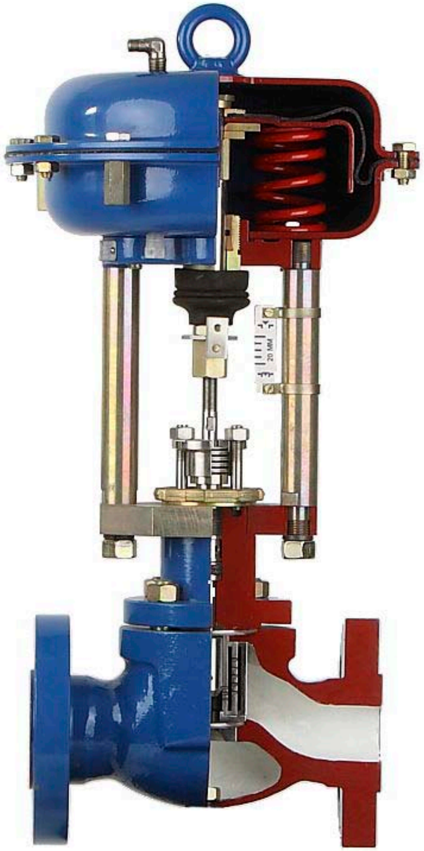
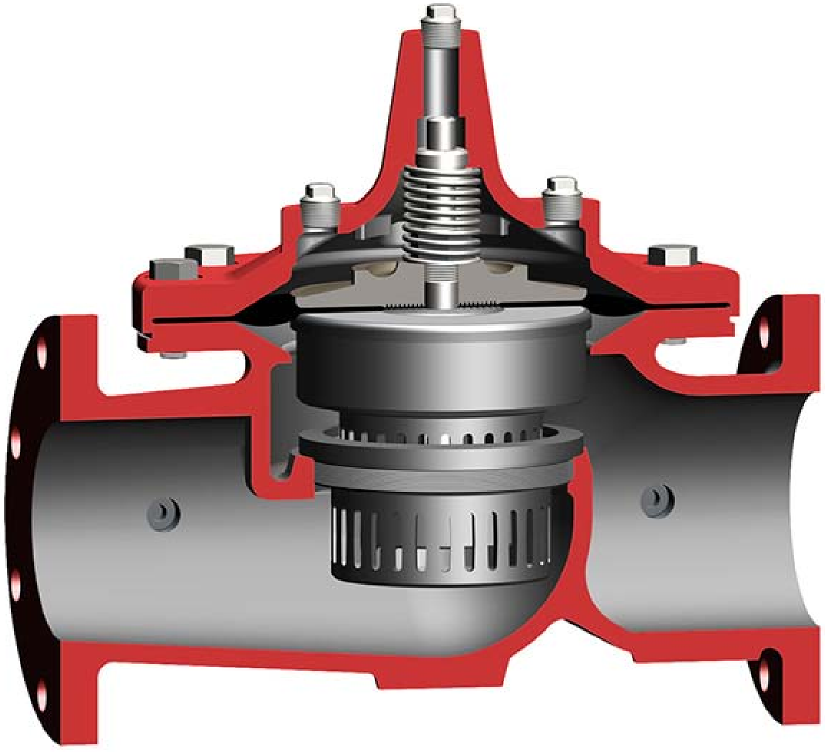
Control Valve





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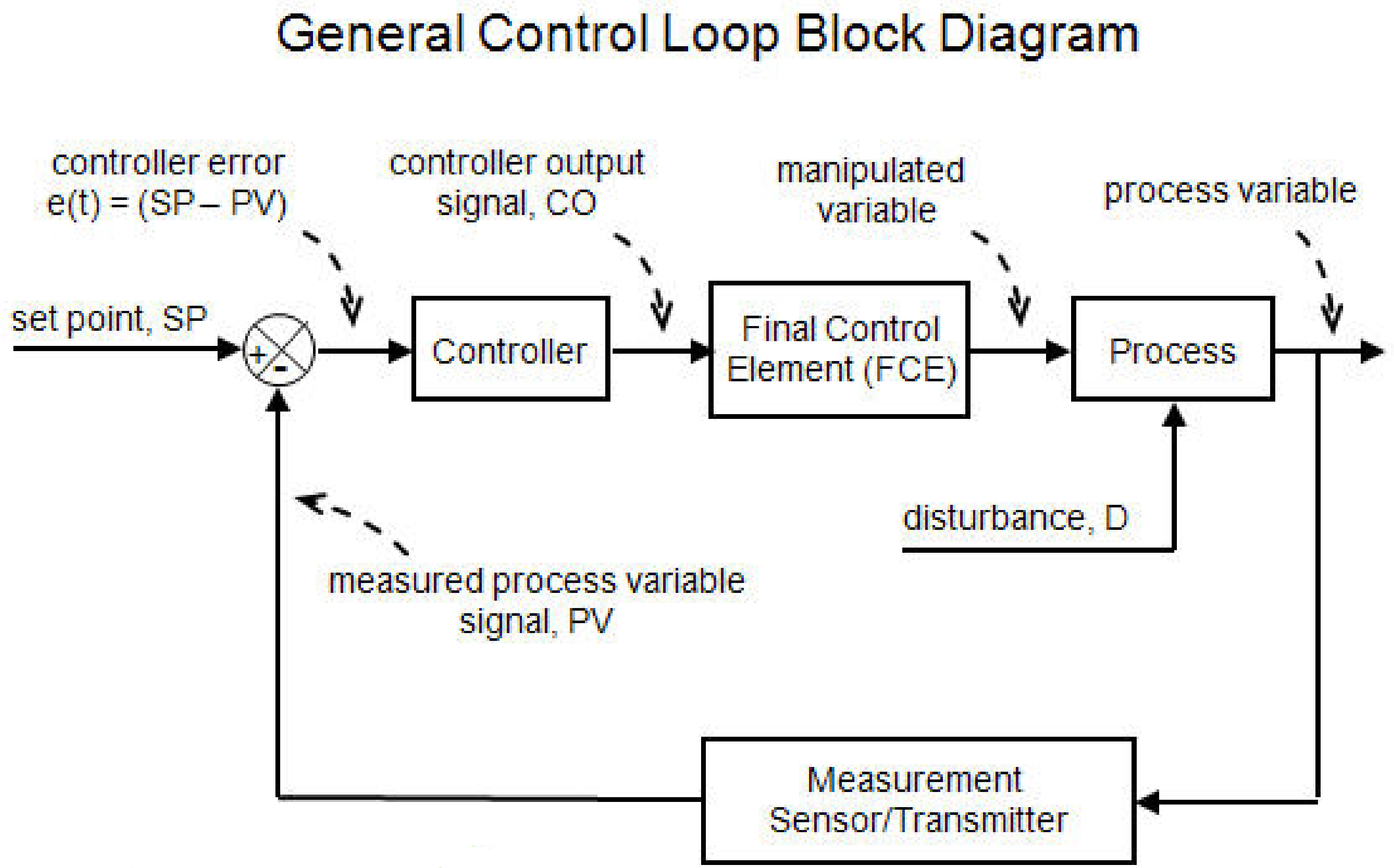
Control Valve



Control Valve

Final Control Elements (FCE):

- The common energy source of final control elements are:
  - Electric
  - Hydraulic
  - Pneumatic

- Electric :
  - Electric Heater, Thyristor Bridge
  - Solenoid
  - Stepping Motor
  - DC Motor
  - AC Motor

Control Valve

- The control valve manipulates a flowing fluid, such as gas, steam, water, or chemical compounds, to compensate the disturbance occurs in the process and keep the process variable as close as possible to the desired set point.

- A "control valve" regulates the flow of fluid through a pipe in response to the signal from a loop controller or logic device.

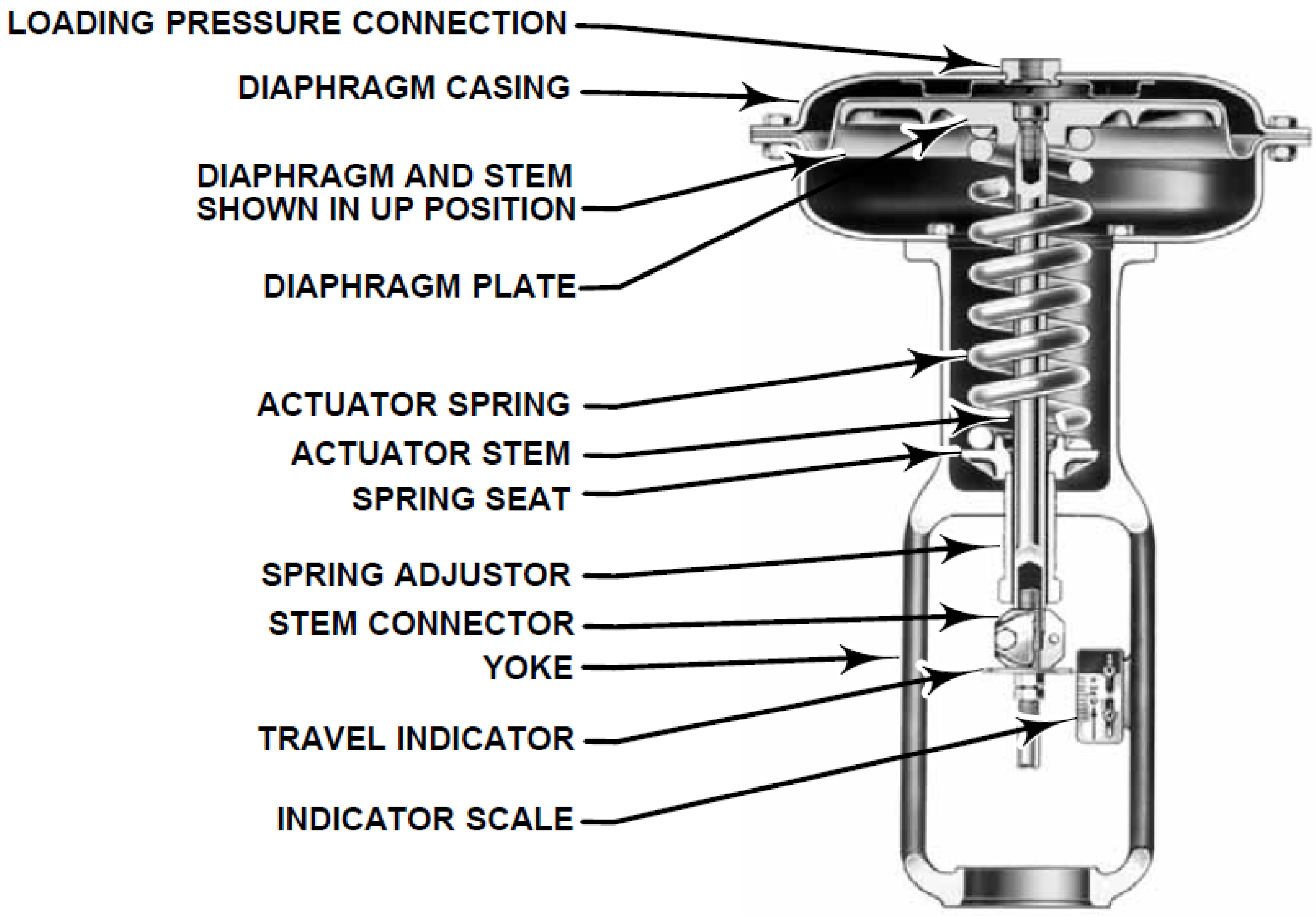
Control Valve- Constructional Parts

Control valves are comprised of two major parts:

- The Valve Actuator, which provides the mechanical power necessary to move the components within the valve body.

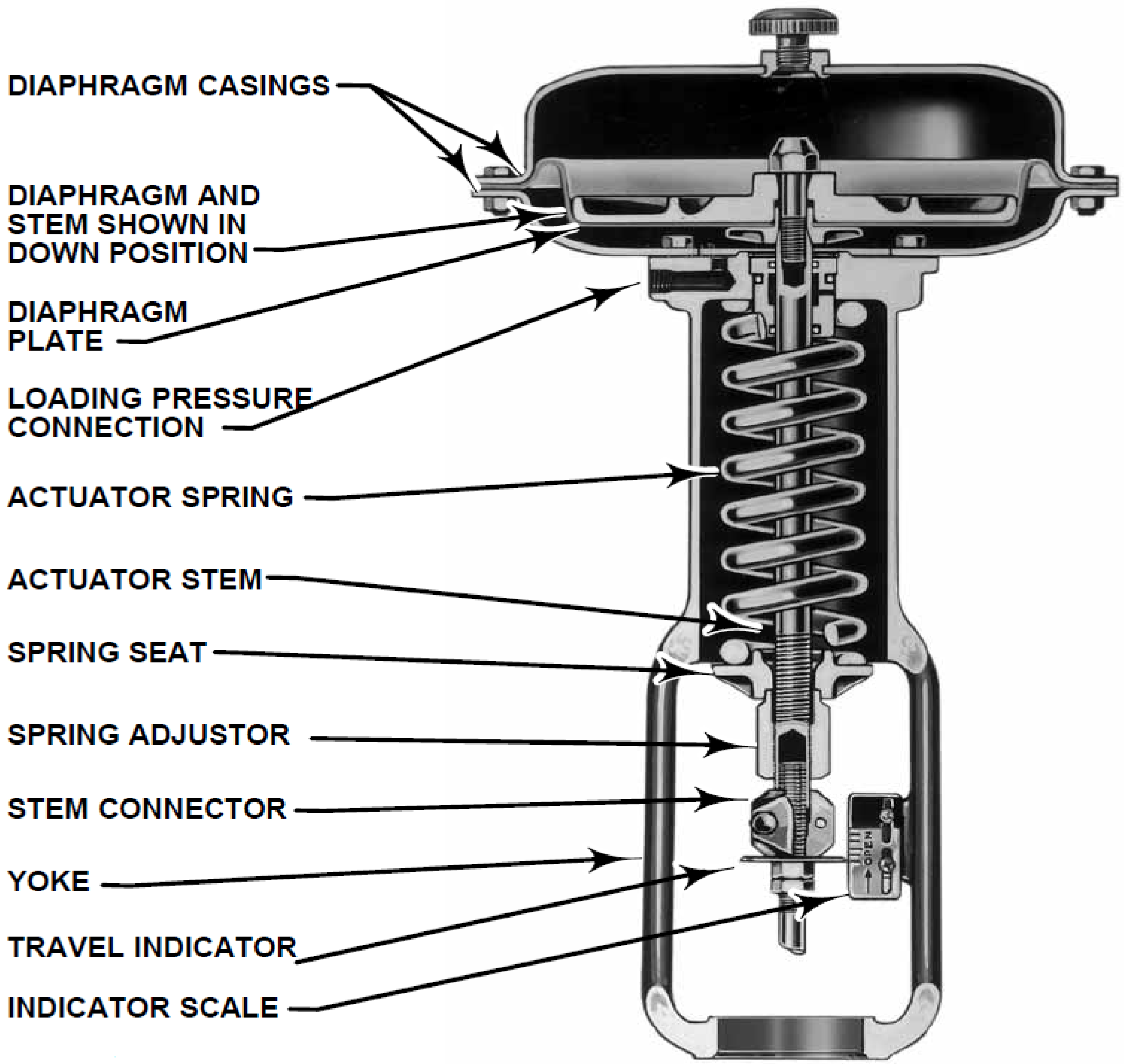
- The Valve Body, which contains all the mechanical components necessary to influence fluid flow.

Major Components of Control Valve



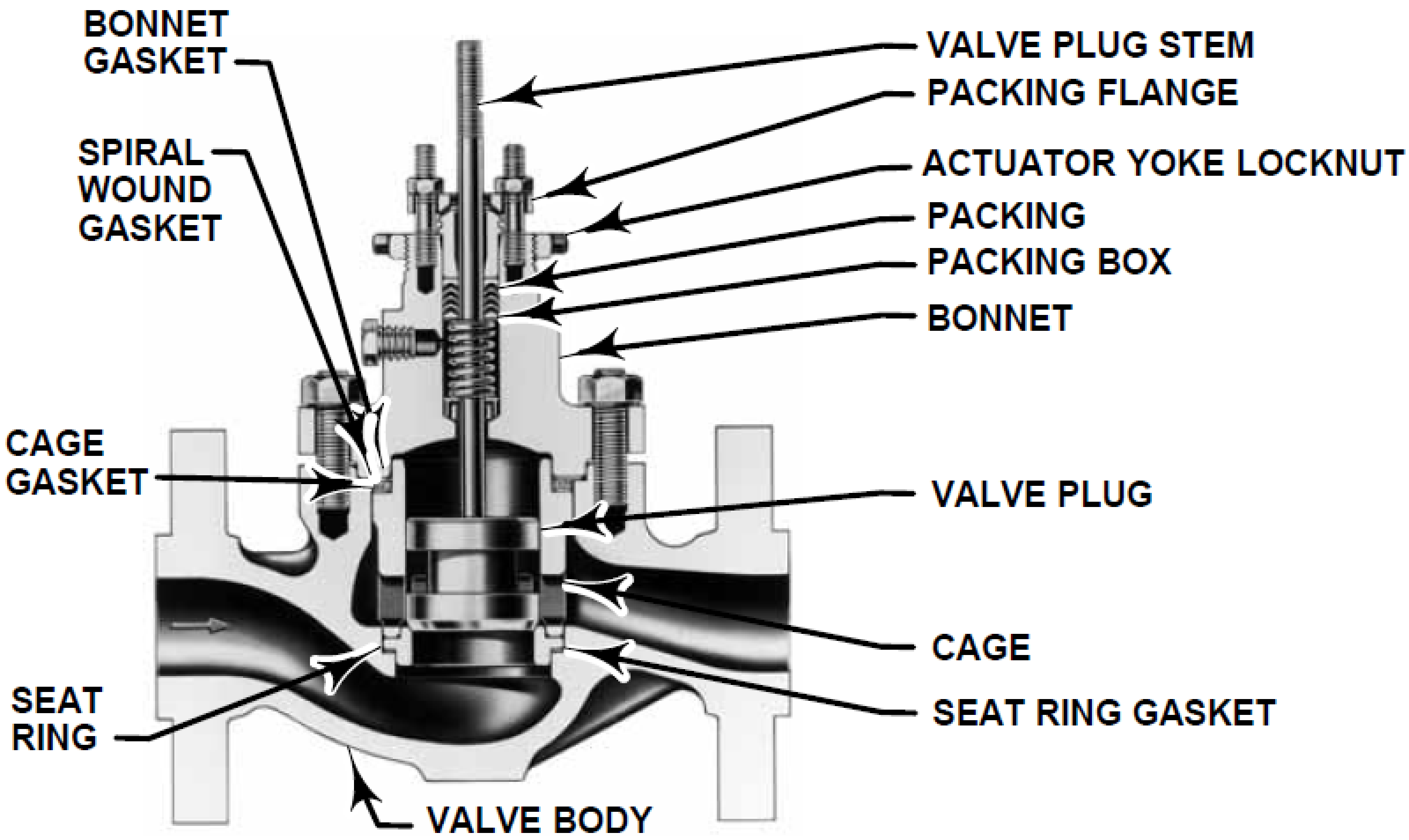
Direct Acting Actuator: A diaphragm actuator in which the actuator stem moves down with increasing diaphragm pressure.

