Flow*Line* Controls

An Engineer's Guide for Sizing and Specifying Pressure Independent Control Valves for Building Services

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I. Introduction

Pressure Independent control valves (PICV’s) are gaining in popularity as an effective tool for controlling temperature differentials on the return lines of air handling units in large scale buildings as well as energy transfer stations in district cooling. Their appeal lies in their ability to effectively control temperature in networks that embed hundreds of components that impact that network's working pressures. Essentially, PICV's are designed to minimize to a large degree the effect of variations in network pressure on the control component, and therefore isolating the control variable: ΔT. As is well accepted in the building services arena, high ΔT's in cooling and heating water based systems go a long way in improving efficiency by decreasing energy consumption through the minimization of pumping cost. Therefore optimizing ΔT is a critical component of the process optimization within building or district energy networks. For example, it is easy to see how raising ΔT in a chilled water based cooling system minimizes the required flow of water as:

$$GPM = (Tons * 24) / \Delta T$$

Hence, by increasing ΔT by a factor of two, the designer would cut the required flow by the same factor (of two) for a given chiller. Lower flow rates translate into savings on several fronts, none the least and most obviously on the pumping station and chiller side.

As the industry's demand for PICV is steadily increasing, a larger number of suppliers are offering what they claim to be viable solutions. However, the building services industry has not yet developed standards by which to evaluate PICV's and with designs increasing in complexity, questions are fast arising about the limitations of the current generation of PICV’s. To make matters worse, once a PICV is installed in a network it is difficult to assess how well it is working, due to the difficulty of isolating its performance from the performance of the remaining components on that network in *vivo*. Indeed, a poorly performing PICV may do more harm than good, adding unnecessary pressure losses while failing to provide the required results. Hence it is becoming increasingly important for designing engineers to have an objective *ex-ante* assessment of the expected performance of a PICV in a given system.

After a discussion on the *modus operandi* of control valves in general, the paper turns toward discussing the different PICV designs that are commercially available. Throughout the entire exposition, a special emphasis is placed on the critical parameters that ought to be considered by the designing engineer in order to assess the quality and the expected performance of this control element. In the process the paper tries to shed some light on some of the marketing myths often advanced in the industry.

II. Pressure Independence Reviewed

One of the factors that influence the flow of fluid through a control valve is the amount of pressure, or differential pressure, impressed across it. At any point in valve plug travel, flow through a valve will typically increase if differential pressure is raised, and decrease if the differential pressure is lowered. A change in pumping pressure can therefore produce a change in rate of flow that is not related to the system controller's output signal.

Adding a differential pressure control component downstream of the control valve addresses the above matter. The idea is to have a differential pressure component that senses two pressure points across the control valve and quickly increase and / or lower its own resistance to flow to stabilize the pressure drop across the control valve section. This can compensate for changes in pumping pressure resulting from pump switching or from varying flow demands in its own, or parallel flow paths, as illustrated in figure 1 below.

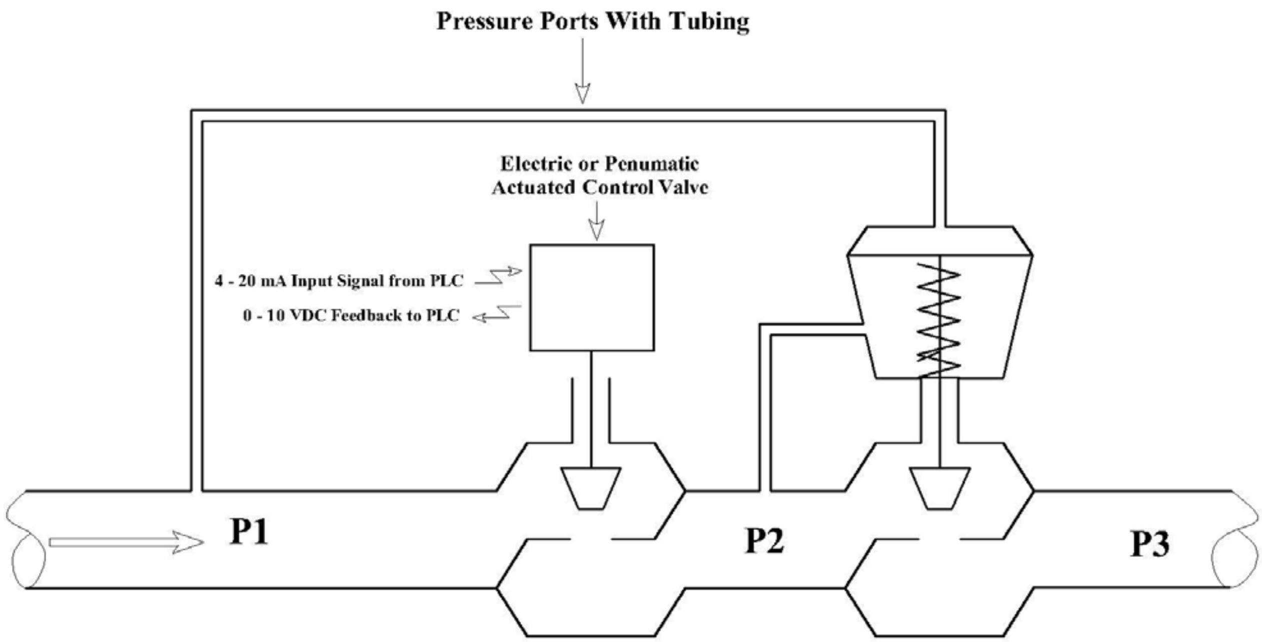


Figure 2.1: A PICV is composed of two components; the first is connected to a PLC and the second acts independently creating backpressure on the line.

The reader would note that the differential pressure control components acts independently of the control valve section and is itself a flow restrictor - in other words: a control element or valve. Moreover, it is self-powered (self-operating) and does not burden or interact with the building automation control system.

With pressure independence, the amount of water flowing through the controlled load (e.g. heat exchanger coil) is more accurate. It is only a function of the control signal, and is less dependent upon varying system pressure. Stability in the control system is enhanced when pressure independence is provided, and the control valve's installed flow characteristic more closely resembles its inherent or constant-pressure characteristic.

However, an important question remains open: what should be the maximum allowable pressure drop across the PICV, i.e. P1 – P3? As previously mentioned, most commercially available PICV's embed the control valve components with the differential pressure control component in one body, however, in an increasing number of situations, specifically when larger sizes and / or higher pressure ratings are required, the only available solutions commercially is one that involves individually mating the two control components, i.e. selecting a control valve with a matched differential pressure control valve. Moreover, the performance of each component must be evaluated and understood separately to better assess the performance of the PICV as a whole unit.

III. Two Port Control Valve Sizing Considerations

a- Two-Port Control Valves Fundamentals

Whilst control valves come in many shapes, some are more commonly found in the bowels of buildings and district energy networks than others. In general, control valves may be split into two categories: reciprocating designs and rotating designs.

i. Reciprocating designs come in two main types:
   - Globe - recognized as the design of choice by *excellence* for accurate continuous control duties. Reciprocating globe valves are offered in a variety of material, ratings and actuation possibilities.
   - Gate – while seldom used in control applications they do provide a viable alternative in on/off applications in large flow applications.
   - Multiple Orifice (MOV) – a new breed of design that features two plates with matching perforated orifices. The orifices divide the flow in jets and pending their alignment would restrict flow. This design is effective in reducing cavitation threats and requires a small footprint. However, its remains costly (relative to its C_v), which has hindered its use in the often competitive building services arena.

ii. Rotating designs come in three main types:
   - Butterfly – recognized in the building service arena as a good performer for on/off applications and its ability to perform continuous throttle control duties in large flow application, despite some well known limitations.
   - Ball – best known for their cost effectiveness for on/off applications in small sized applications.
   - Segmented ball or Rotating Globe – often referred to as E-ball and / or V-ball valves these are essentially a globe design hybrid that feature some (but not all) of the advantages of the reciprocating globe while maintaining some of the benefits of rotating valves: higher C_v's.

This paper looks at the three most common types used in the industry, i.e. reciprocating globe valves, butterfly valves and segmented ball valves. The discussion will skim on some of the general fundamentals to focus on some specific topics that are relevant for the building services industry. For a general industry standard overview with illustrations the reader may consult *The Steam and Condensate - Loop Module 1* as well as the *Control Valve Handbook* both of which are referenced below.

