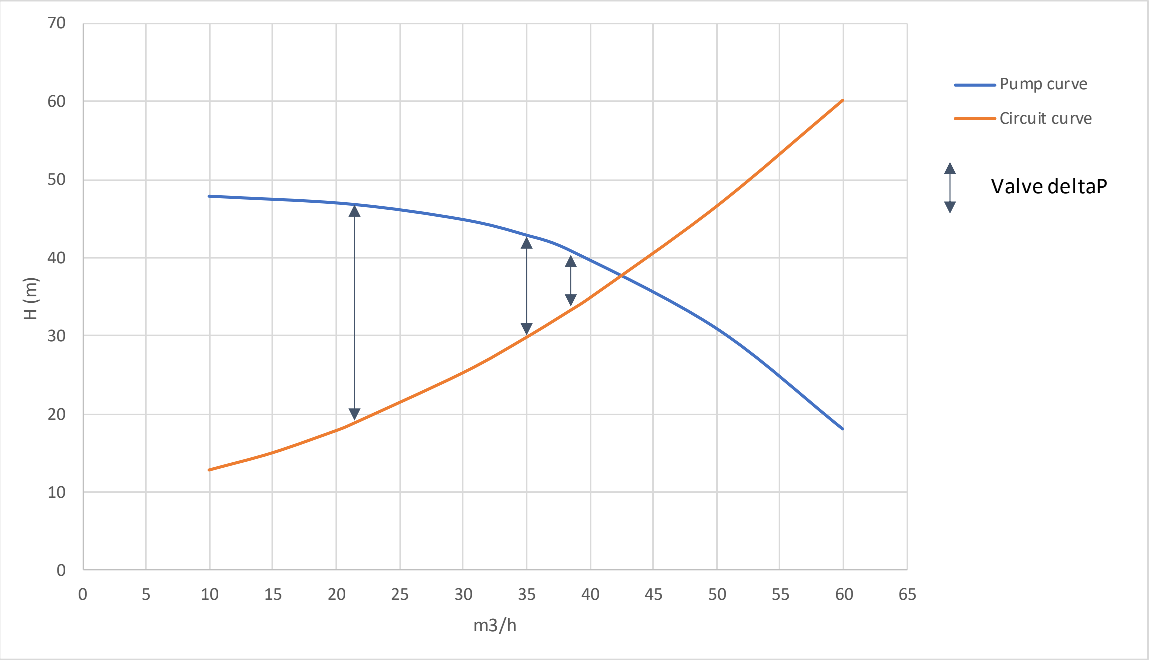
- Normal flow: $DP_{max} = {F_L}^2(P_1 - F_F P_V) = 0.92^2(231.9 - 0.92 * 4)$= 196 kPa
- Maximum flow: $DP_{max} = {F_L}^2(P_1 - F_F P_V) = 0.9^2(193.9 - 0.92 * 4)$= 157 kPa
- Minimum flow: $DP_{max} = {F_L}^2(P_1 - F_F P_V) = 0.94^2(325.9 - 0.92 * 4)$= 287.9 kPa

In all cases, the pressure drop across the valve does not exceed the maximum pressure drop, and there are no risks of critical flow conditions, although the margin is narrow in minimum flow conditions.

This is partly due to the assumption in this example of placing the valve at an elevation and at the end of the pump discharge line to simplify calculations. In a real case, the valve would likely be positioned at ground level for easy access, and the circuit's pressure losses would be distributed more evenly even after the valve. The suction pressure at the valve (P1) would then be higher, while maintaining the same sizing (deltaP across the valve and its corresponding Cv remain unchanged).

Final thoughts

It's worth presenting the hydraulic circuit as a whole, intersecting the pump curve with the total pressure losses (including losses from the downstream equipment and those due to the flow transmitter):



The graph also takes into account the static head. The chart makes it easy to assess the pressure drop across the valve in various conditions analyzed earlier. By converting head values to pressure, the previously calculated values are confirmed, providing an additional check on the calculations. It is also interesting to note the point where the two curves intersect, representing the limit flow rate that can pass through the circuit, beyond which the pump is no longer able to provide the necessary head to overcome all pressure losses.

6. Some references

1. GPSA Engineering Handbook, 12th edition
2. Perry’s Chemical Engineering Handbook, 8th edition
3. Control Valve Handbook, 5th edition