Major Components of Control Valve



Reverse Acting Actuator: A diaphragm actuator in which the actuator stem moves up with increasing diaphragm pressure.

Major Components of Control Valve



Control Valve

The control valve assembly typically consists of

- the valve body,
- the internal trim parts,
- an actuator to provide the motive power to operate the valve,
- positioners,
- transducers,
- supply pressure regulators,
- manual operators,
- limit switches.

Control Valve - Trim

Within a control valve body, the specific components performing the work of throttling (or completely shutting off) of fluid flow are collectively referred to as the valve trim.

Control Valve

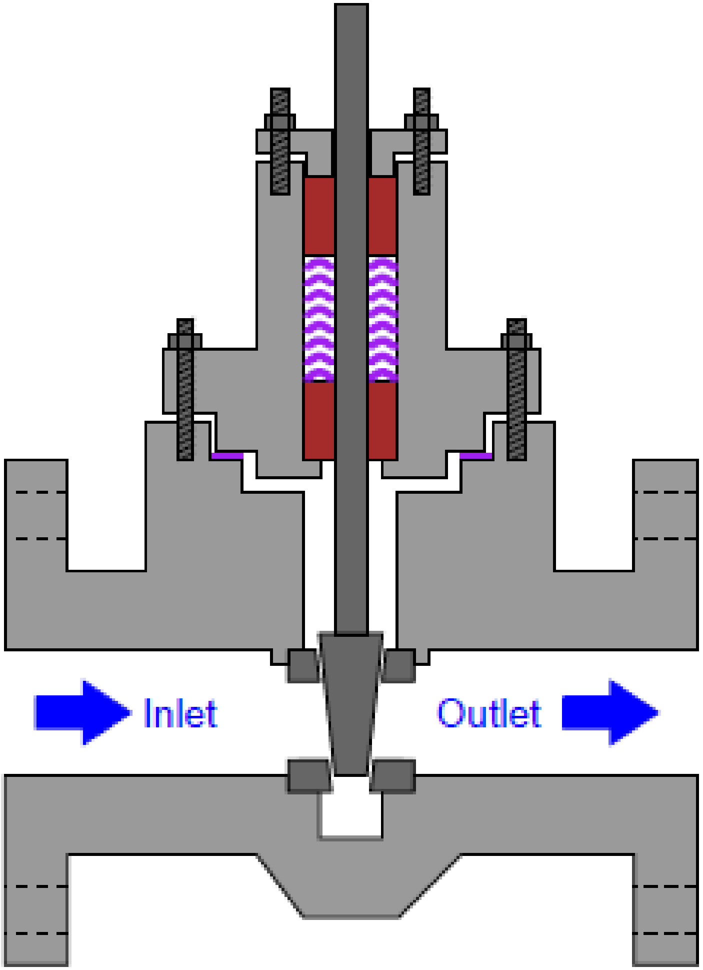
Valves can be broadly categorized based on their functions as:

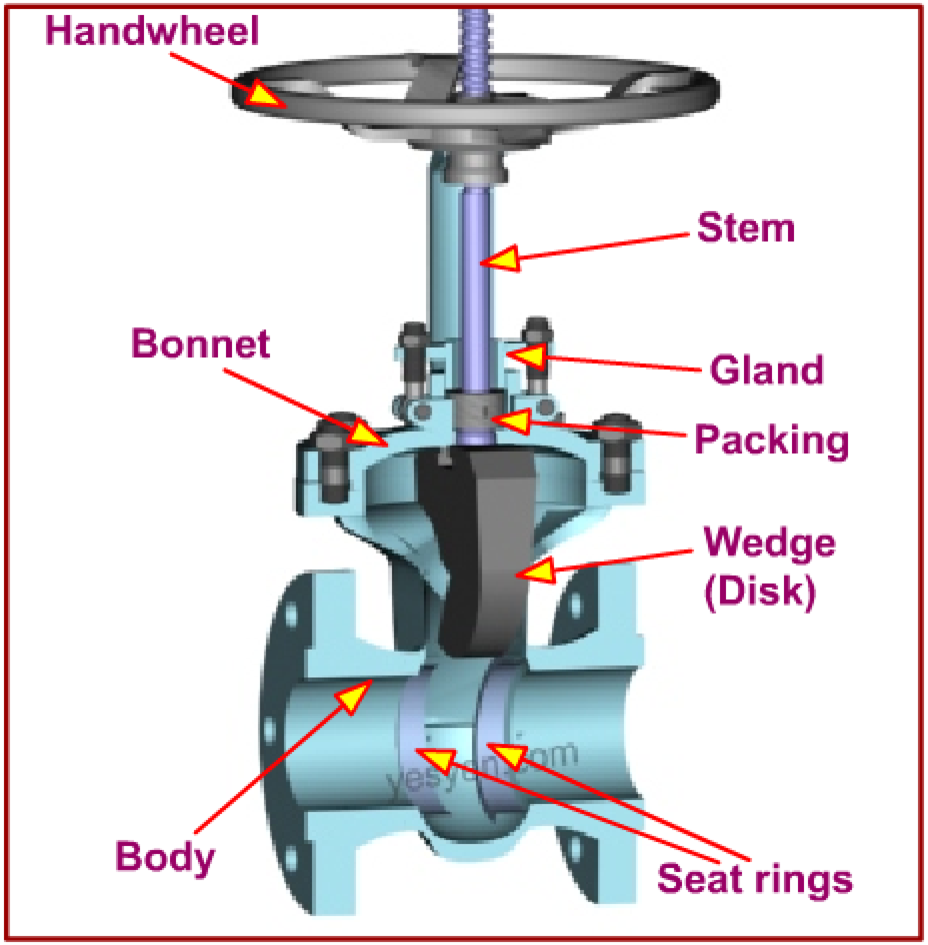
- Stop (Isolation) Valve
- Back Flow Prevention Valve (Check Valve)
- Pressure Relief Valve (Safety Valve)
- Regulating Valve

Types of Regulating Valves

- ✓ GATE VALVES
- ✓ GLOBE VALVES
- ✓ PLUG VALVES
- ✓ DIAPHRAGM VALVES
- ✓ BALL VALVES
- ✓ BUTTERFLY VALVES
- ✓ NEEDLE VALVES
- ✓ CHECK VALVES
- ✓ PRESSURE RELIEF VALVES

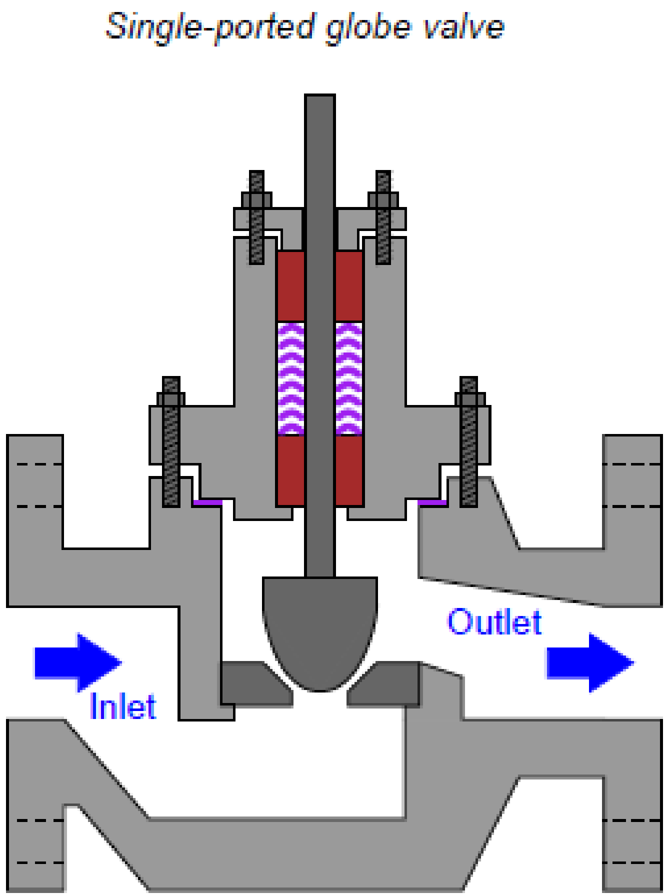
Gate Valves

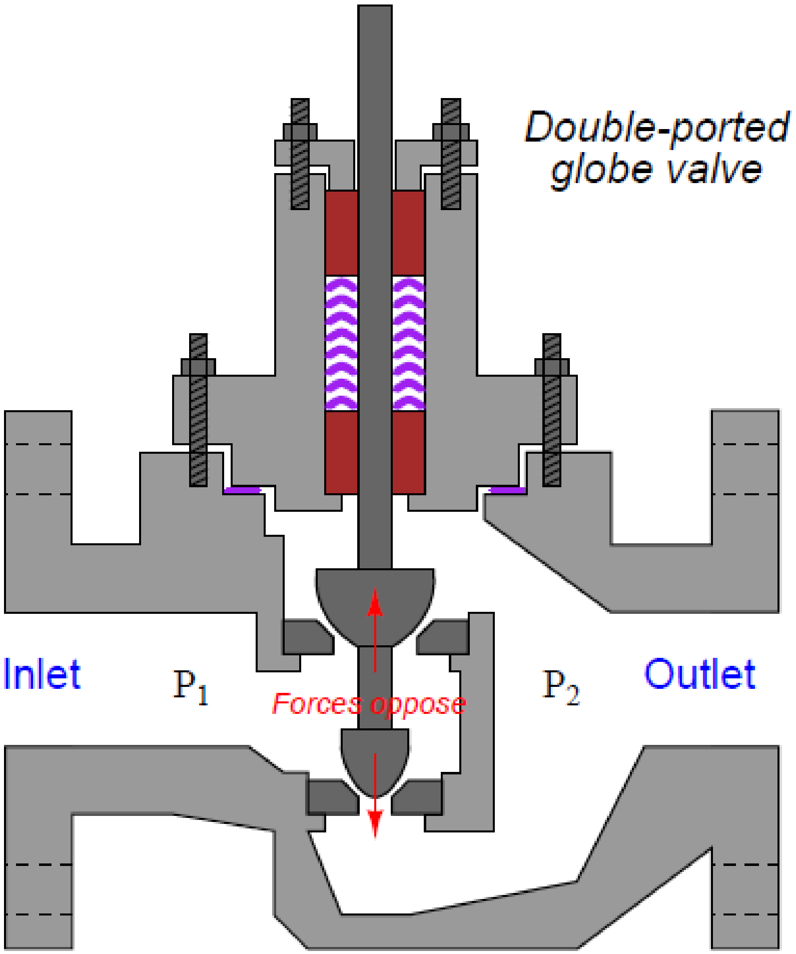




Commonly used as the Isolation Valve

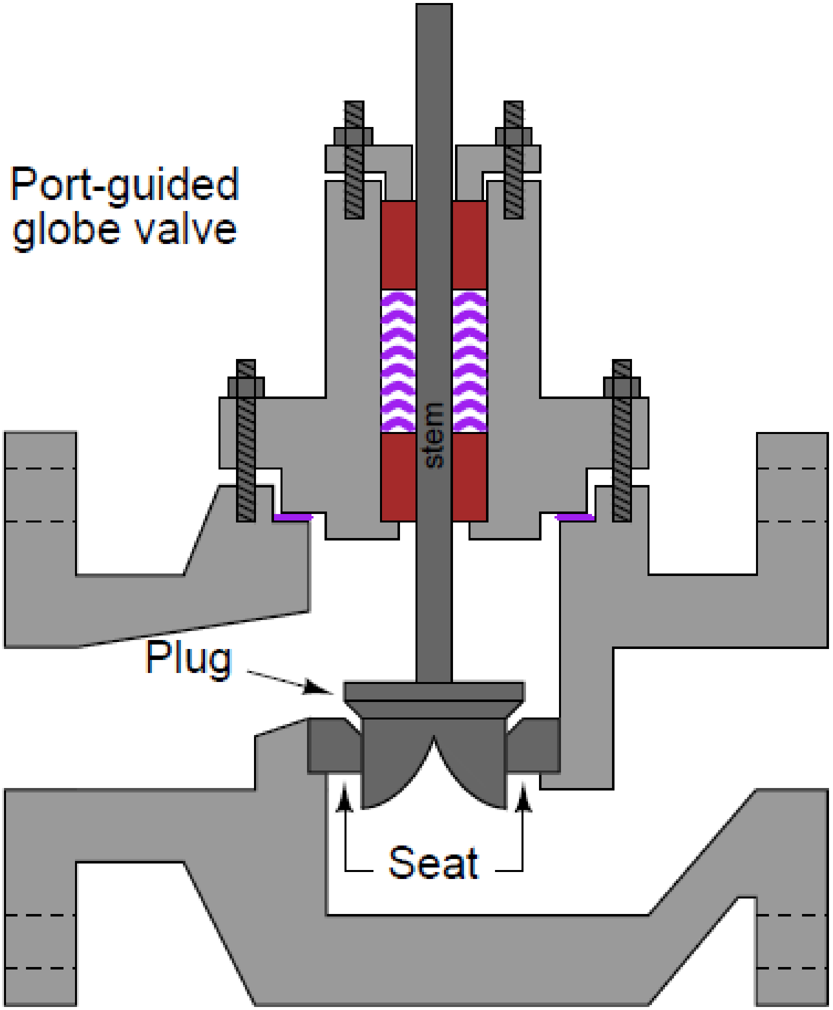
Globe Valves





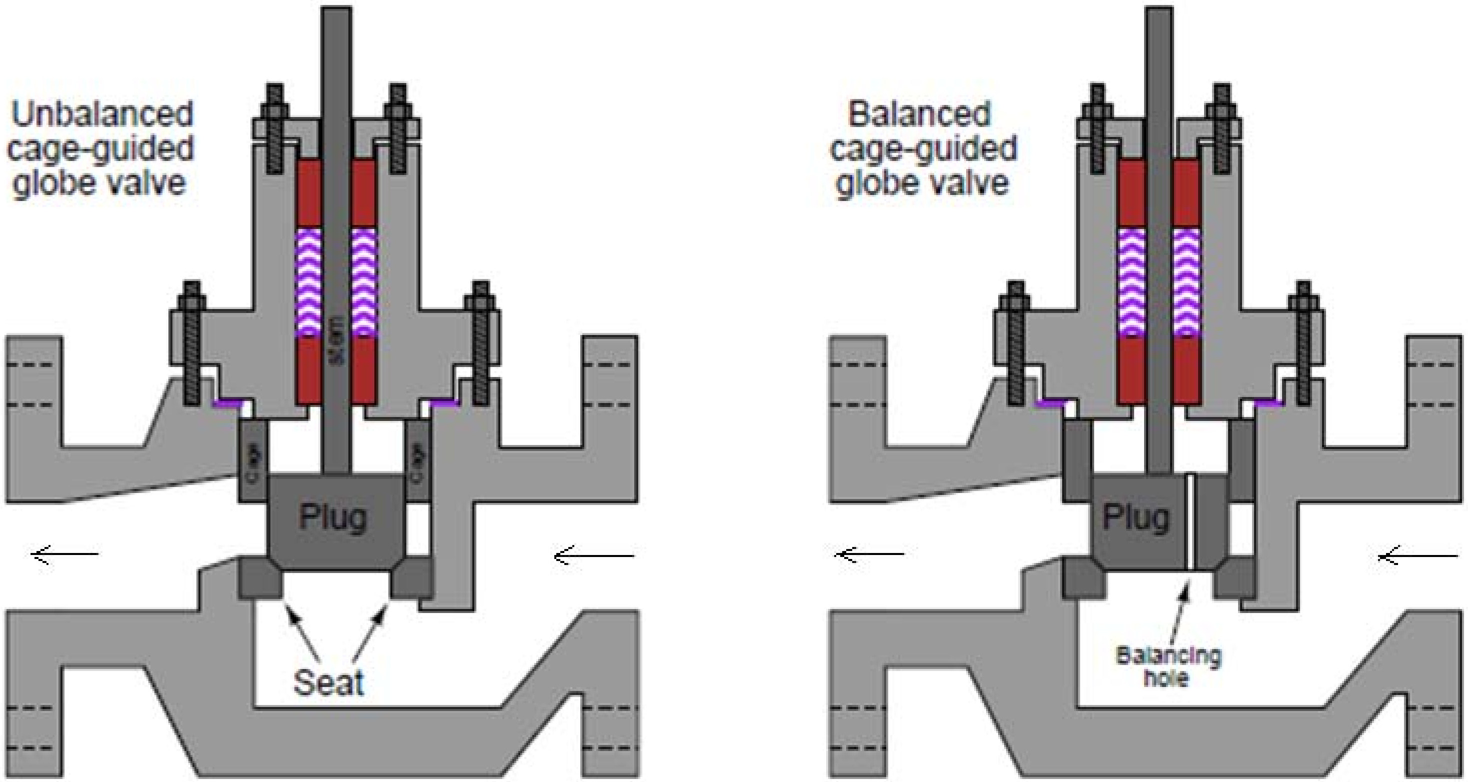
The flow in the valve takes a vertical path from down to top through the seat ring, allowing effective flow control with shorter plug travel .

Globe Valves



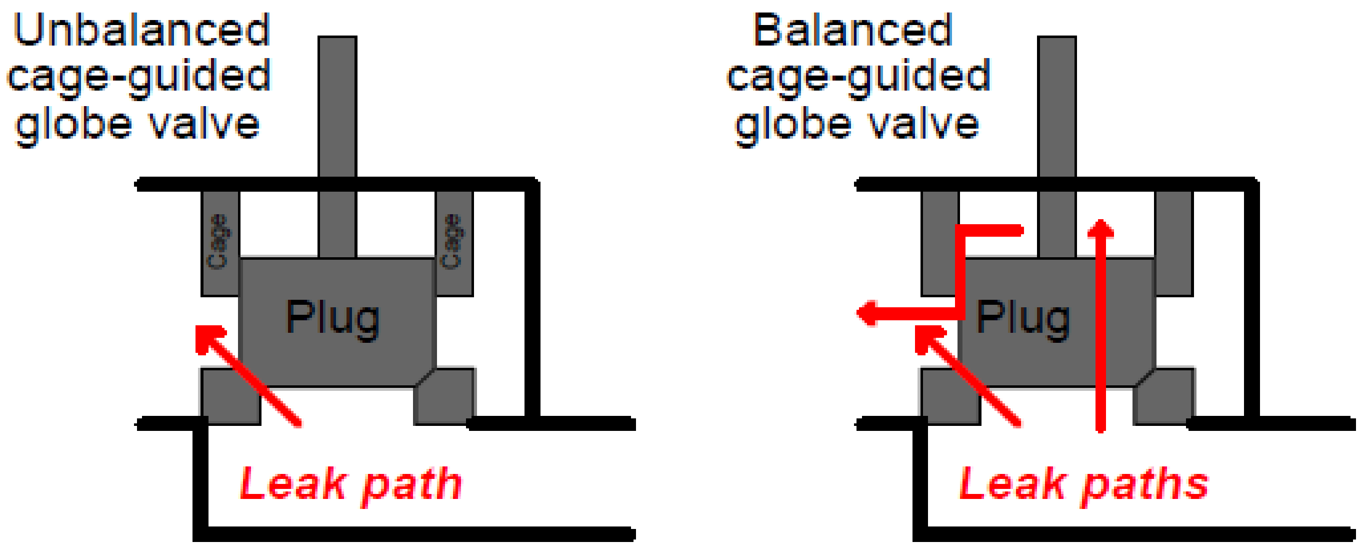
In the port-guided valve, the seat ring acts as a guide for the plug to keep the centerlines of the plug and seat always aligned, minimizing guiding stresses that would otherwise be placed on the stem. This means that the stem may be made smaller in diameter than if the valve trim were stem-guided, minimizing sliding friction and improving control behavior.