<u>Reciprocating Globe Valves</u>

Typical Technical Specifications for Building Services:

- ✓ Body Material (typically found in the building services Market): Iron, Steel, Bronze
- ✓ Common Trim Material: Bronze, Stainless Steel
- ✓ Body Rating: ANSI 125 – ANSI 300 (for equivalency see Appendix B
- ✓ Flow Characteristics: Fast Opening, Linear, Modified linear, Equal Percentage
- ✓ Rangeability: 50 : 1
- ✓ Shut-off: Class III – Class IV
- ✓ Variants: Single Seated Balanced and Double Seated Balanced

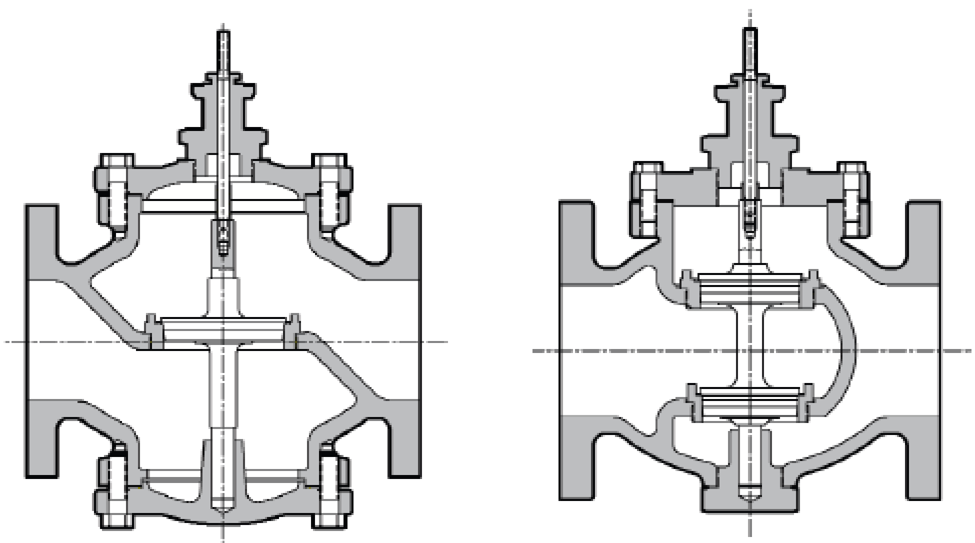


Figure 3.1: Typical reciprocating single seated (left) and double seated (right) globe control valves

The basic design is best characterized by the double 90 degree change in flow of the fluid inside the valve. This characteristic causes higher pressure drops on a given line when compared to their butterfly valves and segmented ball valves counterparts. But it is precisely this feature that makes them best suited for control. The flow path through a globe valve spreads a pressure drop through the entire device, while other valve styles tend to concentrate the pressure drop at the *vena contracta* (see Appendix A). The vena contracta is the place in the final control element where flowing velocity is at its maximum, and pressure is at its minimum. It is the place where phenomena such as "flashing", "choking" and "cavitation" originate. Because it slows pressure drop and recovery rates within its body – see Appendix A – the globe valve is more resistant than ball, plug and butterfly valves to those counter-productive, sometimes destructive events. This inherent stabilizing characteristic of the globe valve enhances its ability to control a fluid stream.

<u>Butterfly Valves</u>

Typical Technical Specifications for Building Services:

- ✓ Body Material (typically found in the building services Market): Iron (elastomer covered), Steel
- ✓ Common Disc Material: Aluminum Bronze, Epoxy coated Iron or Steel
- ✓ Body Rating: ANSI 125 – ANSI 300 (for equivalency see Appendix B
- ✓ Flow Characteristics: Linear, Modified linear
- ✓ Rangeability: 20 : 1 – factoring 30 – 60 usable band.

✓ Shut-off: Bubble Tight

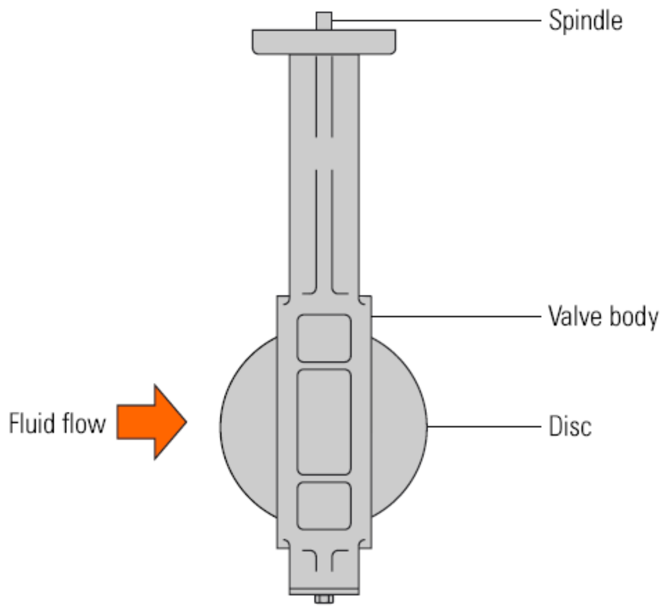


Figure 3.2: A typical side view of a butterfly valve – from "The Steam and Condensate"

Butterfly valves consist of a disc rotating around an axe which closes against a seat. At different stages of rotation, the flow is forced around the disc. The appeal of the butterfly in the building services is driven by its considerably lower initial cost. However, its cost of ownership should be questioned as the valve requires higher maintenance than Globe or E-ball valves.

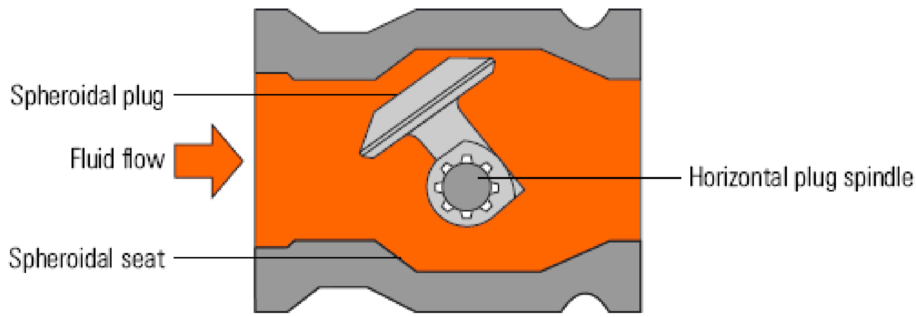
Rotary valves in general and butterfly valves in particular are susceptible to high friction caused by the high seat loads required to obtain shut-off. Because of the high seal friction and poor drive train stiffness, the valve shaft winds up and does not translate motion to the control element. As a result, an improperly designed rotary valve can exhibit significant dead band – see appendix A – that clearly has a detrimental effect on process variability.

Additionally, unlike their reciprocating globe counterpart the pressure drop is focalized around the vena contracta, significantly decreasing its pressure recovery ratio – see appendix A – while increasing its chances of cavitation. This causes many designers to "oversize" butterfly valves. Oversized butterfly valves produce a disproportionately large flow change for a given increment of disc rotation; this phenomenon can greatly exaggerate the process variability associated with dead band due to friction as well as severe distortion in the valve's flow characteristic significantly impacting their seemingly higher rangeability ratio. Keeping in mind that an undersized butterfly valve for control has no control throttling between 60% to 100% of travel. This leaves a very narrow useful throttling band for reasonable control.

Eccentric Plug / Segmented Ball / Rotating Globe Valves

Typical Technical Specifications for Building Services:

- ✓ Body Material (typically found in the building services Market): Steel
- ✓ Common Disc Material: Stainless Steel
- ✓ Body Rating: ANSI 150 – ANSI 300 (for equivalency see Appendix B
- ✓ Flow Characteristics: Linear, Modified linear, Equal Percentage
- ✓ Rangeability: 100 : 1
- ✓ Shut-off: ANSI Class IV if hard seated.



Known under many different names, e.g. eccentric ball valve or quarter turn globe valve, the basic design consists of a spheroidal plug rotating around an axis which closes against a seat. The appeal of the E-ball valve in the building services is driven mainly by its low pressure drop and superior trim wear characteristics. For rotary valves, the E-ball is a better choice compared to a butterfly valve for maximum controllability, with an improved range of control from 0% till 75% of its travel. However, it remains second to its reciprocating counterpart in terms of pressure recovery and general control considerations as discussed above.

So which valve type design is best for control?

The answer depends on the application in question. Reciprocating globe valves have earned their distinction as the preferred control valve style. In non-critical applications and when cost is a consideration then butterfly valves may be a viable alternative despite their inherently inferior control properties and longer term maintenance issues. Segmented ball valves successfully address the maintenance issues but do not match the control qualities of reciprocating globe valves, for all ranges of process conditions. Moreover, segmented ball valves come at a premium whose worth can only be determined by the designing engineer.

Care should be taken in sizing all control valves – see section d below. However, the impact on process variability is exacerbated with wrongly sized rotating valves, in other words oversized globe valves are usually more forgiving.

Lastly, it is important to note that rotating valves have inherently higher dB levels of audible noise compared to reciprocating valves.

b- Control Valve Actuation

The actuation of a control valve involves positioning its moving part (disc or plug) relative to a stationary seat - the flow is hence restricted, thereby impacting the pressures upstream and downstream of the valve. The main tasks of the actuator are to accurately locate the moving part within its span of available travel. Accuracy is determined by a signal sent to the valve via a controller; the speed and fidelity with which the control valve executes the order are the key elements in assessing a control valve's performance capabilities.

There are several ways to actuate a two way control valve – see *The Steam and Condensate - Loop Module 6*, the most common being:

- Pneumatic Actuation
- Electric Actuation.

Electric Actuators are the actuators of choice in the building automation controls, mainly in the building or secondary side – this is especially true when looking at water based cooling and heating systems as opposed to steam. It is obvious to see why. Pneumatic actuators require compressed air which is expensive to obtain and maintain. However, due to their accuracy pneumatic actuators remain the most commonly used form of actuation in industrial applications as well as some applications in district energy within the building services sector. Nonetheless a new generation of electric actuators is making their way into the market that is capable of delivering a pneumatic like performance without the inherent cost associated with this latter.

Typically, three weaknesses have plagued electric actuators:

- Speed
- Ability to handle high pressure shut-off
- Fail safe management

i- Speed: This is typically the Achilles heel of the electrical actuators, significantly increasing their dead time as well as their response time – see Appendix A. How slow is a typical 24V actuator commercially available in the building services market? For reciprocating type valves as an example, travel speed can be as low as 4 second per millimeter on low-end units, while for higher-end units it can reach speeds neighboring 2.0 seconds per millimeter. In other word, it would take most electrically actuated 4" diameter valves approximately 75 - 110 seconds to travel from a full open to a fully closed position. In comparison, the new generation of electric actuator developed by Warren Controls – Amuract – can cover that same distance in less than 8 seconds, yielding a 24VAC actuator that compete with the pneumatic performance.

ii- Ability to Handle High Pressure Shut-off and Fail Safe Management: Shut-off capability is a function of the valve design along with force that can be exerted by an actuator. Most electrically actuated valves, available in the building services industry, are limited to a 5 bar (g) shut-off pressure if using a spring return fail safe option. Higher end valves with shut-off capabilities of 12 bar and above use an external battery powered back controller for fail safe management. In comparison, a pneumatic actuator can be easily designed to be reverse acting or direct acting to naturally accommodate the desired fail safe mode at a much larger range of pressures (with the introduction of a positioner). In other words, with a simple change in the actuation design a pneumatically actuated control valve can either be normally closed or normally open – see *The Steam and Condensate - Loop Module 6*. Once again advances in electronic are helping electric actuators moves into higher grounds. The new Amuract form Warren Controls with its patented "Enerdrive System" is the modern electronic replacement for the spring return and external batteries. Power from the PC board is stored in capacitors to drive the control valve at full torque to its safety position. This is an elegant solution that accommodates multiple power failures. But after all is said and done how important is the shut-off capability to the designing engineer? Simply put is: a control valve is only as good as its weakest performance point.

c- Putting the Two Pieces Together

Since control valves are comprised of a valve and its actuator, both units must be designed in tandem. However, many manufacturers mix and match them on an ad hoc basis. The control valve of choice for any given application should be driven by the optimization of the entire process. "It makes no sense to install an elaborate process control strategy and hardware instrumentation system capable of achieving 0.5% or better process control and then to implement that control strategy with a 5% or worse control valve" – see Control Valve Handbook. In critical applications that impact the efficiency of a process, .e.g. the control of temperature differentials across a coil, control valves should be treated as engineered products.

Not all electric actuators are born equal, and the designing engineer should ensure that all control elements have the right synergy in order to minimize dead band, maximize the response time and achieve the intended accuracy of the entire control valve assembly. In general, most building automation control valves offered on the market are surpassed by their industrial counterparts. Nonetheless, with the advent of a new generation of electrical actuators, and with legislative pressure to produce "green" building the gap is quickly expected to shrink.

Common building automation grade electric actuators have limited resolution, wider dead bands, significant repeatability problems, and total accuracy errors that could as high as 5%. This does directly, negatively impact stated rangeability claims. Therefore actuator selction is critical in the overall performance claims of control valves

d- Sizing a Two-Port Control Valve

When selecting a two-port control valve for an application a designer is faced with two competing considerations.

i- Undersized Control Valves

Under-sizing a control valve, in a system, increases the pressure drop of the entire system – meaning the pumps would use a larger amount of energy simply to pass sufficient water through the system and more specifically through the control valve. This of course is not acceptable in our current quest for energy savings and optimization. Nonetheless, the reader should note that assuming a cost no object scenario, i.e. if we ignore the cost of re-generating sufficient pressure to force the required flow through the control valve, then the accuracy of that control is at an optimal as the entire travel of the valve may be utilized to achieve the desire control.

ii- Oversized Control Valves

Over-sizing a control valve, in that same system, would reduce the amount of energy needed to pump the necessary flow into the system and hence reducing power consumption. However, such savings will come at the cost of a decrease in the accuracy of control, as the initial travel from fully open towards the closed position would have no effect on the control medium and therefore on the control variable. In other words, when a valve is over-sized, significant control can only be achieved when the valve is throttling in the neighborhood of its closed position. Hence, only a relatively small fraction of the valve travel is useful for control. As a consequence, small movements of the valve stem are expected to have a relatively large impact on the control medium, yielding erratic control with poor stability and accuracy, in addition to premature valve failure.

Another problem of process optimization with oversized valves is the distortion that occurs to their inherent flow curve, i.e. the valve's flow plotted as it strokes with a constant pressure drop (ΔP) across that valve. In general control valve's inherent flow characteristic is broadly categorized as follows:

- Linear - flow capacity increases linearly with valve travel.
- Equal Percentage - flow capacity increases exponentially with valve trim travel. Equal increments of valve travel produce equal percentage changes in the existing Cv.
- Modified Linear is approximately midway between linear and equal-percentage characteristics. Fine throttling at low flow capacity and generally linear characteristics at higher flow capacity.
- Quick Opening provides large changes in flow for initial changes in lift. Very high valve gain, not for modulating control. Limited to on-off service, Pilot, or Direct PRV’s / Temperature Regulators.

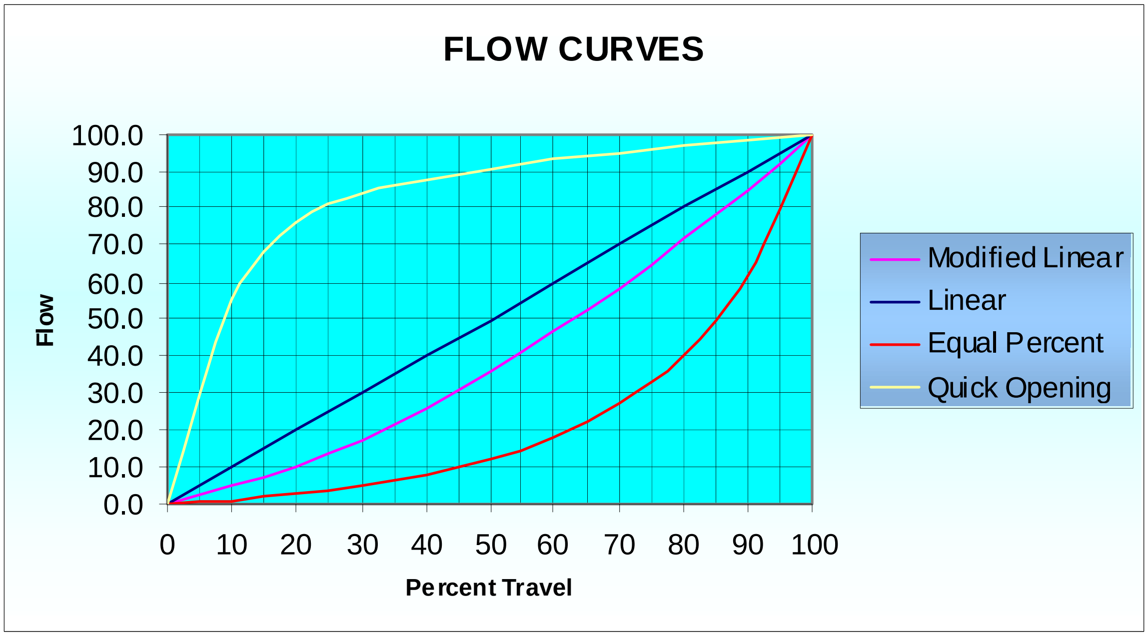


Figure 2: Graphic illustration of inherent flow curve characteristics of control valves - the reader would note that most applications in energy transfer stations / district cooling for example have benefited from equal-percentage or modified linear characteristics.