Globe Valves



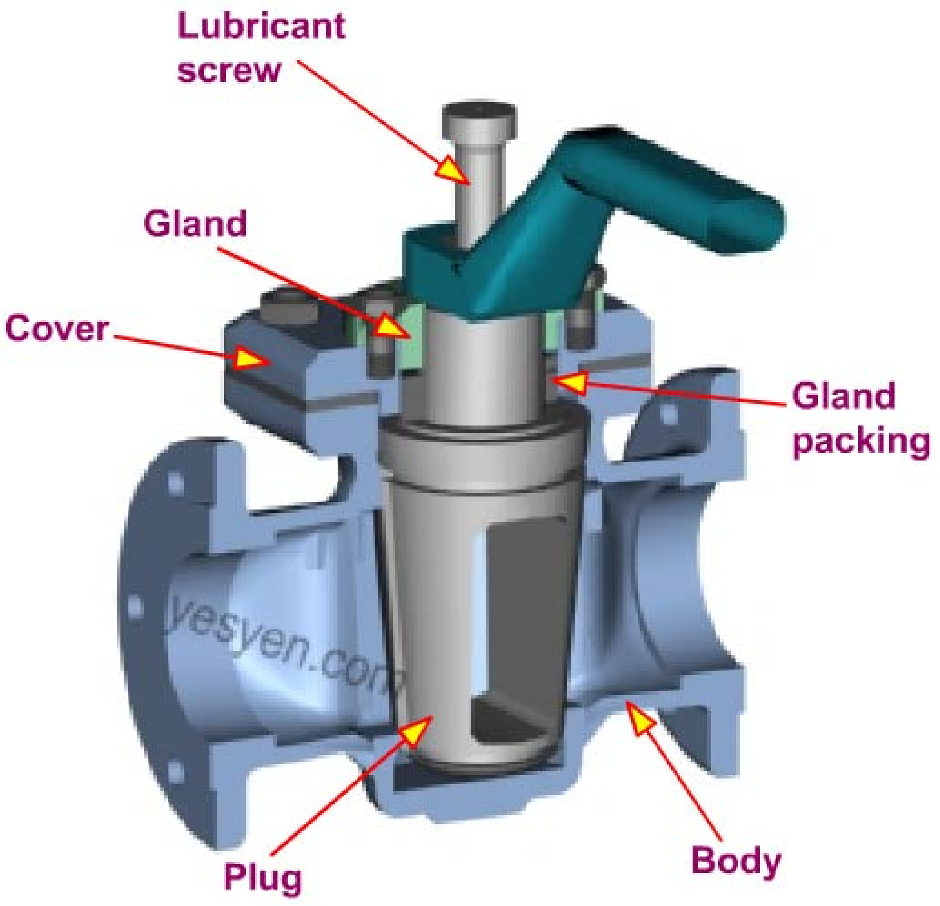
A balanced plug has one or more ports drilled from top to bottom, allowing fluid pressure to equalize on both sides of the plug. This helps minimize the forces acting on the plug which must be overcome by the actuator.

Globe Valves



Balanced and unbalanced cage-guided globe valves exhibit similar characteristics to double-ported and single-ported stem- or port-guided globe valves. Balanced cage-guided valves are easy to position, just like double-ported stem-guided and port-guided globe valves. However, balanced cage-guided valves tend to leak more when in the shut position due to a greater number of leak paths, much the same as with double-ported stem-guided and port-guided globe valves.

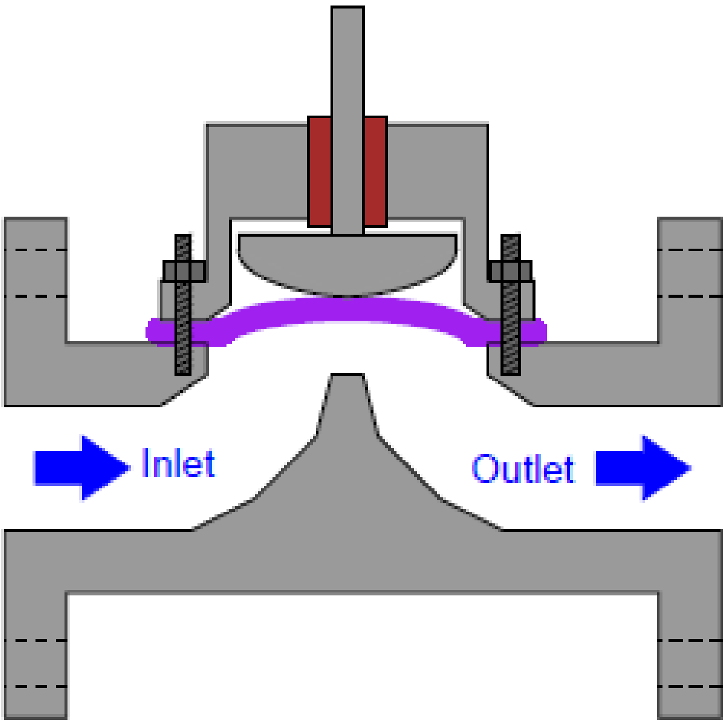
Plug Valves



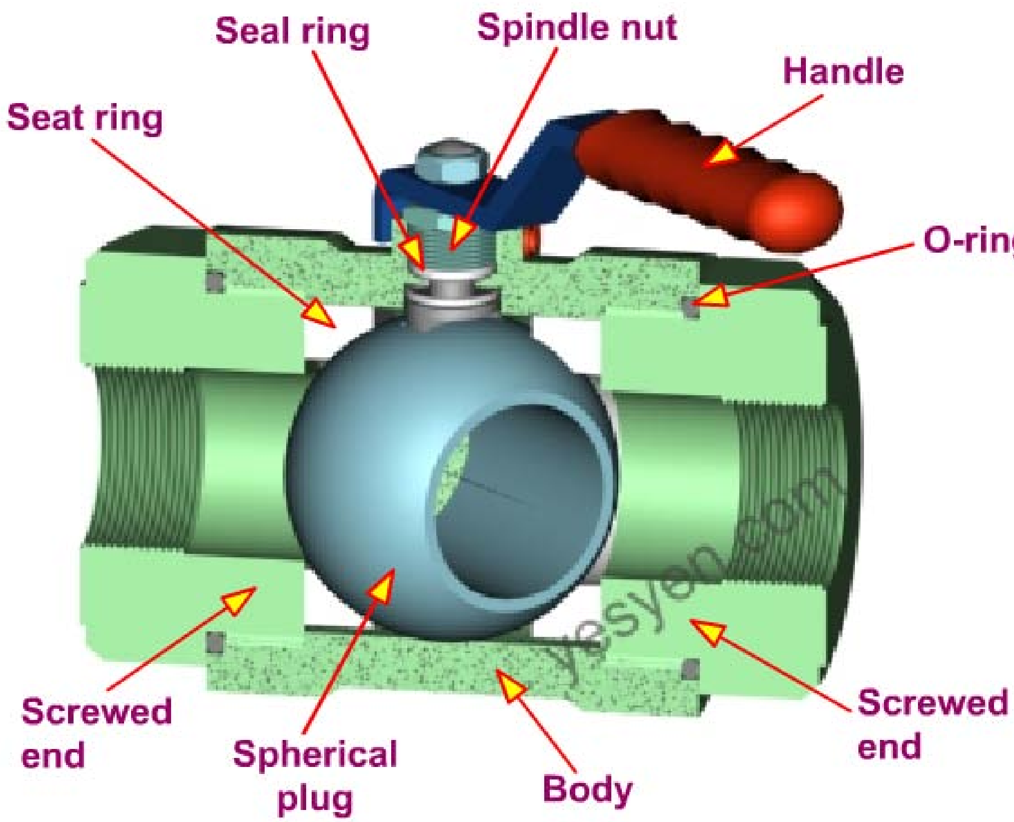
Lubricant screw
Gland
Cover
Gland packing
Plug
Body
yesyen.com

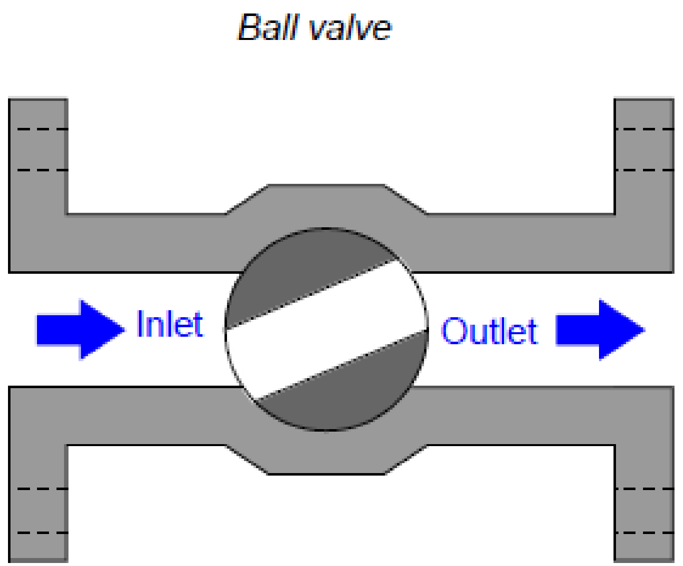
Diaphragm Valves

Diaphragm valve

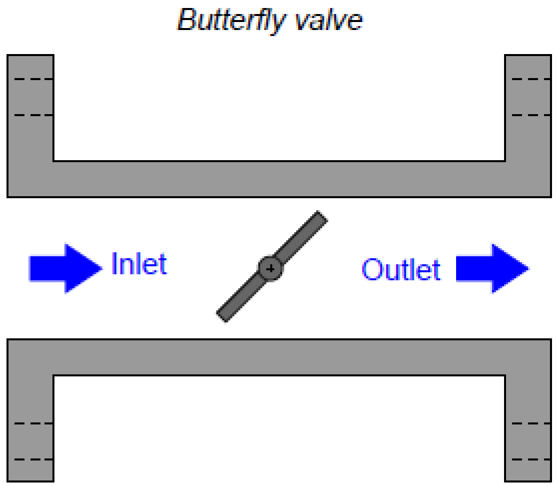


Ball Valves

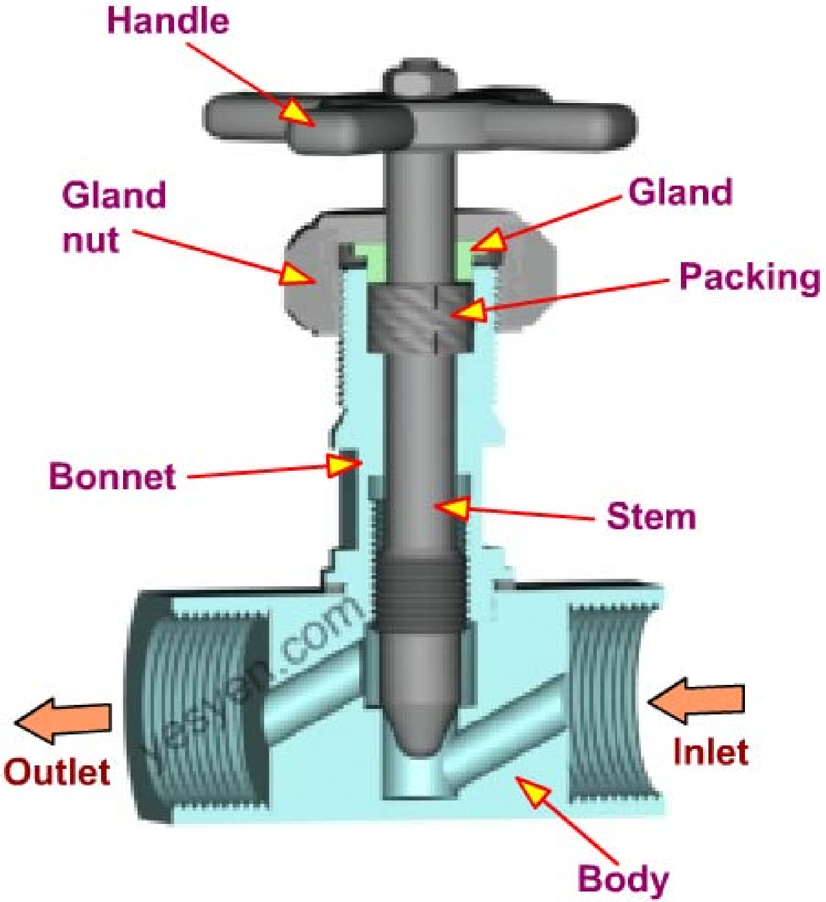

Seal ring
Spindle nut
Handle
Seat ring
O-rin
Screwed end
Spherical plug
Body
Screwed end
yesyen.com


Ball valve
Inlet
Outlet

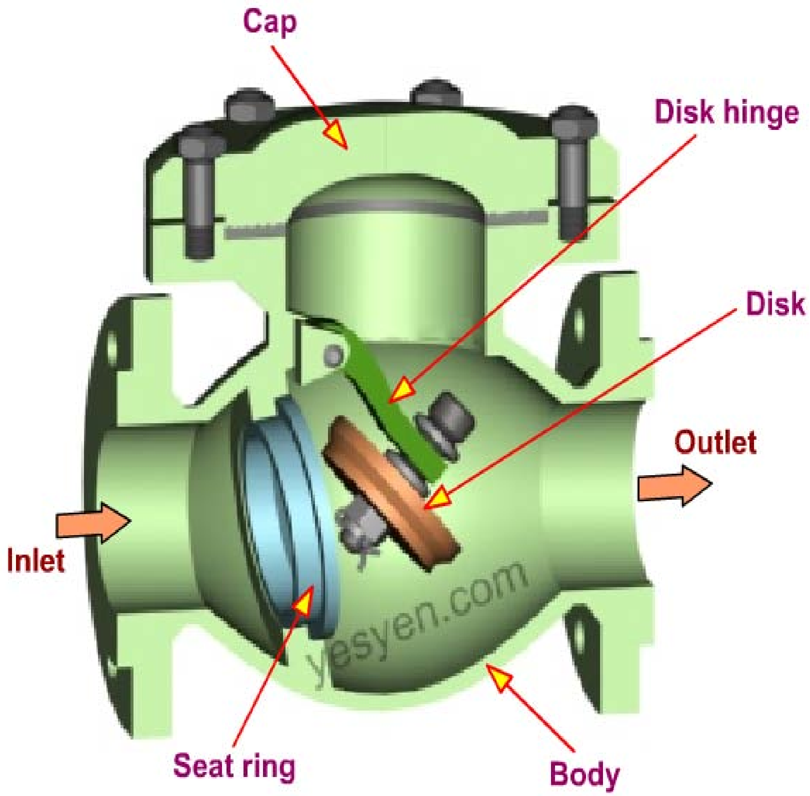
Butterfly Valves



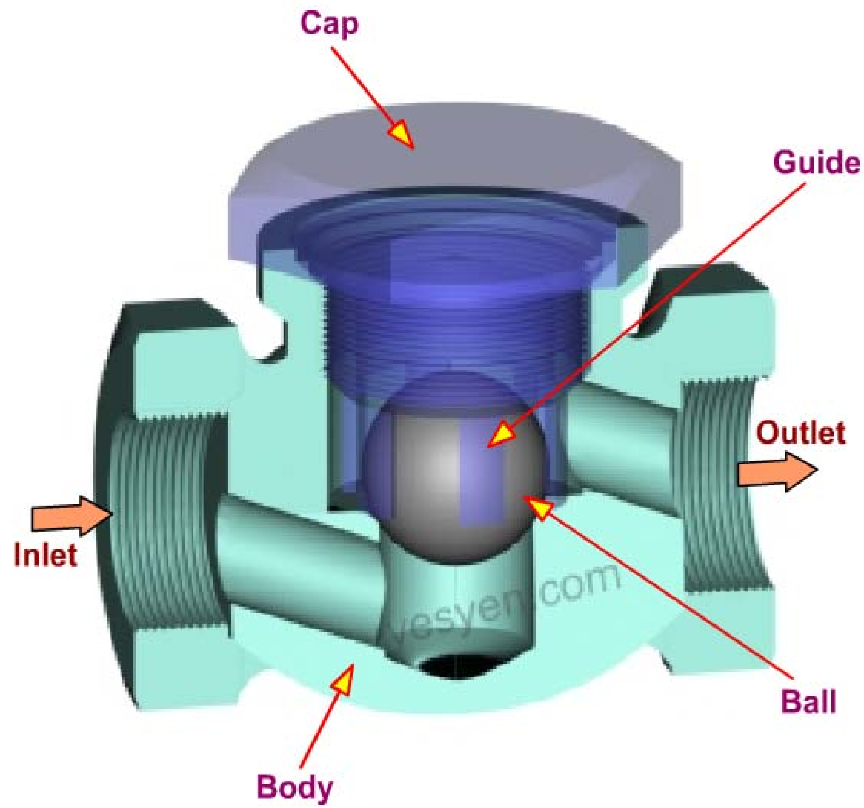
Niddle Valves



Check Valves



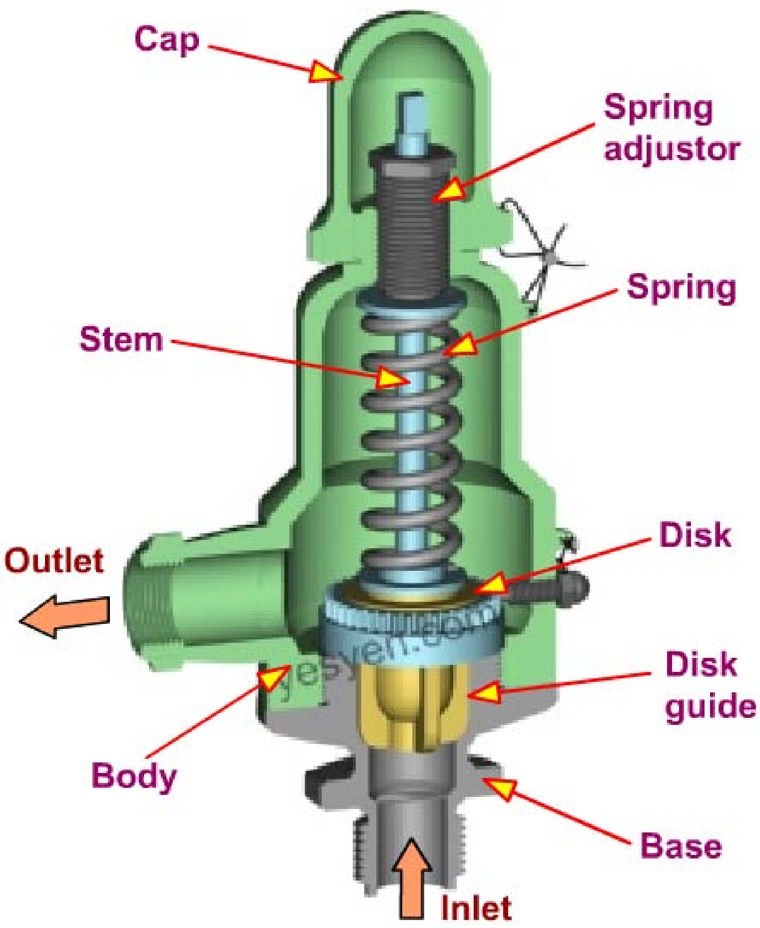
Swing Check Valve



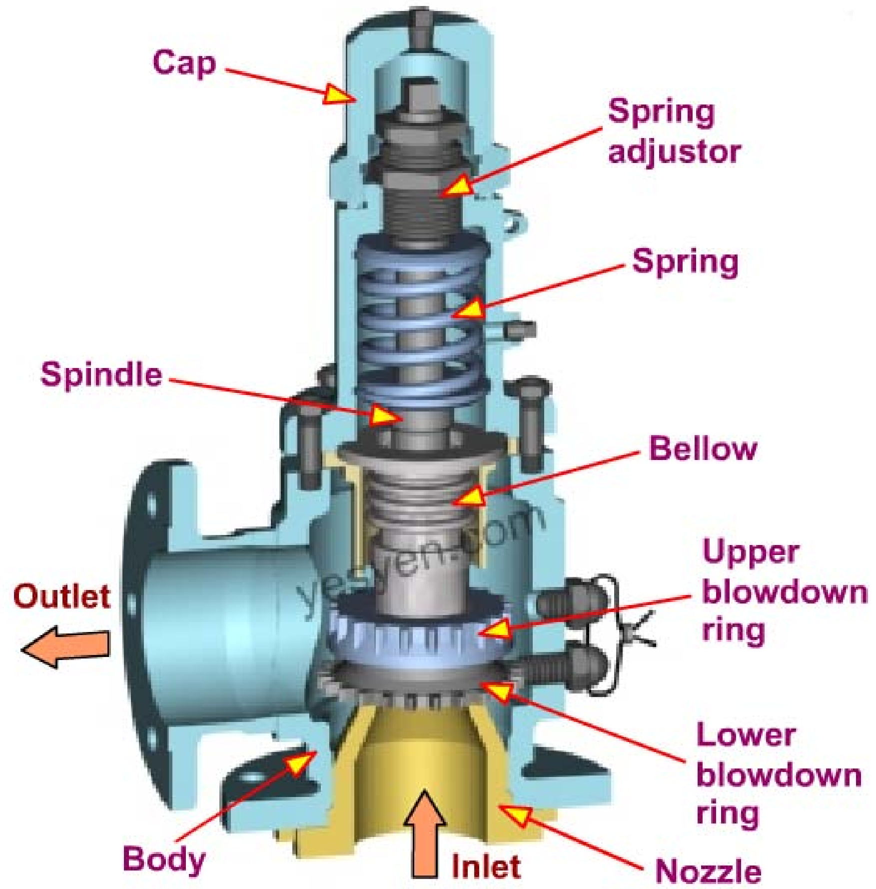
Ball Check Valve

Check valves are designed to prevent backflow of fluid in lines.

Pressure Relief Valves / Safety Valves

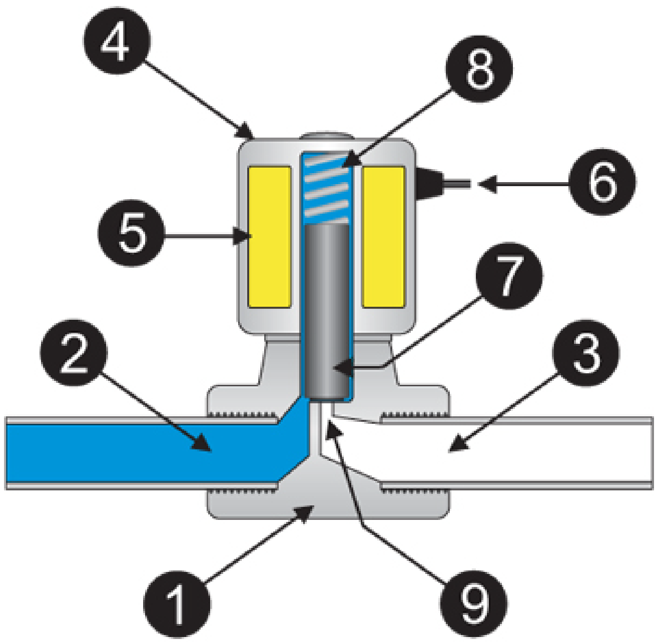


Relief Valves

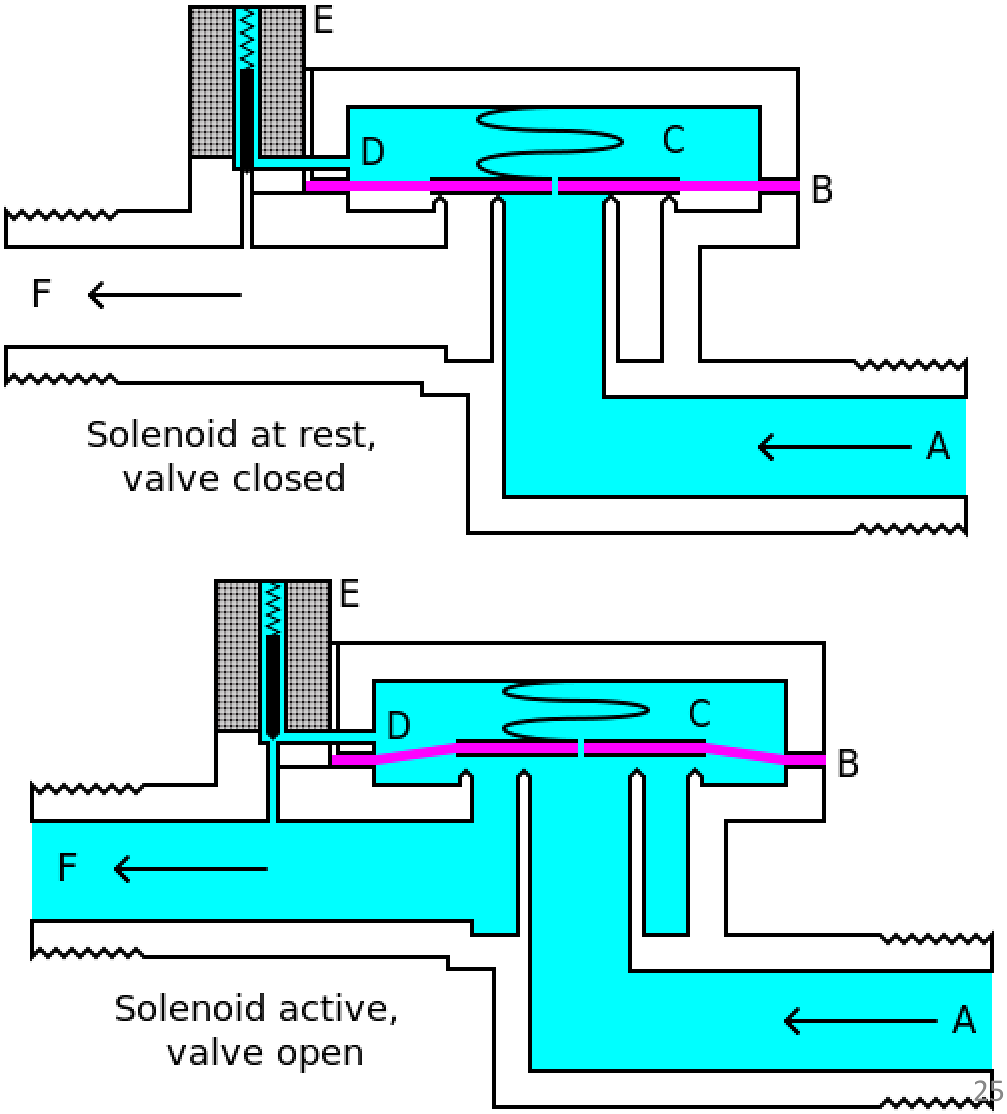


Safety Valves

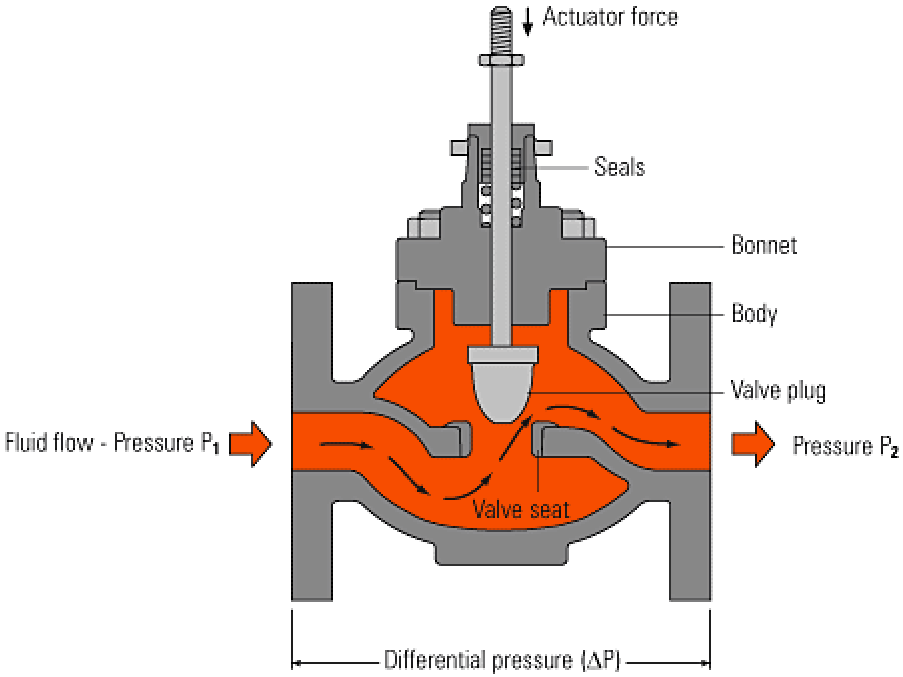
Solenoid Valves



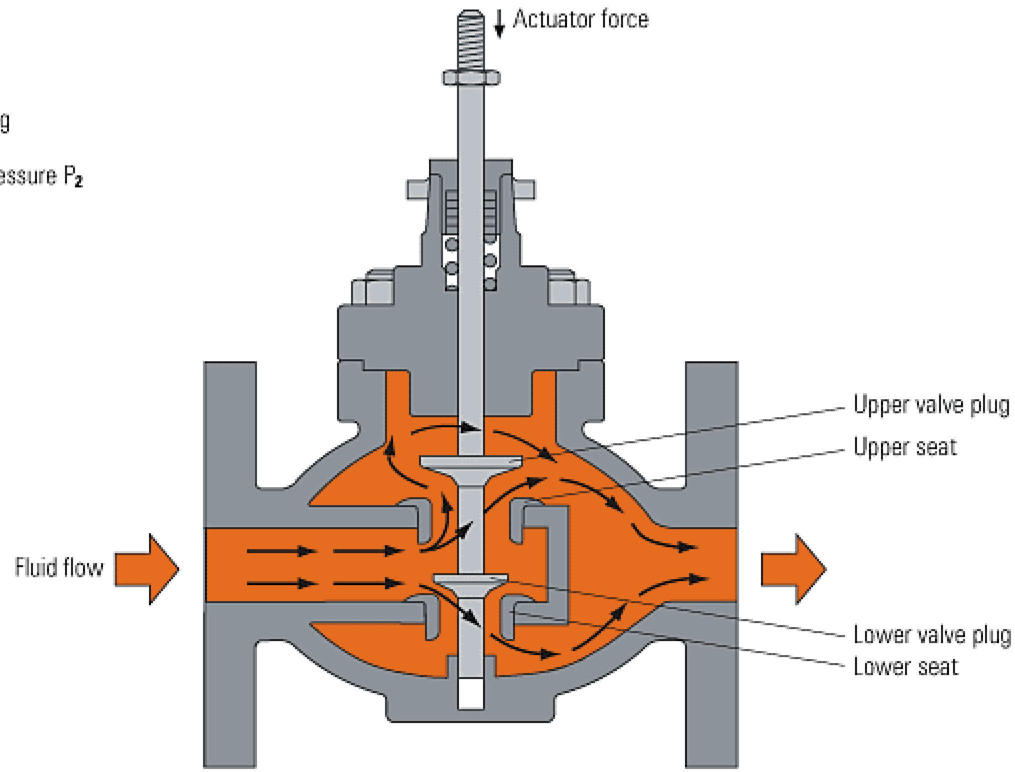
1. Valve Body
2. Inlet Port
3. Outlet Port
4. Coil / Solenoid
5. Coil Windings
6. Lead Wires
7. Plunger
8. Spring
9. Orifice



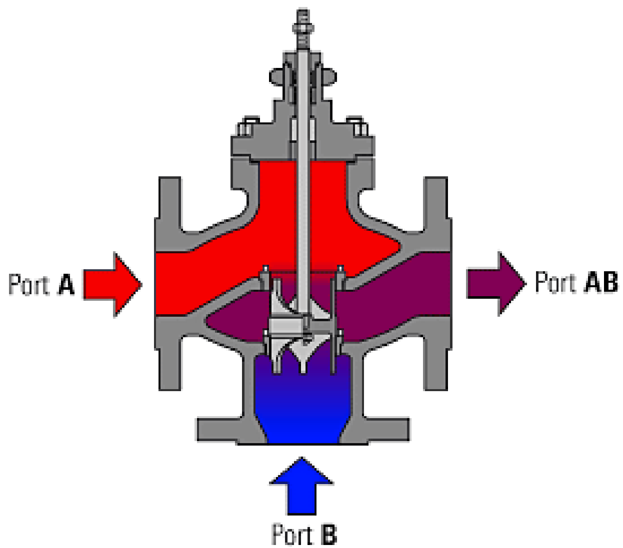
Two Port Valve



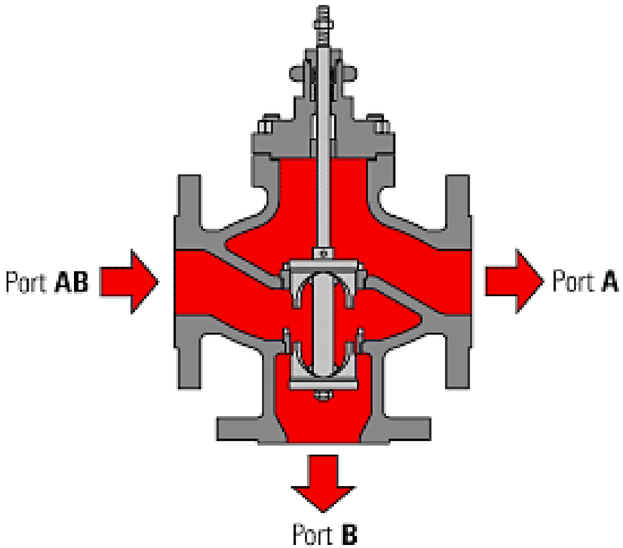
$$(A \times \Delta P) + \text{Friction allowance} = F$$