Control valves installed with pumps, piping, fittings, and other process equipment, however display a pressure drop across the valve that varies significantly the plug moves through its travel. In other words, when a control valve is installed in a large network the ΔP upstream and downstream of the valve is not constant. This results in a distortion to the inherent flow characteristic. The lower the pressure drop from the valves versus the entire network the larger is the distortion. For example a control valve with an equal percentage trim displays the following installed curves under the conditions displayed in the table below, the reader should also note that the deterioration in the control valve's rangeability ratio.

Table 1

Curve	Percent of Pressure Drop from the Valve versus the Network	Rangeability Percent at Max C_v
1	100% (Inherent)	
2	50%	50 : 1
3	20%	25 : 1
4	10%	15 : 1
5	5%	10 : 1
6	2%	7 : 1

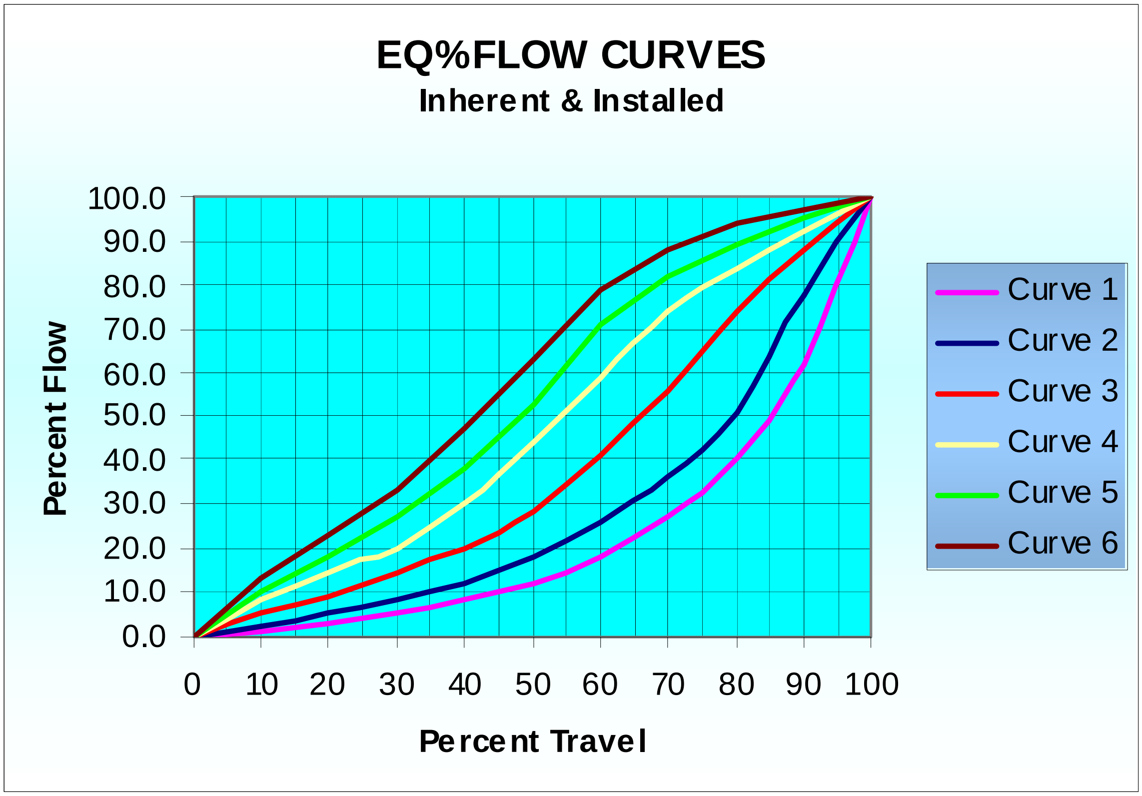


Figure 3: When the percentage of the pressure drop from the valve versus the network becomes negligible, an equal percentage inherent flow curve will display a linear or even a quick opening curve characteristic.

Clearly, the designing engineer must determine the optimal tradeoff between choosing an oversized and an undersized control valve. Proper sizing requires finding a balance in which optimal process control is not outweighed by the resulting energy losses. In other words, minimizing the process variability has a cost, and equilibrium between the two must be determined.

iii- Valve Authority Ratio and Flow Coefficients

A common concept in the industry that embeds the above two considerations is that of "valve authority" within a given system. Mathematically it is easy to see how, as the authority of a control valve is defined as:

$$N = PD\text{cv} / (PD\text{cv} + PD\text{oc}).$$

Where:

*PD*cv = Pressure drop across a fully open control valve

*PD*oc = Pressure drop across the remainder of the circuit, preceding the control valve.

In other words, the valve authority ratio within a system indicates how much of the system's total pressure drop comes from the control valve. It is a common practice in the industry to consider the range between 0.2 – 0.5 as "acceptable" (see Spirax Sarco). Hence, and in general, if the authority is too high (above 50%), then the control valve is likely to be undersized and hence the cost of re-generating the "burnt" energy outweighs the benefits obtained from gains in the process controls. Hence the system would benefit from a larger size valve in order to reduce losses that are driven by excessive pressure drop. If the value is too low (below 20%), then the valve movements will have a marginal impact relative to the total system and hence the valve is likely to be over-sized, yielding poor control and rangeability. The reader would note that the upper bound of 50% and the lower bound of 20% are considered irrespective of the process itself, leaving for the designing engineer the leeway to optimize the overall process within the [0.2 – 0.5] interval.

From a mathematical perspective, the above discussion may be captured in the following optimization problem:

Max N (Valve Authority) = *PD*cv / (*PD*cv + *PDo*c)
Subject to the following constraints:

- Max allowed pressure drop over a given loop is limited to design specific upper bound
- 25% $\geq$ N $\geq$ 50%
- Other pressure drop constraints that may be relevant to the process

In case the maximum flow rate of the circuit / system is given, then it becomes easy to map the required authority to the required flow coefficient – the key sizing variable; as:

$$C_v = V \text{ x } \textbf{(}\text{square root } (G/PD\text{cv}))$$

Where:

C_v = the flow coefficient
V = flow rate
G = specific gravity of the liquid (control medium) – Water = 1.

Hence, determining the required valve authority when the flow rates as well as the maximum allowed system pressure drops are known becomes tantamount to determining the required C_v and then selecting the valve that closely marches this value.

Two-Port Differential Pressure Control Valve Sizing Considerations

The main task of a differential pressure component of the PICV is to restrict the flow around the control valve component to maintain a constant differential pressure across that valve. As such many designers rightfully refer to the differential pressure component as a differential pressure control valve (DPCV). All PICV's embed both the control valve component as well as the DPCV component; most are even housed in one body. Nonetheless, for the sake of our engineering discussion we will treat the DPCV as a separate control entity to give us a deeper design understanding.

a. Differential Pressure Control Valves Fundamentals

Most Differential Pressure Control Valves (DPCV's) embed a spring loaded diaphragm globe valve which senses the nodal pressure at points P1 and P2 as illustrated in figure 4 below. The valve is set to travel open or close so as to maintain a desired differential pressure value, most DPCV's are pre-set at 5 psi. The valve's sensitivity and accuracy is directly linked to the spring tension and the overall diaphragm surface. Larger diaphragms while more expensive have a distinct advantage in terms of sensitivity performance, ultimately impacting the pressure control accuracy of the DPCV.

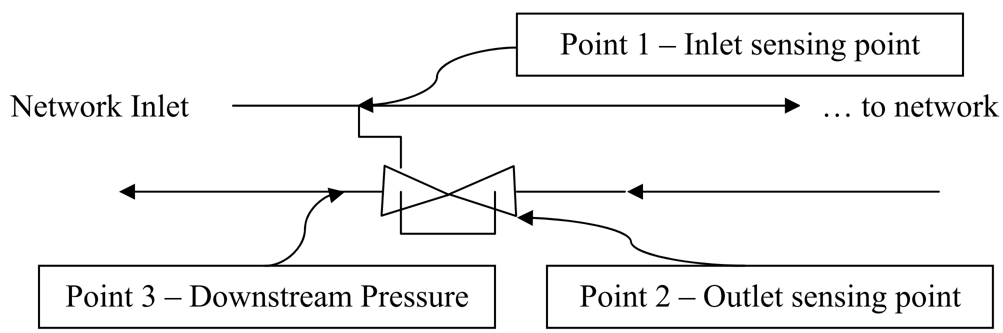


Figure 4: Partial network with DPCV in installed on the outlet.