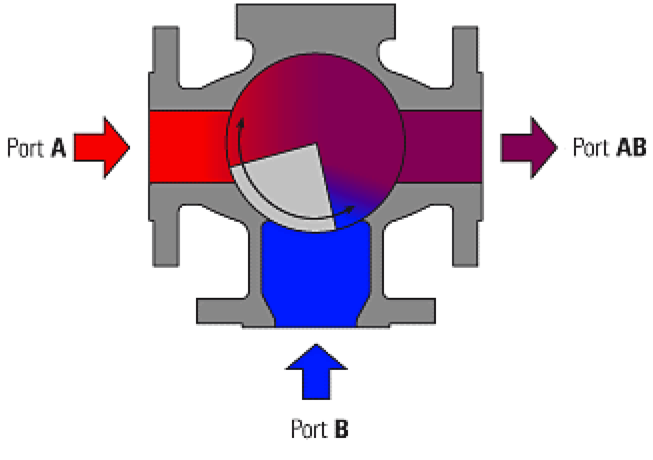
Three Port Valve



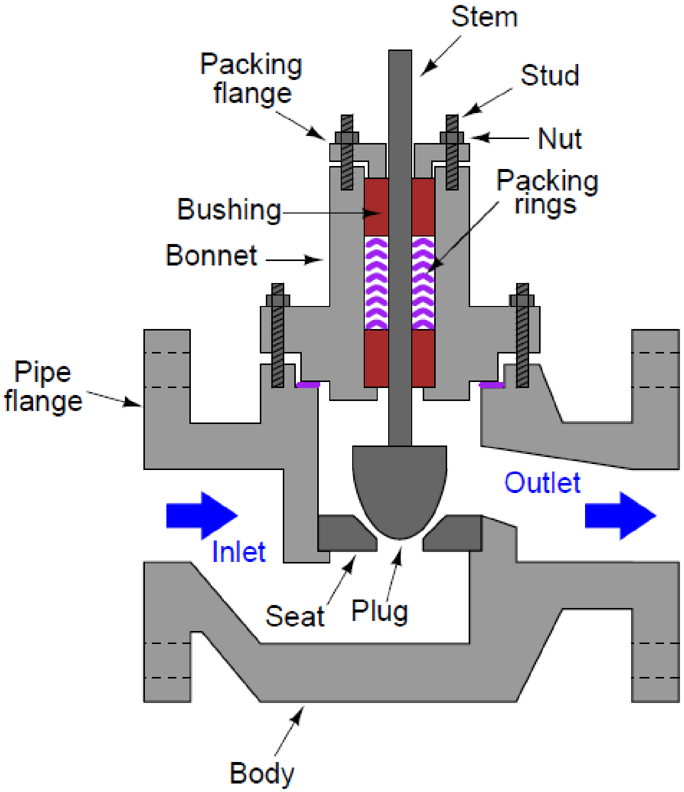
Mixing

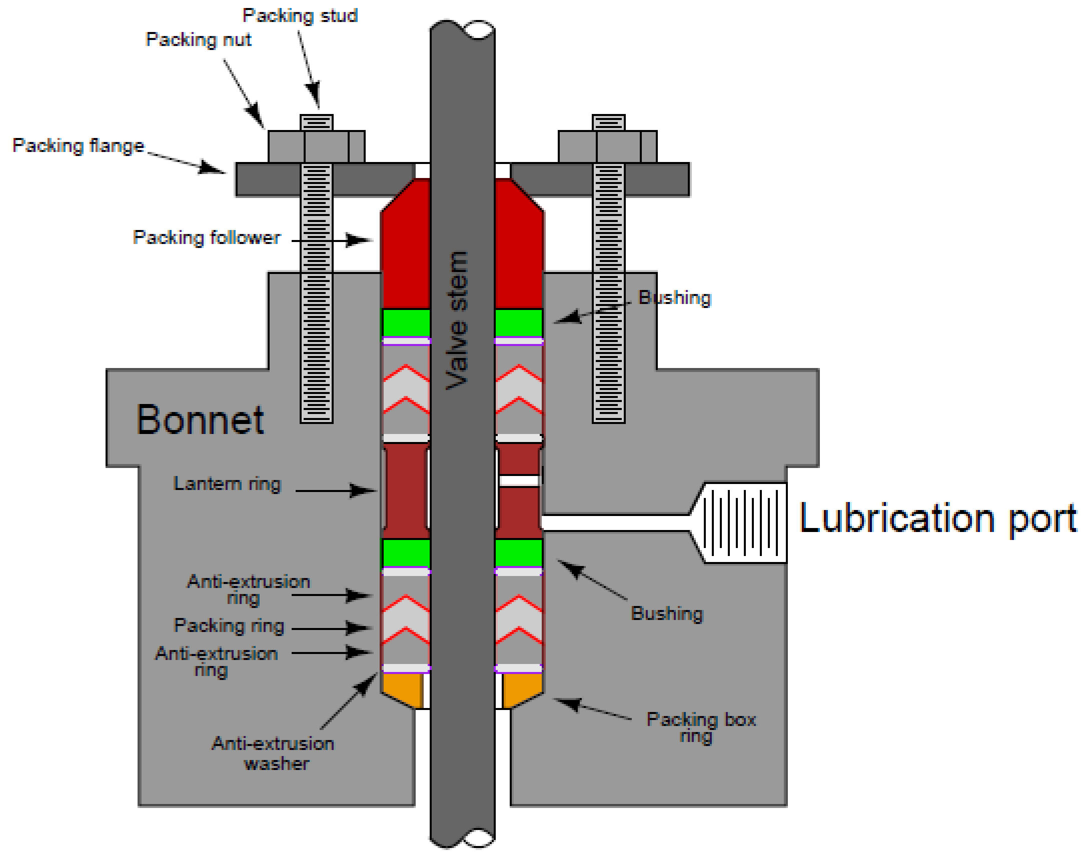


Diverting



Valve Packing





All stem-actuated control valves require some form of seal allowing motion of the stem from some external device (an actuator) while sealing process fluid such that no leak occurs between the moving stem and the body of the valve. The general term for this sealing mechanism is packing.

Valve Seat Leakage

It is important that the control valve be able to completely stop fluid flow when placed in the "closed" position. Although this may seem to be a fundamental requirement of any valve, it is not necessarily so. In many applications, there may have some allowable leakage, where as in some other application needs tight shut-off. For this reason, several classifications for control valves, rating them in their ability to fully shut off are available in accordance with ANSI/FCI 70−2 and IEC 60534-4.

Class	Maximum allowable leakage rate	Test pressure drop
I	(no specification given)	(no specification given)
II	0.5% of rated flow capacity, air or water	45-60 PSI or max. operating
III	0.1% of rated flow capacity, air or water	45-60 PSI or max. operating
IV	0.01% of rated flow capacity, air or water	45-60 PSI or max. operating
V	0.0005 ml/min water per inch orifice size per PSI	Max. operating
VI	Bubble test, air or nitrogen	50 PSI or max. operating

Pneumatic Actuators

The fail-safe mode of a pneumatic/spring valve is a function of both the actuator’s action and the valve body’s action, where, upon loss of actuating energy supply, will cause a valve closure member to be fully closed, fully open, or remain in the last position, whichever position is defined as necessary to protect the process.

Direct/Reverse acting Actuators:

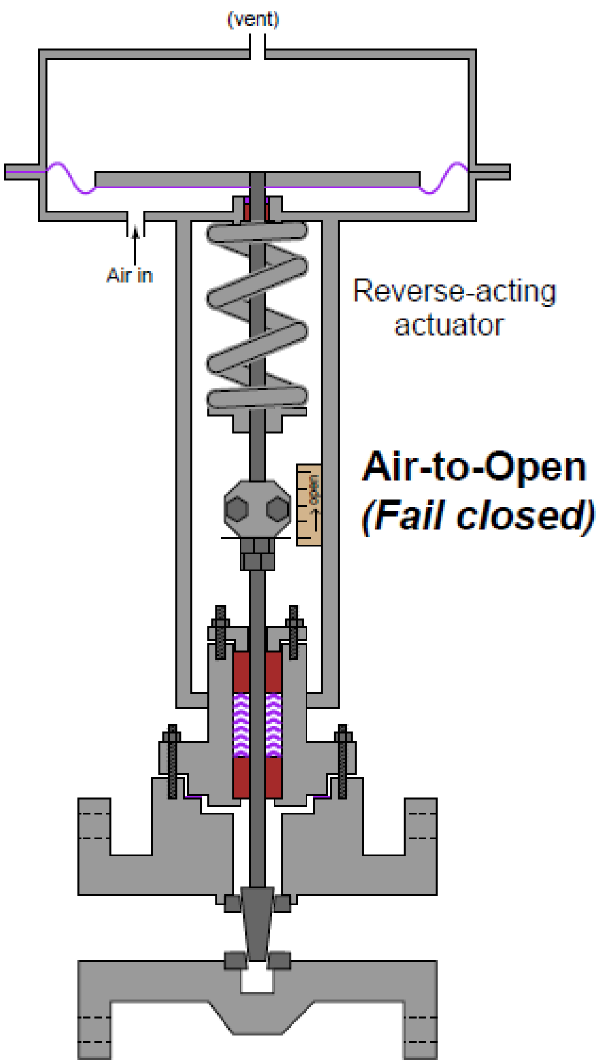
- Direct-acting actuator pushes down on the stem with increasing pressure.
- Reverse-acting actuator pulls up on the stem with increasing pressure.

Direct/Reverse acting Valve Bodies:

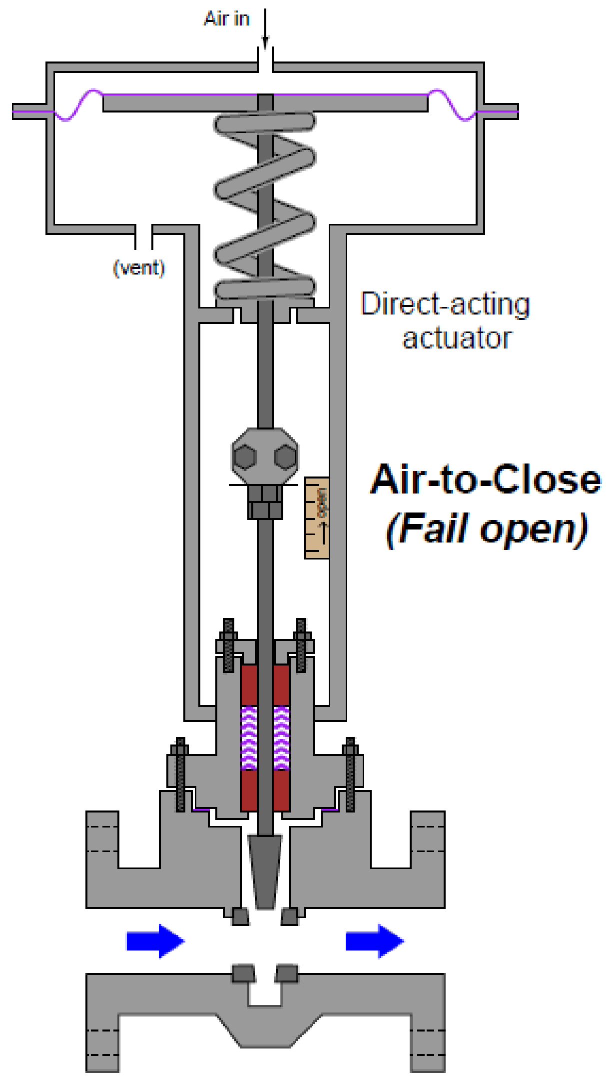
- Direct-acting if they open up when the stem is lifted.
- Reverse-acting if they shut off (close) when the stem is lifted.

Thus, a sliding-stem, pneumatically actuated control valve may be made air-to-open or air-to-close simply by matching the appropriate actuator and body types.