In the above example, the role of the DPCV is to maintain a constant differential pressure between P1 and P2. To do so the DPCV throttles open or close, hence impacting the nodal pressure at P2 as well as at P3. To see how, suppose the nodal pressure at P1 goes up relative to P2, hence $\Delta P = (P1 - P2)$ goes up. Then the DPCV will shut down effectively increasing the back pressure on P2 and the system - in order to retrieve the set equilibrium – and decreasing the nodal pressure at P3. In other words the drop across the whole system P1 to P3 would go up as a result of an increase in the inlet pressure.

It is instrumental to select a DPCV with a minimal pressure drop under full flowing conditions – with the valve in the full open position – to optimize energy savings while maintaining intended control. This is tantamount to selecting the DPCV with the highest C_v value possible – subject to the line size and the ability of the valve to perform the required job.

If the spring loaded diaphragm valve is used to actuate the valve stem directly, then the DPCV is said to be direct acting. If the spring loaded diaphragm valve is used as a pilot to actuate a larger secondary valve then the DPCV is said to be pilot operated. Most DPCV's commercially available for the building service market are direct acting. Most DPCV's available in the waterworks market for sizes 4" and above are of the pilot operated to accommodate larger sizes and flows.

DPCV vary in both accuracy and flow performance. Most DPCV's offered in the building services market often have reduced ports (lower C_v 's) with smaller matching diaphragm. Reduced port DPCV's exhibit energy losses that may even outweigh their benefit on a network. Table 2 below shows the flow rate of two six inch units. At the same pressure drop efficiency is reduced by more than 37%.

Table 2

	Typical Direct Acting Globe Style DPCV – 6" (150mm)	Typical Full Ported Globe Style DPCV – 6" (150mm) **- Warren Controls**
Flow Rate	40.0 l/s	**64.0 l/s**
Expected Pressure Drop	0.56 bar (g)	**0.56 bar (g)**

b. Larger Sized Differential Pressure Control Valve Actuation for Larger Sizes

Field practitioners are often challenged when it comes to actuating globe valves once they reach sizes greater than 14". Pilot operated DPCV's offer a cost effective alternative in large flowing systems, since they rely on a smaller spring loaded "pilot" valve to actuate a larger valve. All pilot operated DPCV's are composed of two essential parts: a **main globe style valve** (through which the main flow of water passes), and an externally piped pilot valve. The **main valve** is actuated by changing the volume of fluid in its actuating chamber. The flow itself is regulated via the pilot valve which is piped to sense two pressure points on the line. Hence the pilot acts as a travel regulator for positioning the valve as illustrated in the diagram below.

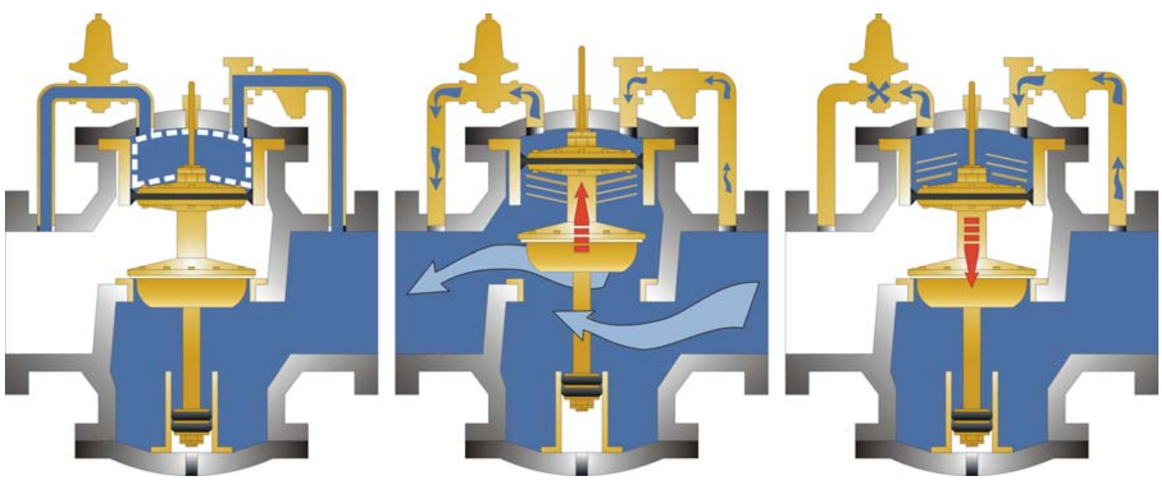


Figure 5: Actuating a piston balanced pilot operated globe style valve

Pilot operated DPCV's come in two types: diaphragm style and piston style. The working principle for both styles is essentially the same, however, diaphragm valves, as the name suggests, utilize a spring and diaphragm to aid in the stem travel. While piston style valves rely primarily on the balance between an upper / lower pistons and the inlet pressure of the fluid to do the job, a comparison table is given below – the reader would note that the water tamer design is no more than a variation on the piton style valve topology and should be used only when severe cavitation is suspected.

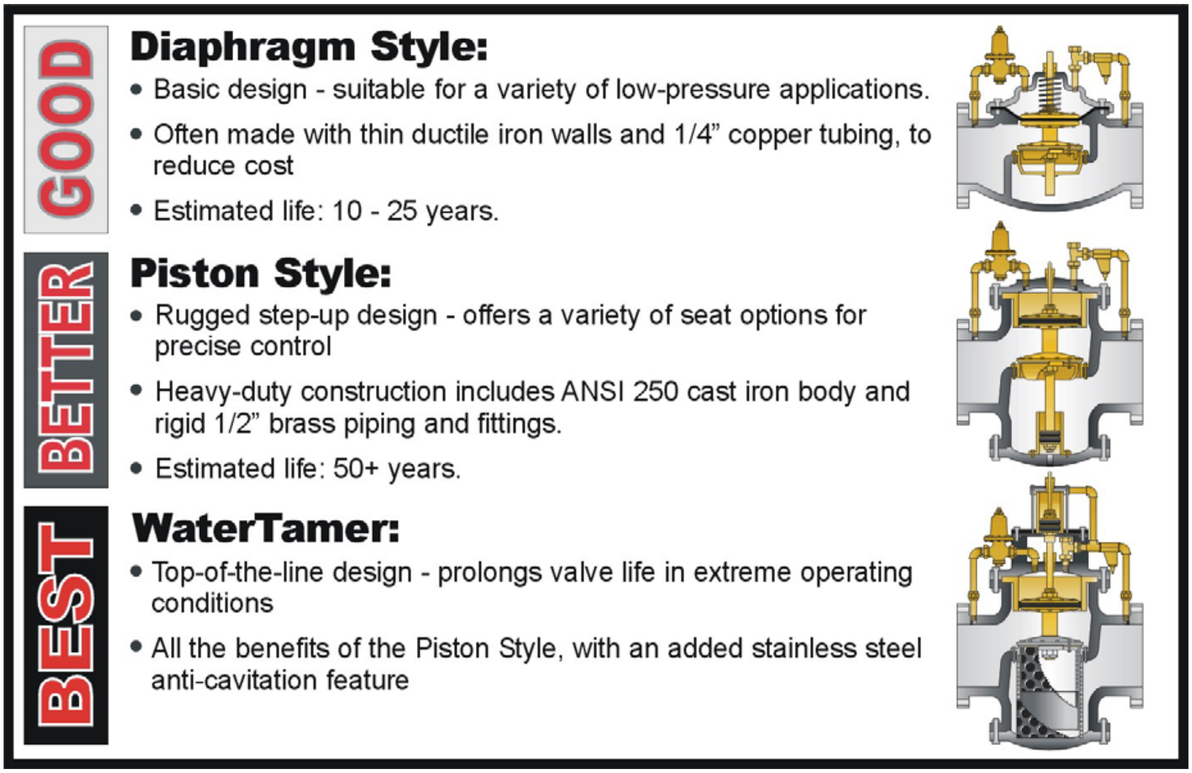


Figure 6 - a cross section view of diaphragm and piston style globe valves

The advantages of piston balanced valves are numerous, the most important ones being:

- No sudden, catastrophic failures (piston packing wears gradually)
- 100% Hydraulic Operation – No springs required
- Over 10 criteria specified for every valve (no single compromising design to handle both throttling and non-throttling applications)
- With routine preventative maintenance, provide decades of trouble free operation
- All parts easily replaceable in-line, through top of valve
- Rugged, flexible design is customizable if conditions change
- Standard construction includes rigid brass pipe, versus copper tubing
- Optimized control as the travel distance allows for a proper machining of the seat disc and hence creating the desired flow characteristic.
- Maximum size for the diaphragm valve is 24" in full port and 32" in reduced port (24" effectively) – Maximum size for the piston balanced style valves is 60" in full port.
- For sizes smaller than 12" piston balanced valves have a higher power loss (pressure drop as a result of actuation) than diaphragm valves. However for larger sizes – 14" and above both designs become equally efficient.

So for smaller sizes – less than 12" – direct acting full ported DPCV as well as full ported pilot operated DPCV's may be considered. While for larger sizes piston styled pilot operated valves would be the valve of choice.

c. Sizing The Differential Pressure Components

Once the control valve is optimally sized, and using the same argument presented in sections above, it becomes clear that the C_v of the DPCV should be more or less the same as that of the control valve, i.e. its authority ratio should range between [0.2; 0.5]. In other words, the authority ratio of the DPCV should not deviate from that of the control valve over which range it is meant to keep the ΔP constant throughout the valve travel – Boysen also arrives at the same conclusion albeit approaching the problem differently.

One important feature for the DPCV is the provision of an externally adjustable pressure differential setting. The idea is to ensure that the differential pressure is adjustable to meet the pressure drop on the control valve in the fully open position and at maximum flow. This feature is essential in the commissioning and initial balancing of the system to ensure the minimum pressure is met while maintaining the maximum intended flow.

Having looked at the fundamentals of the two components that make up a PICV, i.e. the control valve component and the differential pressure control valve component, we then turn to analyzing the different design possibilities for pressure independent control valves.

IV. PICV Designs and Considerations

Several PICV's are commercially offered. All are meant to be electrically actuated. They differ significantly in design and yield different results. For simplicity, they may be grouped as follows.

- Internally actuated spring and plate DPCV
- Externally actuated direct acting DPCV.

Designers may chose to match a control valve with a DPCV instead of specifying a complete PICV assembly. The risk would be in incorrectly matching the two components. However, the upside is attained when larger sizes and / or higher pressure rating are required due to the commercial unavailability of PICV for these large size or high pressure ranges..

a- Internally Actuated Spring and Plate DPCV – a Description

As depicted in the figure below, the flow goes through a first stage of control: the control valve component. Flow in this stage is more or less restricted according to an external PLC signal that is driven by temperature transducers. Once past the first stage the flow then goes into the DPCV component. At this point, the flow is divided in two paths that are directly pushing against a moving plate – which is held by a set of springs. The plate's position relative to a seat determines the flow across this second component. The plate is pushed "in" or "out" as a function of the pressure differential upstream and downstream of the plate. The spring tension determines the set differential pressure on the control valve component.

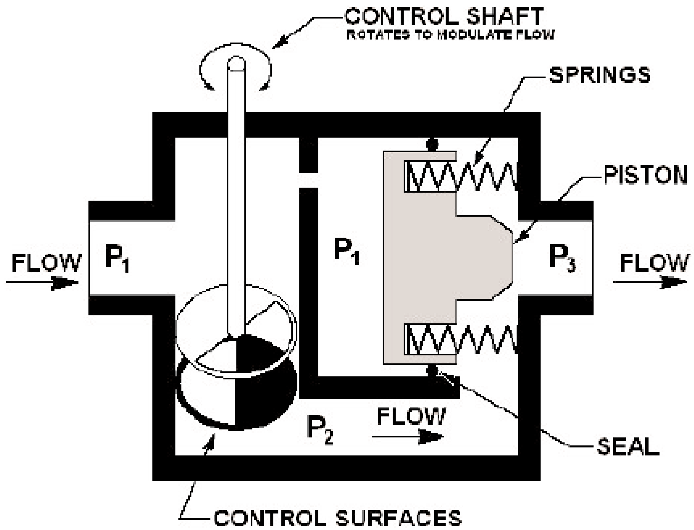


Figure 7: Typical internal spring and plate design – used in Flowcontrol's Delta P

A variant of FlowControl's design is the one found in Flowcon's (Grizwold) SM valves. Operating on the same principle the plate is replaced with a diaphragm and the rotating control component is replaced with a reciprocating one.

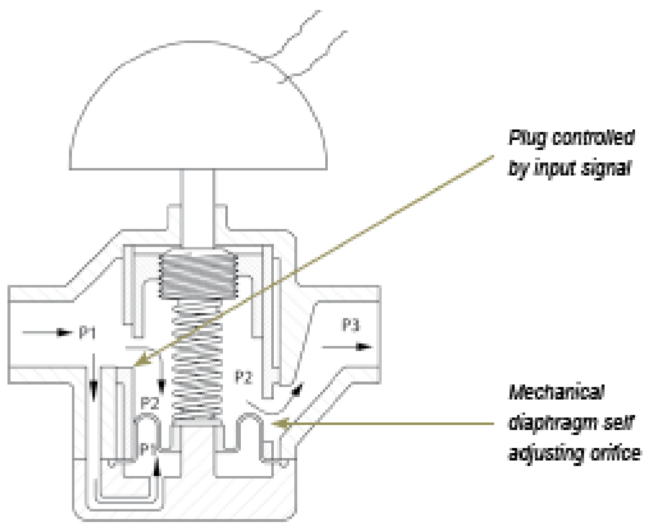


Figure87: Typical internal spring and diaphragm design – used in Flowcon's SM series

The merits of the internally actuated DPCV's in general are the reduced footprint of the valve in the circuit. However, longer term maintenance is an issue as the entire valve body must be dismounted to reach the internal spring and diaphragm.

b- Externally Actuated Direct Acting DPCV – a Description

Like all current generation of PICV's the first component controls flow as result of commands from the PLC, while the second component impacts flows as results of changes in differential pressures across the first component (the control vale). As the name suggests, the internal plate and springs in externally actuated direct acting DPCV's are replaced with a an external actuator as depicted in the diagram below. The actuator senses the static pressure from the capillaries and remains in equilibrium as long as the differential pressure across the control valve component remains unchanged. Unlike internally actuated DPCV's the medium does not flow through the actuator.

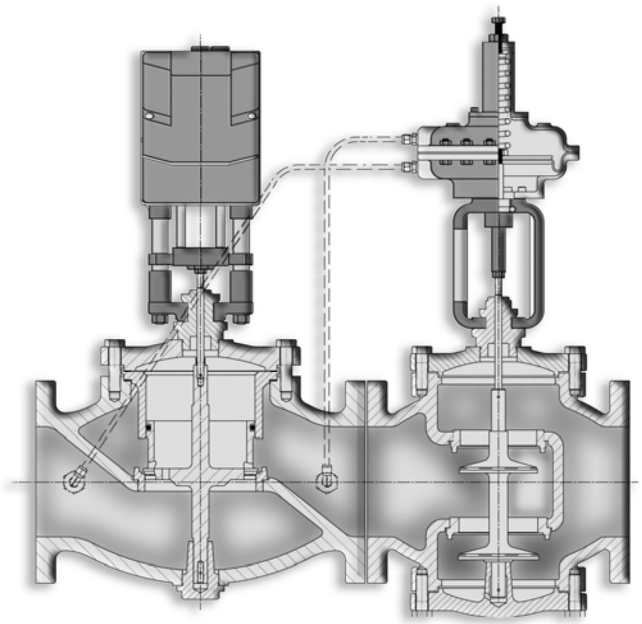


Figure 9: Typical externally actuated design – used in Warren Control's PICV

A variant of the Warren Controls unit is TA's KTM 50 unit which uses opposing plugs and seats.

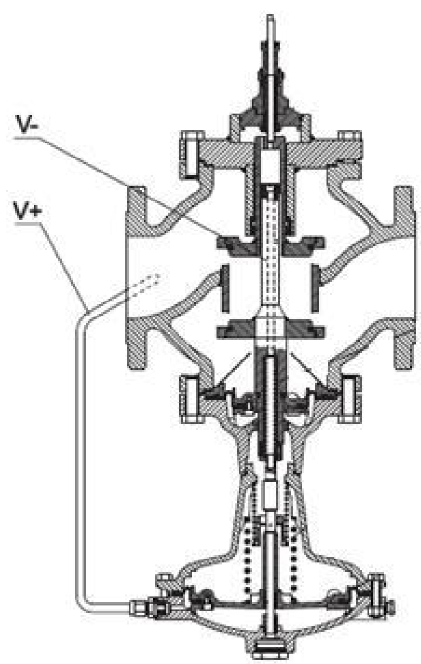


Figure 10: Typical externally actuated design – used in TA's KTM 50

Unlike traditional two way control valve designs the flow in the KTM 50 pushes the seat downward (toward its closed position) on the control valve element and upward (toward its open position) on the DPCV component actuator.

c- Are marketed PICV's better than matching a first rate control valve with a first rate DPCV?