Pneumatic Actuators

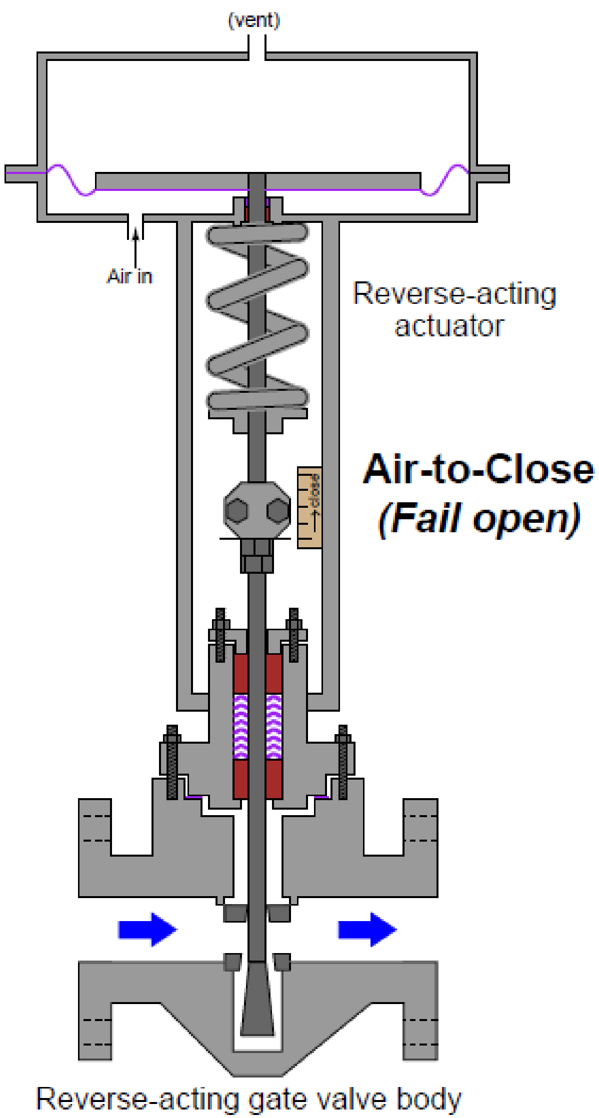


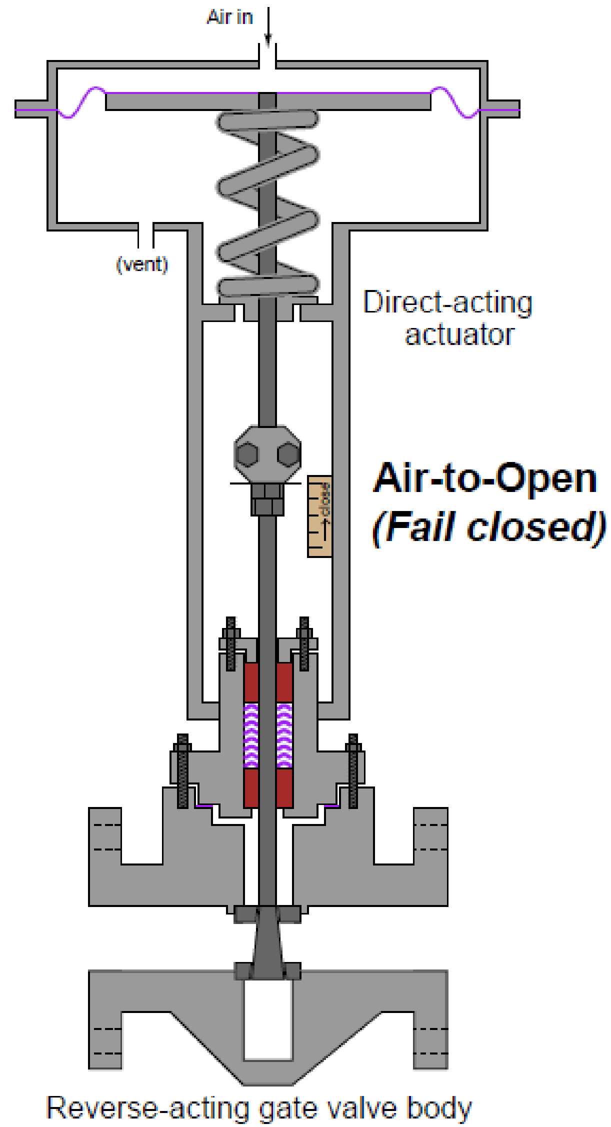
Direct-acting gate valve body



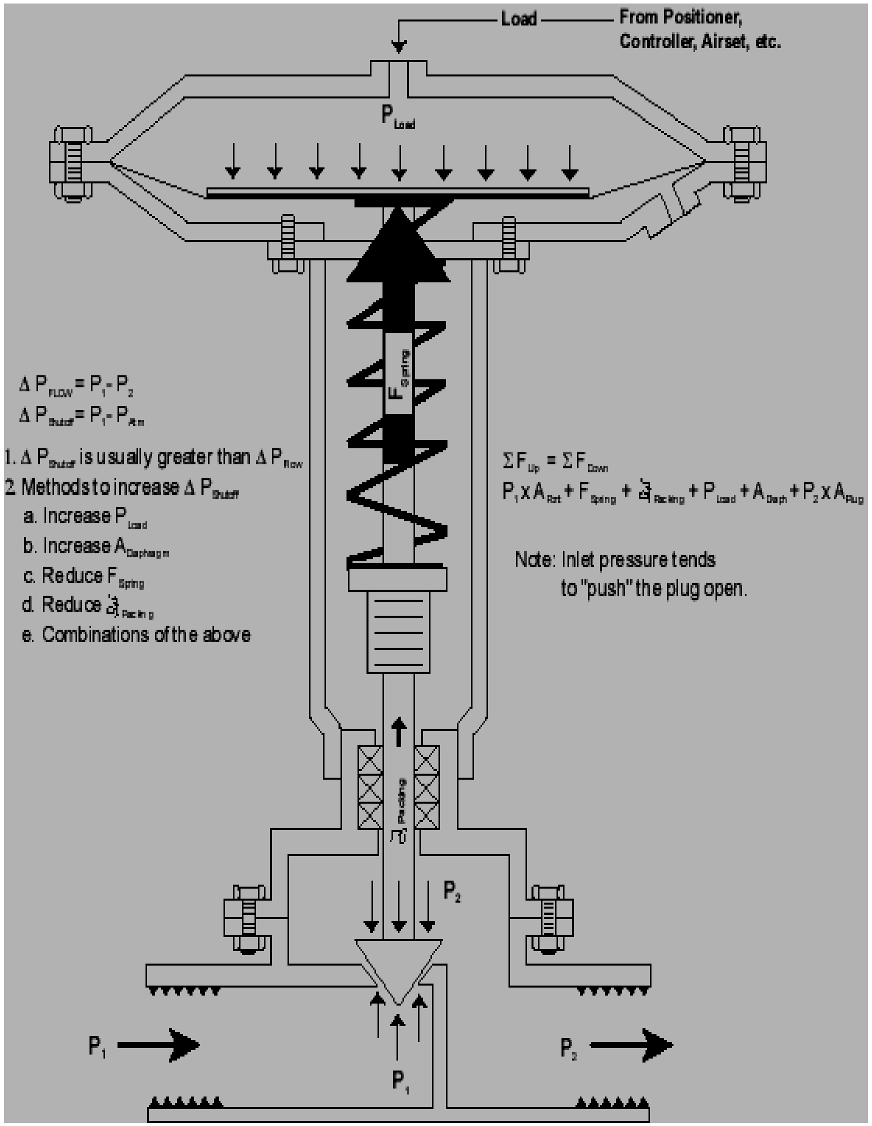
Direct-acting gate valve body

Pneumatic Actuators





Air To Close Valve



$$\Delta P_{FLOW} = P_1 - P_2$$

$$\Delta P_{\ SHUTOFF} = P_1 - P_{LOAD}$$

1. Usually $\Delta P_{\ SHUTOFF} > \Delta P_{\ FLOW}$

2. $$\Sigma F_{up} = \Sigma F_{down}$$

$$\boldsymbol{P_1 \times A_{port} + F_{spring} + \zeta_{Packing}}$$

$$\boldsymbol{= P_{LOAD} \times A_{Diaphragm} + P_2 \times A_{plug}}$$

3. Methods to increase Δ P *$_{SHUTOFF}$*

i) Increase P_{LOAD}

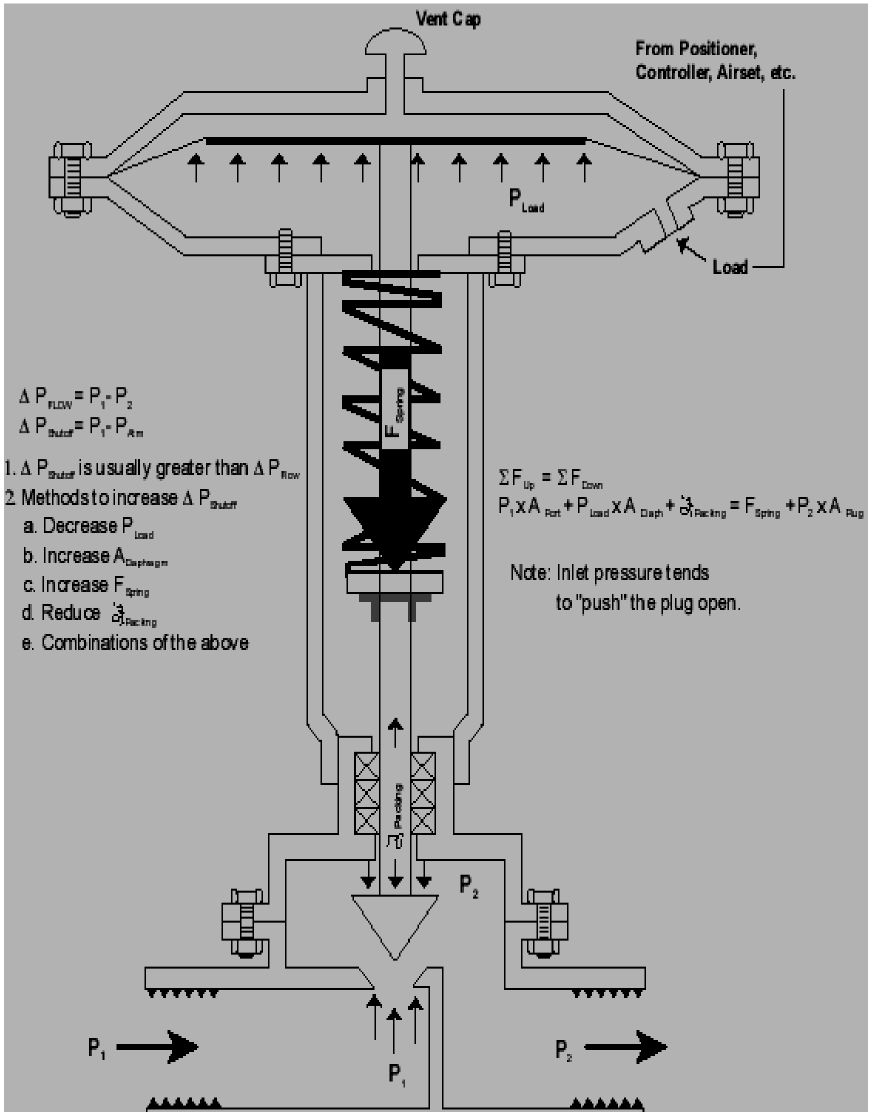
ii) Increase $A_{Diaphragm}$

iii) Reduce F_{Spring}

iv) Reduce ζ *$_{Packing}$*

Note: Inlet Pressure tends to push open plug

Air To Open Valve



$$\Delta P_{FLOW} = P_1 - P_2$$

$$\Delta P_{SHUTOFF} = P_1 - P_{LOAD}$$

1. Usually $\Delta P_{SHUTOFF} > \Delta P_{FLOW}$

2. $\Sigma F_{up} = \Sigma F_{down}$

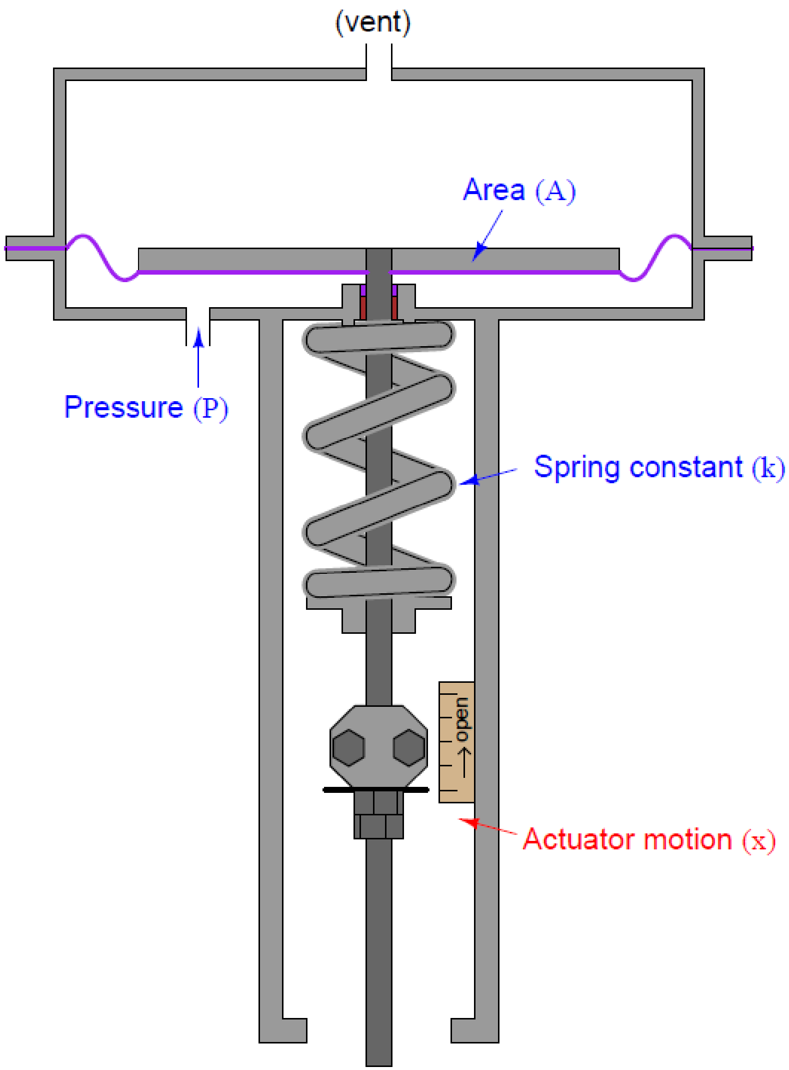
$$P_1 \times A_{port} + P_{LOAD} \times A_{Diaphragm} + \zeta_{Packing}$$

$$= F_{Spring} + P_2 \times A_{plug}$$

3. Methods **to increase $\Delta P_{SHUTOFF}$**
   - i) Decrease P_{LOAD}
   - ii) Increase $A_{Diaphragm}$
   - iii) Increase F_{Spring}
   - iv) Reduce $\zeta_{Packing}$

Note: Inlet Pressure tends to push open plug

Actuator Bench-Set



- Valve actuators provide force to move control valve trim.
- For precise positioning of a control valve, there must be a calibrated relationship between applied force and valve position.
- Most pneumatic actuators exploit Hooke's Law to translate applied air pressure to valve stem position:

$$F = kx$$

- The force on diaphragm of area (A) due to actuating fluid pressure (P) is:

$$F = PA$$

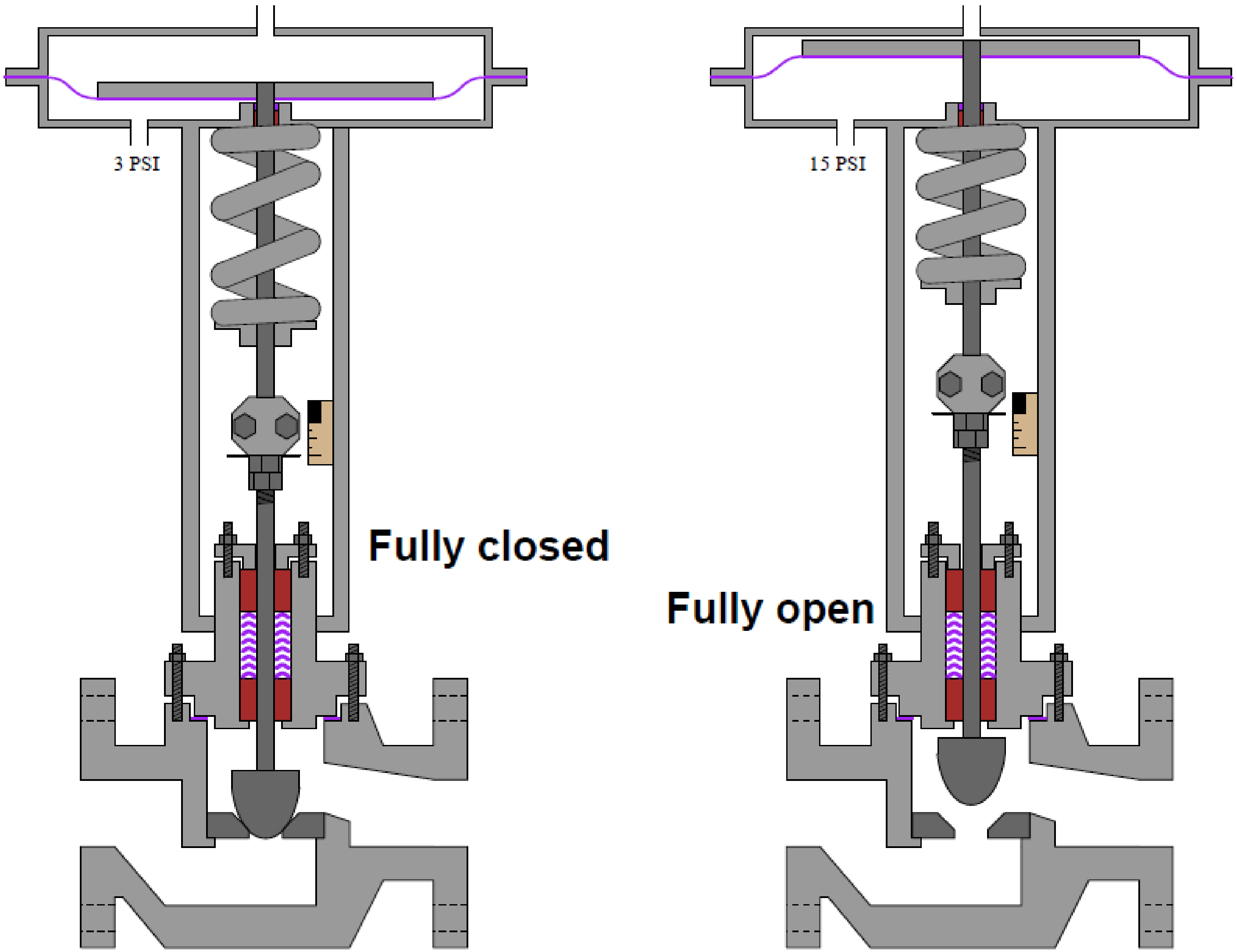
- Hence

$$kx = PA \quad or \quad x = \frac{PA}{k} \quad i.e. \quad x \propto P$$

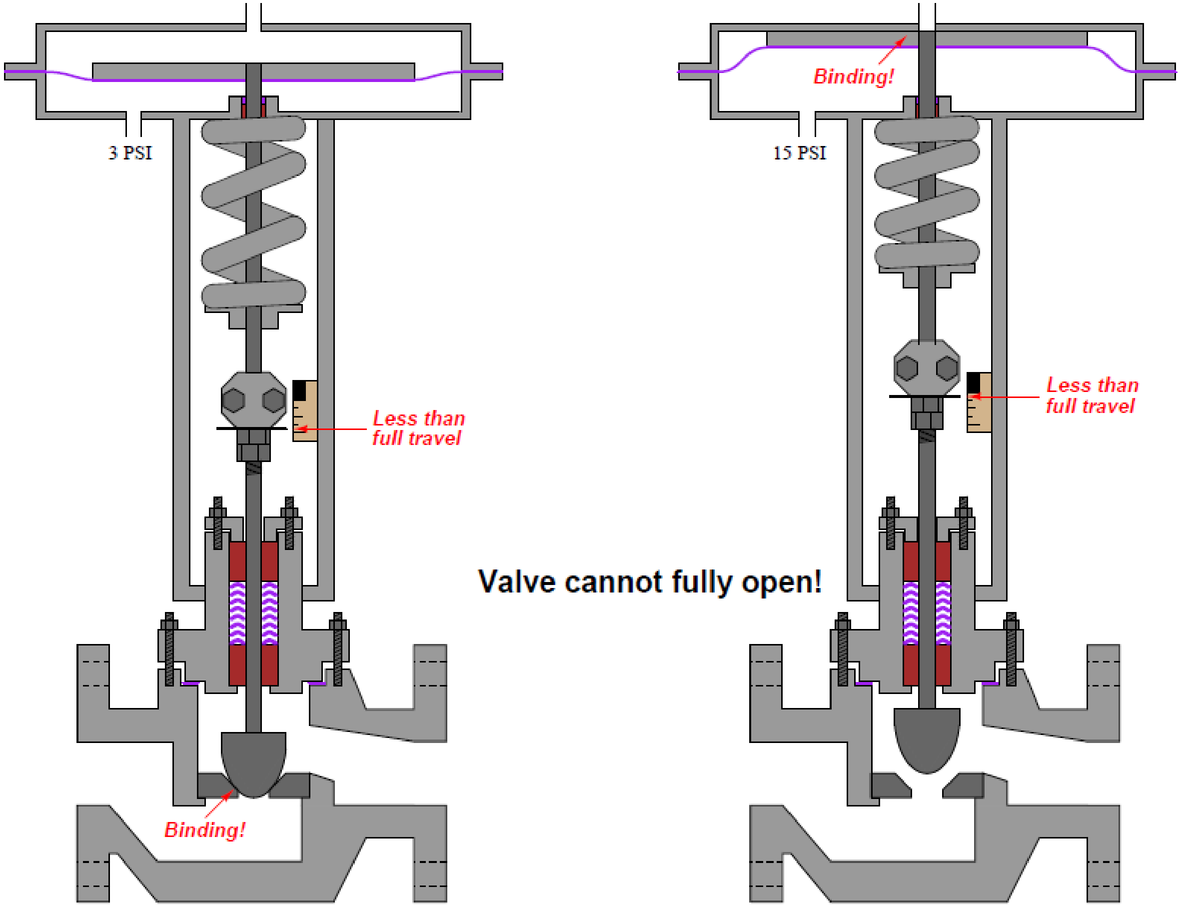
Actuator Bench-Set

- When a control valve is assembled from an actuator and a valve body, the two mechanisms must be coupled together in such a way that the valve moves between its fully closed and fully open positions with an expected range of air pressures (3-15 PSI).
- There are really only two mechanical adjustments that need to be made when coupling a pneumatic diaphragm actuator to a sliding-stem valve: the stem connector and the spring adjuster.
- The stem connector mechanically joins the sliding stems of both actuator and valve body so they move together as one stem.
- This connector must be adjusted so neither the actuator nor the valve trim prevents full travel of the valve trim.
- Thus stem length has been properly set by adjusting the stem connector.
- The spring adjuster is adjusted to set for the proper bench set pressure. This is the pneumatic signal pressure required to lift the plug off the seat. For an air-to-open control valve with a 3 to 15 PSI signal range, the "bench set" pressure would be 3 PSI.

Actuator Bench-Set

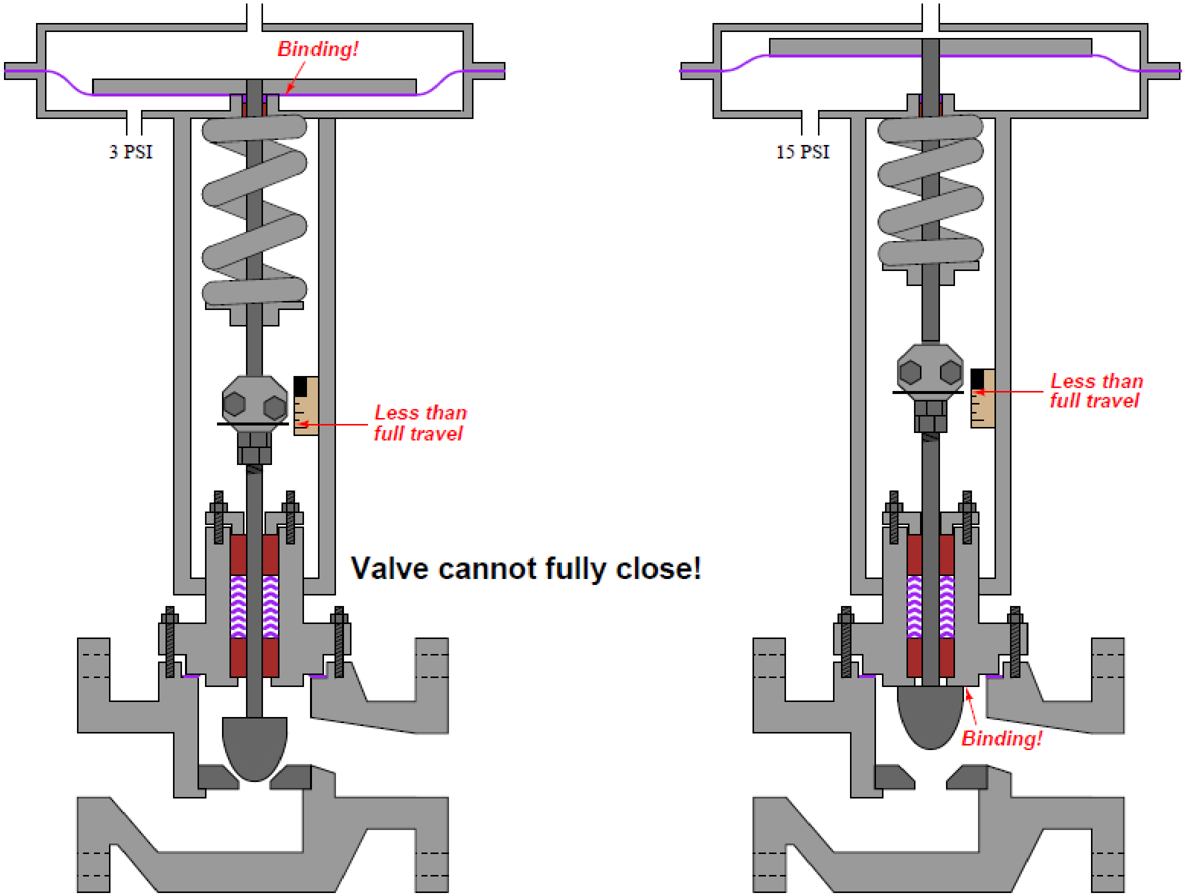


Actuator Bench-Set



If the stem connector is set with the actuator and valve stems spaced too far apart (i.e. the total stem length is too long), the actuator diaphragm will bind travel at the upper end and the valve plug will bind travel at the lower end. The result is a valve that cannot ever fully open.

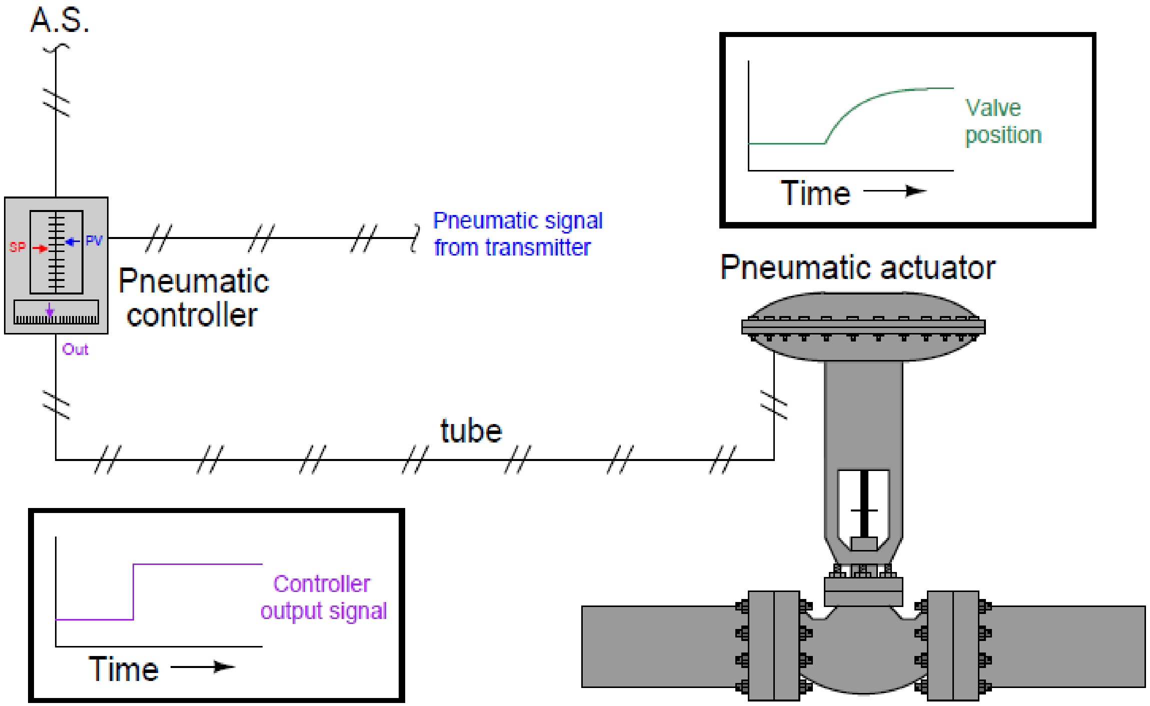
Actuator Bench-Set



If the stem connector is set with the actuator and valve stems too closely coupled (i.e. the total stem length is too short), the actuator diaphragm will bind travel at the lower end and the valve plug will bind travel at the upper end. The result is a valve that cannot ever fully close.