The first thing to remember is that the PICV is first and foremost a control valve. Hence all points raised with regards to control valves in sections II and IV are equally relevant to evaluating a PICV. A good control valve is one that minimizes the process variability while burning the least amount of energy.

The clear advantage of using PICV's as one unit is that the control valve component and the DPCV component are engineered in tandem. Moreover, they are factory matched, set and tested. Moreover, by specifying complete PICV sets, the designing engineer minimizes the probably of faulty installations on site.

Another, advantage of specifying PICV is to have one central point of responsibility for the flow control, instead of having two devices where system responsibility is not clear.

The advantage of separately matching the control valve with a DPCV is in addressing atypical applications. For example, in applications where system flow is as high as 140 l/s per valve, integrated PICV do not yet commercially exist. The same is true for when flowing differential pressures are outside industry norms.

V. Recommendations on Specifying PICV's

a. First Order of Business: determining the upper and lower bounds for the maximum acceptable pressure drop across the unit

Not all PICV flow equally. Some "flow" better than others. This can be seen by examining the flow variance at a fixed pressure drop of the different marketed designs. For example, a 4" PICV from Warren Controls flows better than bigger sized valves from other brands set at 5 psi.

Table 3

Maximum Flow Capacity in l/s @ the Stated Pressure Drop Settings				
	Brand A - at 5 psi (0.34 bar) factory fixed setting	**Brand B - at 5 psi (0.34 bar) factory fixed setting**	**Brand C - at 2.2 psi (0.15 bar) factory fixed setting**	**Warren Controls – at 5 psi (0.34 bar) adjustable setting**
2.5"	4.2	n/a	5.8	9.2
3"	7.2	10.2	n/a	12.7

4"	9.6	19.9	12.5	24.0
5"	23.3	n/a	16.7	38.1
6"	23.3	42.9	55.6	59.2
8"	n/a	88.0	63.9	96.0
10"	n/a	139.0	n/a	135.5

Pressure drop is a function of the internal port sizes, valve plug travel and the PICV's architecture. For example PICV with externally actuated DPCV's tend create less pressure drop when compared to PICV's with internally actuated DPCV's.

Sizing a PICV is not should follow the same logic as the one highlighted in section III. In other words the authority ratio from the entire PICV, i.e. both the pressure drop across the control valve plus the pressure drop across the DPCV components, should range within 30% to 50%. Some designers prefer to specify the authority ratio of the Control valve component separately; in this case the range to be considered would be within a [20% - 27%] band.

To see how, recall that:

$$N = PD\text{cv} / (PD\text{cv} + PD\text{oc}) \ (1)$$

If the PICV is considered as one valve then the above equation may written as:

$$N = PDpicv / (PDpicv + PDoc)$$

$$\rightarrow \quad N = PDcv + PDdpcv / (PDoc + PDcv + PDdpcv)$$

As elaborated section IV, the C_v of the control valve component and the Cv of the DPCV component in a properly sized DPCV must be as closely matched as possible. So equation 1 may written as follows.

$$0.5 = 2PDcv / (PDoc + 2PDcv)$$

$$\rightarrow \quad 0.5\,(PDoc + 2\,PDcv) = 2PDcv$$

$$\rightarrow \quad 0.5PDoc + PDcv = 2PDcv$$

$$\rightarrow \quad 0.5PDoc = PDcv$$

Hence *PDcv* should be around 25% if the required authority ratio on the entire PICV is 50%.

Myth: All PICV's have 100% percent authority

Truth: Up to defining the authority ratio per equation 1 above, this is mathematically impossible. Most PICV manufacturers which make such claims, usually mean to say that since the pressure drop across the control valve component of the PICV is constant at all flows then the control valve can control equally well at both part load and full loads. Hence the control valve has a good control over 100% of the load. The reality of the matter is that only the pressure drop across the control valve element is kept constant. The pressure drop across the DPCV component - and thereby the PICV itself - is <u>not constant</u> and varies significantly with the valve's plug travel.

Some respectable authors have gone to great lengths in advancing alternative authority ratio definitions that support the 100% authority claim. But for a concept like the authority ratio to be useful, it ought to be conducive to sizing and / or conducive to providing measurable performance results. Indeed the major consideration behind looking at the authority ratio is to gain an insight into how well the valve controls when installed "against" a coil or a heat exchanger. So were all PICV's have a 100% authority regardless of the loop in which they are installed, then any PICV can control equally well in all situations regardless of the flow and pressure drop conditions, in other words we would have a one sizes fits all valve, which is an absurdity.

The presence of the DPCV component around the control valve ensures that this latter operates at a constant pressure drop and therefore as seen in section one its installed flow curve characteristic is the same as its inherent flow curve characteristic. This means that the valve rangeability ratio is maximized and the valve can effectively control at part load.

b. Second Order of Business: determining the pressure requirements.

i- Body Pressure Ratings

In the early days of valve manufacturing, only three body pressure ratings were specified: standard, medium and extra heavy. There was no common definition of any of these ratings and manufacturers often described the factory tests and in some cases included the actual bursting pressure, so users could assign whatever working pressure and safety factor they wished. Today, the standard in-use by the American Society of Mechanical Engineers, ASME / ANSI B16 "Valves-Flanged, Threaded, and Welding End" is the root document from which many (though not all) testing specifications establish their baseline test pressures. The ASME document specifies the working pressure for the established pressure classes in a range of materials.

For example, the maximum pressure / temperature relationship for cast iron flanged fittings according to ANSI B16.1 are given in the table below:

Table 4

Temperature (degree F)	Pressure Class	
	125 #	**250 #**
32 – 150	175	400
175	170	385
200	165	370
225	157	355
250	150	340
275	145	325
300	140	310
350	125	280

According to ASME B16.1 a hydrostatic body test for a class 250 fitting - whose working pressure boundary at 32 to 150 degrees F is 400 psi – ought to be greater than 600 psi for the shell test (400 x 1.5). To pass the test, no indication of leakage or material deformation should be observed.

Most PICV's on the market today have a body rating of ANSI 125# (even PN16) and above. But, body rating tells only part of the story, namely that the valve will not leak at operating pressures below say 175 psi. The real question is how well does the control valve perform at those pressure boundaries?

ii- Shut-off Capability

It may appear common sense to state that there is little sense in specifying a control valve whose body pressure rating goes up to is 27 bar when its stem plug can only throttle at pressures no greater than 4 bar. However, a quick review of the industry reveals that many PICV manufacturers do exactly that. Many state the body pressure rating as a proxy for the valves ability to operate at the same rating. As argued in section III, a control valve is only as useful as its weakest performance point and most PICV manufacturers do not design their unit with actuation abilities that are commensurate with the valve body pressure.

To understand whether a control valve will even throttle in a particular application, its shut-off data must be clearly stated. Ideally the shut-off capabilities must closely match its body pressure rating. Moreover, as discussed in section III, the designer must ensure that the actuator valve combination minimize dead band and maximize the response time. Control valves must be conceived with their actuator. Shut-off data must account for the valve's topology – balanced versus unbalanced as well as all friction losses that are inherent to the valve stem travel, types and quality of the packing.

In practice, shut-off issues for PICV's are more complex than for reciprocating two way control valves as the designing engineer must consider to parameters. The first is the electrical actuator – which was covered in section III. The second is the mechanically (pressure) actuated control component. Both elements have to properly respond to higher pressures. The PICV should be designed with some synergy in mind, so for an application in which the working pressure may be as high as 20 bar both a PN25 and / or ANSI 250# valve rating may be specified, however, it is imperative to specify the close-off pressures to be greater than 20 bar for both the electrical actuator as well as the spring and diaphragm (plate) of the DPCV component. This point presents a major hurdle for PICV's with internal spring and plate (diaphragm) design, to see why our attention must turn the third and final pressure consideration.

iii- Differential Pressure Ratings

Simply put, differential pressure is the upstream pressure minus the downstream pressure across a valve in a given operating condition. In a closed loop setup, such as chilled water distribution networks, high differential pressures across a given control valve are observed when the valve's plug (or disc) is hovering close to its seat over a sustained period of time.

For a two way control valve, sustained high differential pressure ratings typically erode the valve's seat, affecting the valves leakage performance at first and impacting its overall performance on a longer term. However, since by definition the control valve component of a PICV is upper bounded by the differential pressure setting of the DPCV component, which is usually set at 5 psi (.34 bar), then differential pressure ratings seems moot when considering the control valve component of the PICV. Rather, pressure differential considerations must be shifted to the DPCV component, which will have to "absorb" the remaining balance.

When is the DPCV component subjected to high differential pressures? Typically when the electrically actuated control valve component is open and the ΔP across the control valve is large enough to cause the DPCV to throttle downward. If the control valve is properly selected, then this situation will occur when the ΔT requirement is met and the flow is greater than the required flow.

The flow differential boundaries of the DPCV component are limited by:

- The seat differential pressure upper bound rating – which can go up to 100 psi (6.9 bar) for bronze trims and up to 150 psi (10.4 bar) for stainless Steel, <u>and</u>
- The spring and diaphragm (plate) pressure boundaries.

For most PICV's, the flow differential pressure limitation are driven by the pressure limitation of the spring and diaphragm assembly. In low pressure applications the DPCV component must be build to withstand differential pressure of up to 90 psi (6 bar) while in medium pressure applications the DPCV component must withstand up to 150 psi (10 bar). In high pressure applications (operating pressures > 25 bar) the minimum operating differential pressure must not drop below 15 bar and ideally should go as high 25 bar.

With externally actuated direct acting DPCV's the above discussion is tantamount to insuring that

1. The actuator is capable Handling the static pressure
2. The actuator can shut-off at the operating pressures
3. The valve seat can withstand the differential pressures.

Internally balanced DPCV's, on the other hand, are more challenging as the springs and plate are actually driven by the flow. So at high differential pressures the spring motion is compromised. The trade-off then would be in either using a high tension springs which negatively impact the unit's sensitivity or using a low tension springs whose performance is greatly deteriorated at higher pressures.

So how well do most PICV's fare? A quick survey suggest that few PICV's are capable of operating at pressure boundaries – where the required shut-off pressures <u>and</u> the required differential pressure boundaries – are greater than 145 psi (10 bar).

Table 5

<table>
<tr><th colspan="5">Pressure Ratings</th></tr>
<tr><th></th><th>Brand A</th><th>Brand B</th><th>Brand C</th><th>Warren Controls</th></tr>
<tr><td colspan="5"><u>Body Pressure Rating</u></td></tr>
<tr><td>Standard Pressure Model</td><td rowspan="2">27 bar</td><td>10.4 bar</td><td>16 bar (PN 16)</td><td>12 bar (ANSI 125#)</td></tr>
<tr><td>High Pressure Model</td><td>20.7 bar</td><td>25 bar (PN 25)</td><td>27.5 bar (ANSI 250#)</td></tr>
<tr><td colspan="5"><u>Maximum Operating Pressure (Shut-off capability)</u></td></tr>
<tr><td>Electric Actuator Standard Shut-off</td><td>Not Specified</td><td>Depends On the Actuator</td><td>Depends On the Actuator</td><td>12 bar</td></tr>
<tr><td>Electric Actuator High Pressure Shut-off</td><td>n/a</td><td>Depends On the Actuator</td><td>Depends On the Actuator</td><td>27.5 bar</td></tr>
<tr><td>Mechanical Actuator Standard Pressure Shut-off</td><td>Not Specified</td><td>Not Specified</td><td>Not Specified</td><td>10.3 bar</td></tr>
<tr><td>Mechanical Actuator High Pressure Shut-off</td><td>n/a</td><td>Not Specified</td><td>Not Specified</td><td>20.7 bar</td></tr>
<tr><td colspan="5"><u>Maximum Differential Pressure</u></td></tr>
<tr><td>Standard Pressure Model</td><td>4 bar</td><td>4.8</td><td rowspan="2">Insufficient Info</td><td>10.3 bar</td></tr>
<tr><td>High Pressure Model</td><td>n/a</td><td>6.2</td><td>Custom</td></tr>
</table>

c. **Third Order of Business: Determining the required differential pressures setting of the DPCV across the control valve**

As mentioned earlier one of the greatest advantages of externally actuated DPCV's is the ability to amend pressure differential setting over the control valve component. The ideal setting should be equal to the pressure drop across the control valve at fully open and under full flow conditions. Hence the importance of sizing the control valves appropriately. Undersized control valves would often mean pressure setting capabilities on the DPCV that are outside the typical ranges encountered in the field, i.e. 3 – 6 psi (0.2 – 0.4 bar). It is interesting to point, that the [0.2; 0.4] range signifies authority ratios in the range of 35% to 60% over the PICV unit (20% to 35% when considering the control valve element alone.

VI. Conclusion

PICV's objective is no different than traditional two way control valves. Their main role is to reduce process variability and maximize efficiency. In large network with several control elements and components pressure changes increase process variances, pressure independent control valves (PICV's) are a viable solution to this problem, however just like any control valve, PICV's must be engineered and sized with a good deal of rigor, otherwise they may become counterproductive within the process. This paper has hoped to give the designing engineer an insight on the issues facing the building automation industry in general when dealing with PICV. As a general rule of thumb and just as in plain control valves, a PICV is as good as its weakest design feature, and many of the PICV commercially available on the market have inherent weaknesses from a control perspective. Special attention must be given to the quality of the valve(s), actuator(s) and the ability of the PICV to perform its job under the ever increasing performance requirements.

PICV's are bound to evolve in the near to medium future adding new features and improve performance characteristics, driven by an increasing focus on efficiency and advancement in control technologies. An embodiment of such advancements can be seen in some of the industrial electrical actuators which have yet to make their way into the building automation industry. As discussed in the paper, actuators are becoming faster, more accurate and more intelligent.

References:

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2- Spirax Sarco, SC-GCM CM Issue 1, Block B, Module 6.3: Control Valve Sizing for Water System, 2005
3- Emerson Process Management, Control Valve Handbook, fourth edition, 2005
4- The Engineering Tool Box, Valve Authority, http://www.engineeringtoolbox.com

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About the Authors:

Mr. Alameddine has an MA in mathematical economics from the University of Pittsburgh. He has been designing and promoting integrated industrial spraying systems solutions as well as control valve solutions for over 16 years.

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Appendix A – Glossary

F_L - Liquid Pressure Recovery Factor: a measure of the valve's ability to convert the kinetic energy of the fluid at the vena contracta back into pressure. The internal geometry of the valve determines the value of F_L. High F_L's usually lead to higher probabilities of cavitation.

Rangeability Ratio: The ratio of the largest flow coefficient to the smallest flow coefficient in which the deviation from the specified inherent flow characteristics does not exceed the limits stated in *ISA 75.11*. Inherent rangeability is an indication of how well the valve control the effective orifice created by the closure member-to-stroke curve.

This ratio is a useful tool for making an initial selection however, it does not consider the accuracy of the positioner/linkage, the instabilities of the process fluid, the inability to control areas near the seat and the changing pressure drop with flow rate. A more meaningful definition of rangeability recognizes the variation in pressure drop and is expressed as the ratio of maximum Cv (at minimum pressure drop) to minimum Cv (at maximum pressure drop). Rangeability can vary when this definition is applied.

Table 6

Valve Type	Inherent Characteristic	Rangeability	Pressure Recovery Factor - F_L*
Reciprocating Globe	Equal Percentage, Linear and Fast Op.	30:1 to 50:1	0.8 to 0.9
Eccentric Rotary	Linear and Modified Linear	100:1	0.55 to 0.6
Ball – Standard Bore	Linear	20:1	0.55 to 0.6
Butterfly 60° Open	Linear and Modified Linear	20:1	0.3 to 0.7
Butterfly 90° Open	Linear	20:1	0.55

*: High F_L values signify lower cavitation risks

Dead Band: The range through which an input signal can be varied, upon reversal of direction, without initiating an observable change in the output signal. Dead band is the name given to a general phenomenon that can apply to any device. For the valve assembly, the controller output (CO) is the input to the valve assembly and the process variable (PV) is the output. When the term Dead Band is used, it is essential that both the input and output variables are identified, and that any tests to measure dead band be under fully loaded conditions.

Dead Time: The time interval in which no response of the system is detected following a small (usually 0.25% - 5%) step input. It is measured from the time the step input is initiated to the first detectable response of the system being tested. Dead Time can apply to a valve assembly or to the entire process.

Process Variability: A precise statistical measure of how tightly the process is being controlled about the set point. Process variability is defined in percent as typically (2s/m), where m is the set point or mean value of the measured process variable and s is the standard deviation of the process variable.

Response Time: Usually measured by a parameter that includes both dead time and time constant. When applied to the valve, it includes the entire valve assembly.