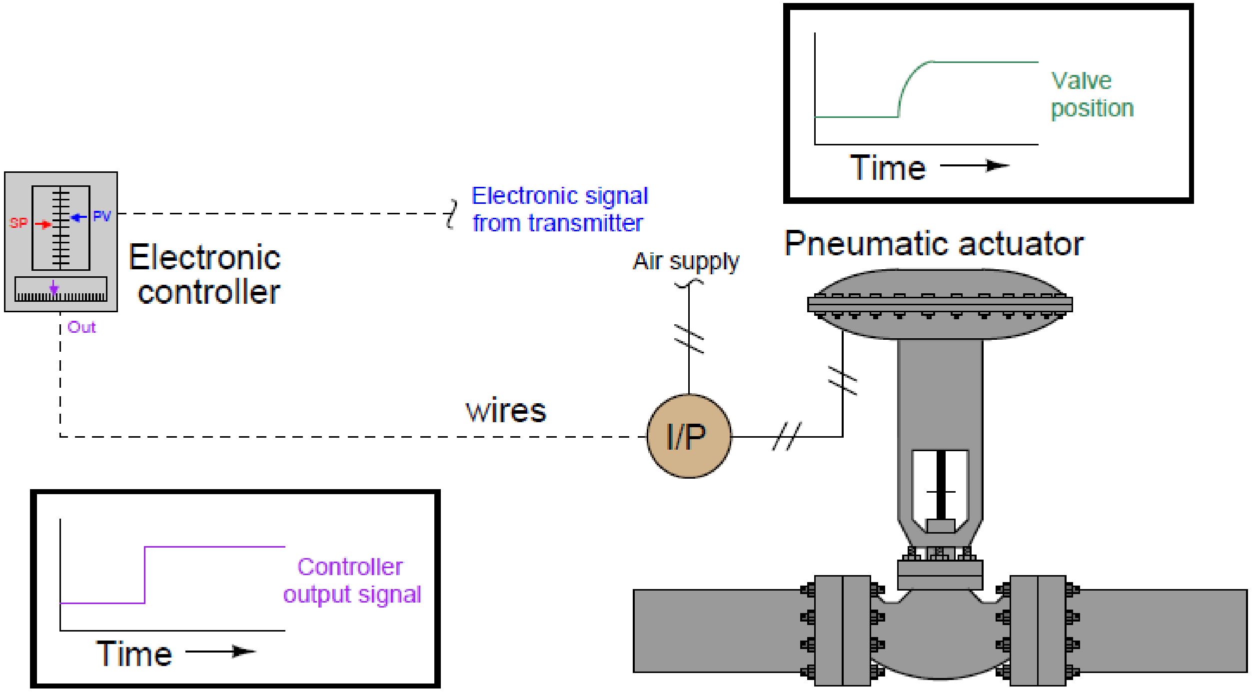
Pneumatic Actuator Response

- A limitation inherent to pneumatic valve actuators is the amount of air flow required to or from the actuator to cause rapid valve motion.
- The combined effect of air-flow friction in the tube, flow limitations inherent to the controller mechanism, and volume inside the valve actuator conspire to create a sluggish valve response to sudden changes in controller output signal.



Pneumatic Actuator Response

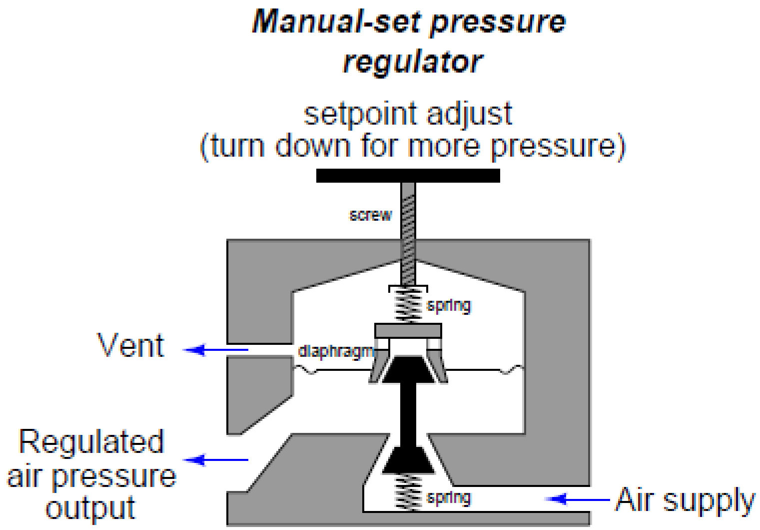
- If the pneumatic valve actuator is driven by an I/P transducer instead of directly by a pneumatic controller, the problem is lessened by the ability to locate the I/P close to the actuator, thus greatly minimizing tube friction and thus minimizing the "time constant" (τ) of the control valve's response.

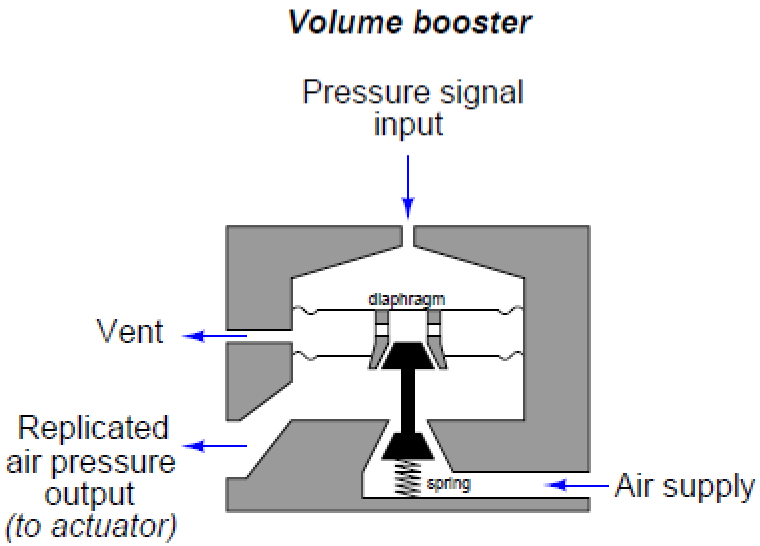


- Still, if the pneumatic actuator is particularly large in volume, an I/P transducer may experience trouble supplying the necessary air flow rate to rapidly actuate the control valve. Certainly the problem of time delay is reduced, but not eliminated, by the close-coupled location of the I/P transducer to the actuator.

Pneumatic Actuator Response

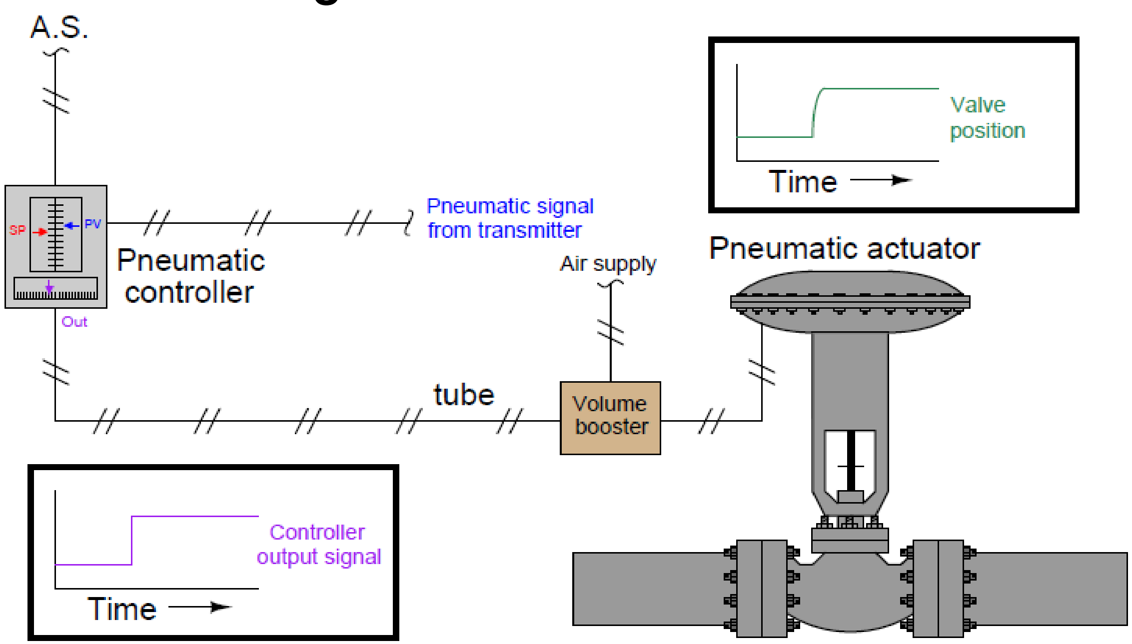
- One way to improve valve response in either type of system (full-pneumatic or I/P-driven) is to use a device known as a volume booster (Pneumatic Relay) to source and vent compressed air for the valve actuator.
- A "volume booster" is a pneumatic device designed to reproduce a pneumatic pressure signal (1:1 ratio), but with far greater output flow capacity.
- A 3 to 15 PSI pneumatic pressure signal applied to the input of a volume booster will result in an identical output signal (3 to 15 PSI), but with greatly enhanced flow capacity.





Pneumatic Actuator Response

- A pneumatic control system equipped with a volume booster would look something like this.



- Of course, enhanced air flow to and from the actuator does not completely eliminate time delays in valve response. So long as the flow rate into or out of an actuator is finite, some time will be required to change pressure inside the actuator and thus change valve position.

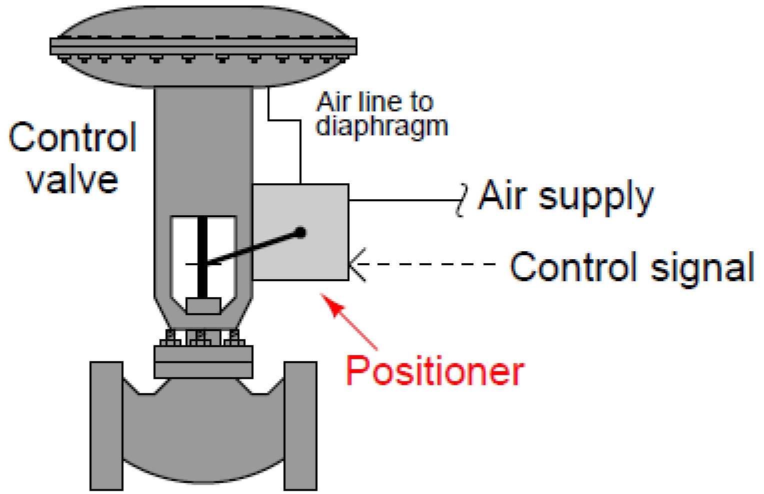
Valve Positioners

- Springs work quite nicely to convert mechanical force into mechanical motion (Hooke's Law : $F = kx$) for valve actuators if and only if the sole forces involved are the diaphragm or piston force against the spring's resistance force. If any other force acts upon the system, the relationship between actuating fluid pressure and valve stem travel will not necessarily be proportional.
- Unfortunately, there typically are other forces acting on a valve stem besides the actuating fluid pressure's force and the spring's reaction force. Friction from the stem packing is one force, and reaction force at the valve plug caused by differential pressure across the plug's area is another. These forces conspire to re-position the valve stem so stem travel does not precisely correlate to actuating fluid pressure.
- A common solution to this dilemma is to add a positioner to the control valve assembly.

Valve Positioners

- A positioner is a motion-control device designed to actively compare stem position against the control signal, adjusting pressure to the actuator diaphragm or piston until the correct stem position is reached.

- Positioners essentially act as control systems within themselves. The valve's stem position is the process variable (PV), the command signal to the positioner is the set-point (SP), and the positioner's signal to the actuator is the manipulated variable (MV) or output.



- The technical term for this type of control system is cascade, where one controller's output becomes the set-point for a different controller. In the case of a valve positioner, the positioner receives a valve stem position set-point from the main process controller.

Valve Positioners

- Inputs are:
  - Supply air (usually 20PSI)
  - Valve position (PV)
  - A valve position (command) signal (SP)
    - Either 3-15PSI or
    - 4-20ma

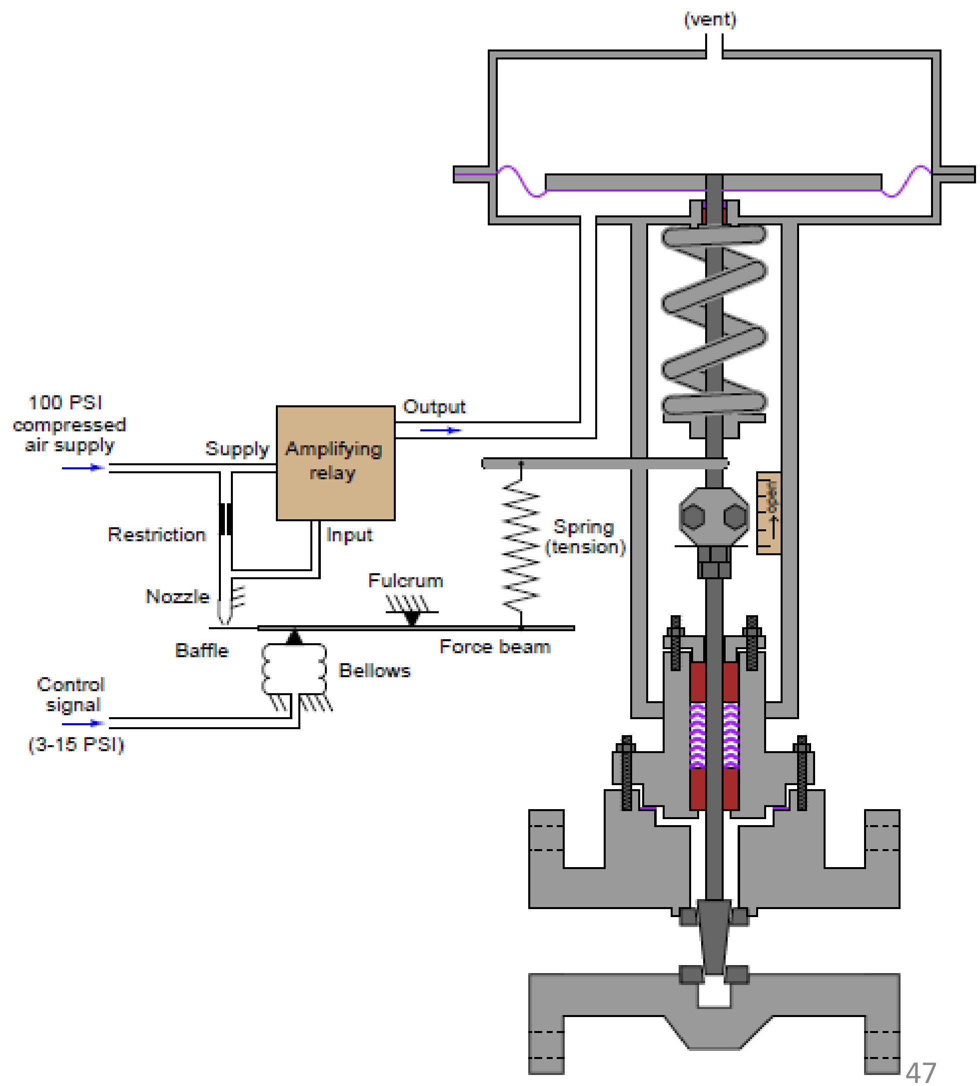
- Output is a valve position
  - Actually output is air pressure to the actuator (MV)

- Control valve positioners are typically constructed in such a way to source and vent high air flow rates, such that the positioner also fulfills the functionality of a volume booster (that is why the positioner needs 20 PSI air supply). Thus, a positioner not only ensures more precise valve stem positioning, but also faster stem velocity (and shorter time delays) than if the valve actuator were directly “powered” by an I/P transducer.

Positioners Type

Force-Balance pneumatic valve positioner

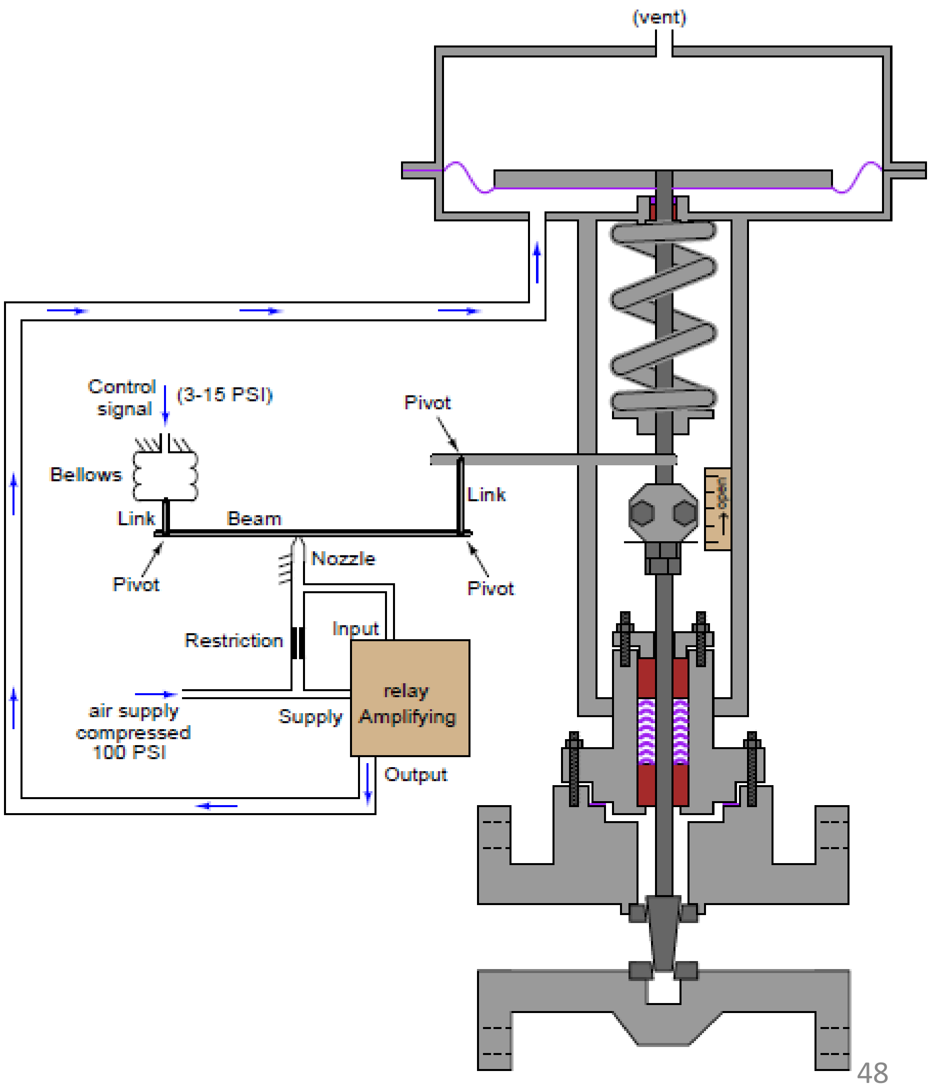
The control signal for this valve is a 3 to 15 PSI pneumatic signal, coming from either an I/P transducer or a pneumatic controller (neither one shown in the illustration). This control signal pressure applies an upward force on the force beam, such that the baffle tries to approach the nozzle. Increasing backpressure in the nozzle causes the pneumatic amplifying relay to output a greater air pressure to the valve actuator, which in turn lifts the valve stem up (opening up the valve). As the valve stem lifts up, the spring connecting the force beam to the valve stem becomes further stretched, applying additional force to the right-hand side of the force beam. When this additional force balances the bellows' force, the system stabilizes at a new equilibrium.



Positioners Type

Motion-Balance pneumatic valve positioner

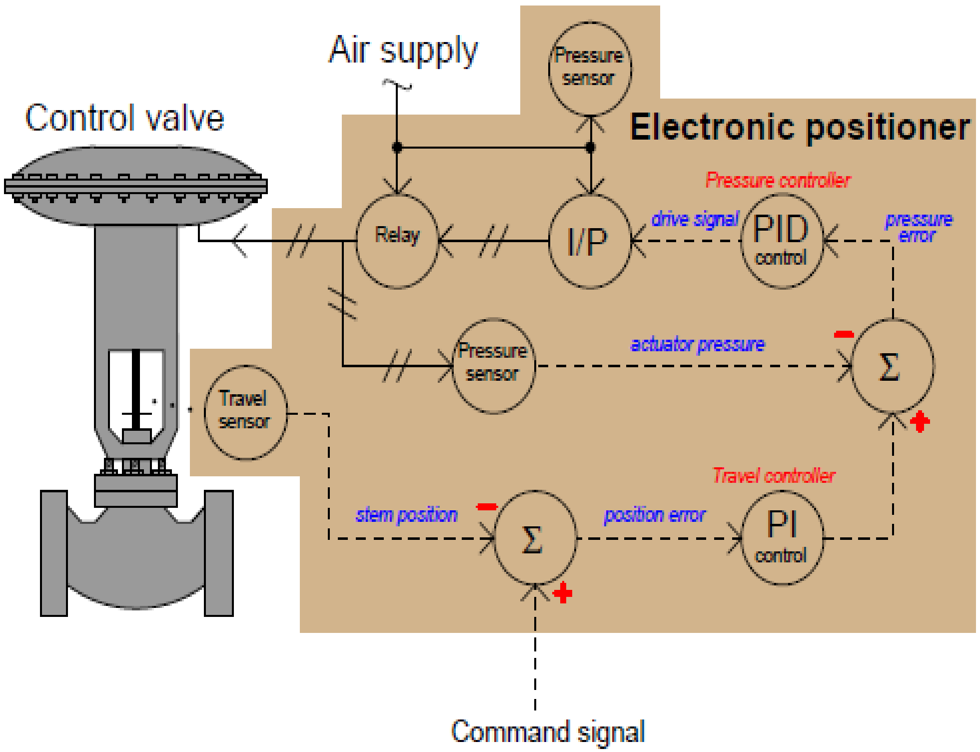
The control signal for this valve is a 3 to 15 PSI pneumatic signal, coming from either an I/P transducer or a pneumatic controller (neither one shown in the illustration). In this mechanism, an increasing signal pressure causes the beam to advance toward the nozzle, generating increased nozzle backpressure which then causes the pneumatic amplifying relay to send more air pressure to the valve actuator. As the valve stem lifts up, the upward motion imparted to the right-hand end of the beam counters the beam's previous advance toward the nozzle. When equilibrium is reached, the beam will be in an angled position with the bellows' motion balanced by valve stem motion.



Positioners Type

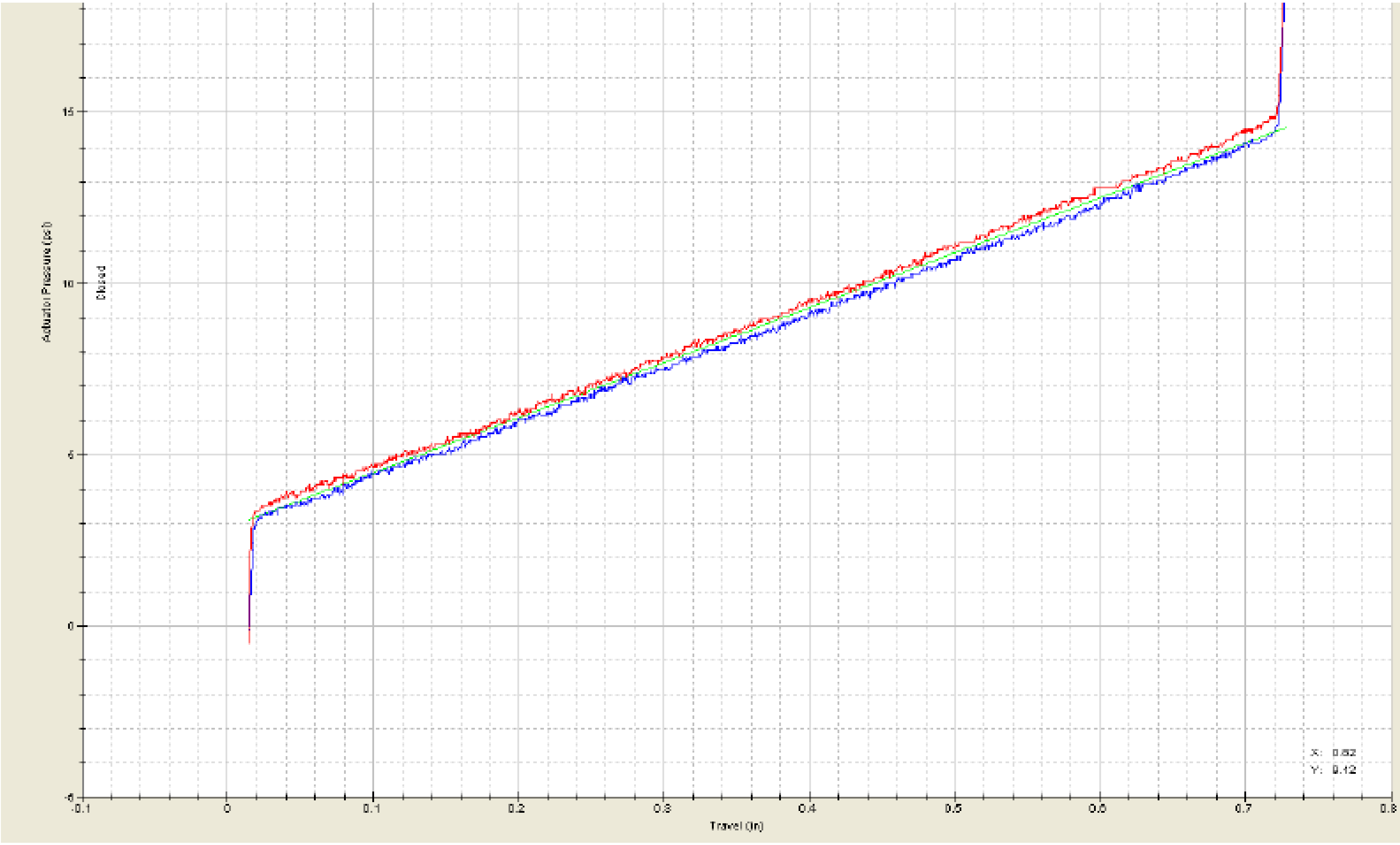
Electronic Positioners

There are two control algorithms working together to maintain proper valve position: one monitoring and controlling pressure applied to the actuator (compensating for changes in air supply pressure that might otherwise affect the valve's position) and the other monitoring and controlling stem position itself, sending a cascaded control signal to the pressure control components. These two control "loops" are sometimes referred to as the pressure and travel loops, or the major and minor loops, respectively.



The command signal tells the positioner where the valve stem should be positioned. The first controller inside the positioner (PI) calculates how much air pressure at the actuator should be needed to achieve the requested stem position. The next controller (PID) drives the I/P converter as much as necessary to achieve that pressure. If anything causes the valve stem to not be at the commanded position, the two controllers inside the positioner work together to force the valve to its proper position.

“Valve Signature” showing the behavior of an air-to-open globe valve



Valve Signature

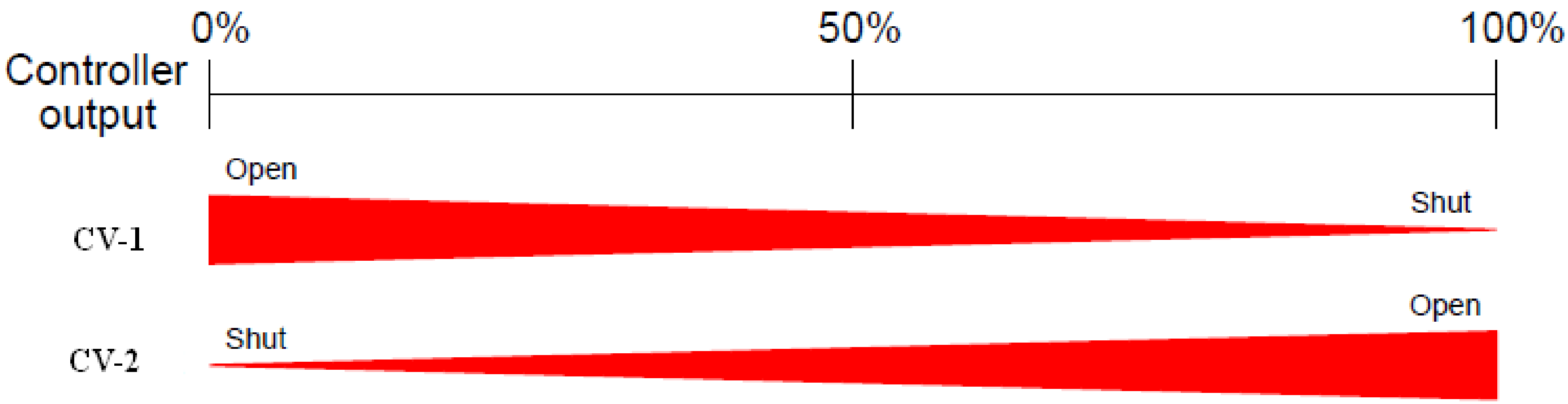
- The red graph shows the valve's response in the opening direction where additional pressure is required to overcome packing friction as the valve moves open (up).
- The blue graph shows the valve as it closes, less pressure applied to the diaphragm now to allow the spring's compression to overcome packing friction as the valve moves closed (down) to its resting state.
- The sharp turns at each end of this graph show where the valve stem reaches its end positions and cannot move farther despite further changes in actuator pressure.
- Each plot is roughly linear in accordance with Hooke's Law describing the behavior of the valve spring, Any departure from a single linear plot indicates the onset of some other force(s) on the valve stem other than the spring's compression. This is why we see two plots vertically offset from each other.
- Packing friction is another force acting on the valve stem besides the spring's compression.
- When the valve is opening, friction works against the actuator's air pressure (assuming an air-to-open valve), requiring additional air pressure to maintain motion. When the valve is closing, though, packing friction works in the same direction as the actuator's air pressure "helping" the valve stay more open than it should. This is why the positioner must maintain less actuator air pressure for any given position while moving closed than while the valve moves open. The difference in air pressure moving open versus moving closed at any given stem position is proportional to twice the dynamic packing friction. Stated mathematically, $F_{packing} = (P_{opening} - P_{closing})A$.

Control Valve Split-Ranging

- There are many process control applications in industry where it is desirable to have multiple control valves respond to the output of a common controller.
- Control valves configured to follow the command of the same controller are said to be split-ranged, or sequenced.
- A few different modes of control valve sequencing are commonly seen in industry: Complementary, Exclusive, and Progressive.

Complementary Valve Sequencing

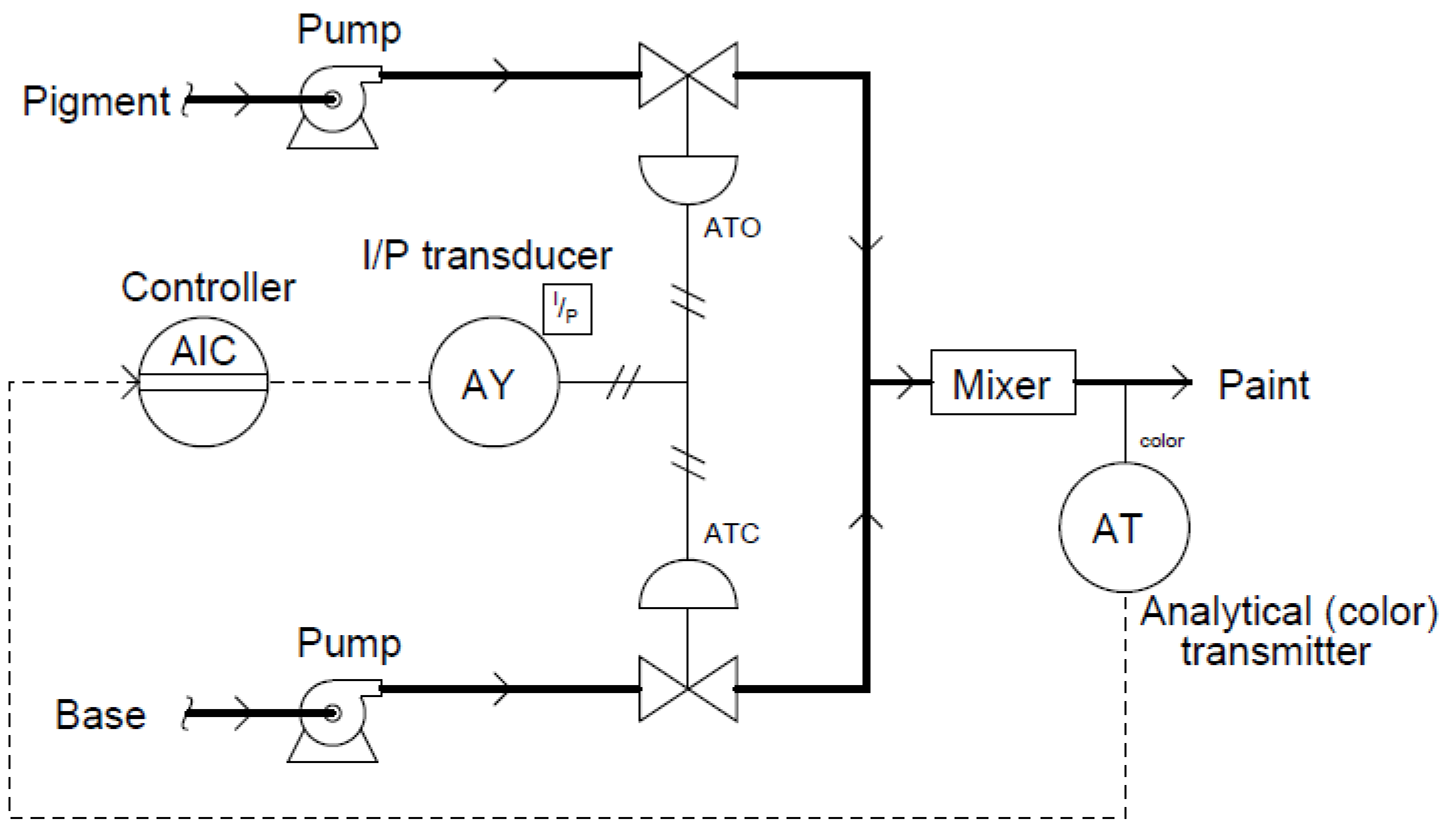
- With this form of split-ranging, there is never a condition in the controller's output range where both valves are fully open or fully shut. Rather, each valve complements the other's position.



Controller output (%)	I/P output (PSI)	CV-2 (stem position)	CV-1 (stem position)
0 %	3 PSI	fully shut	fully open
25 %	6 PSI	25% open	75% open
50 %	9 PSI	half-open	half-open
75 %	12 PSI	75% open	25% open
100 %	15 PSI	fully open	fully shut

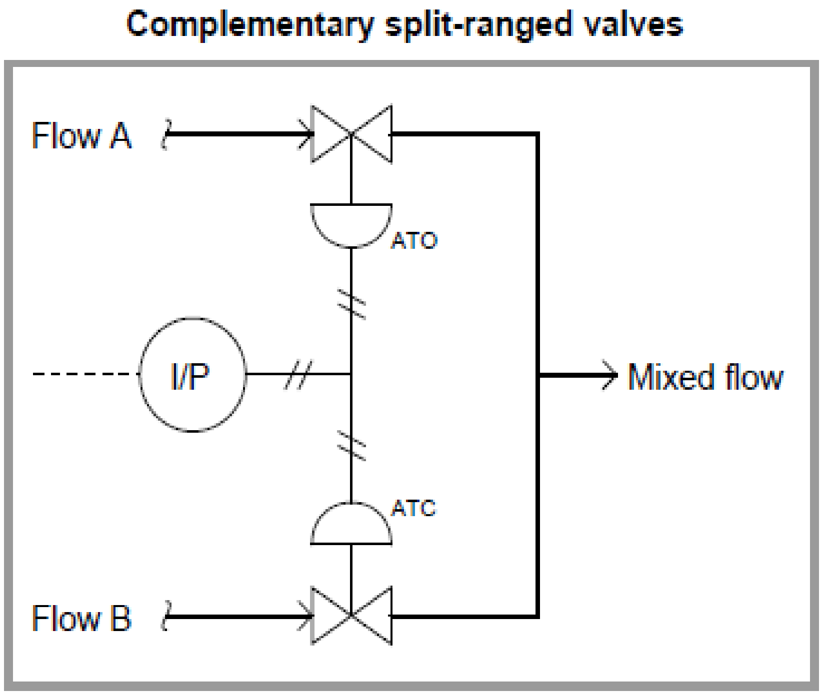
Complementary Valve Sequencing

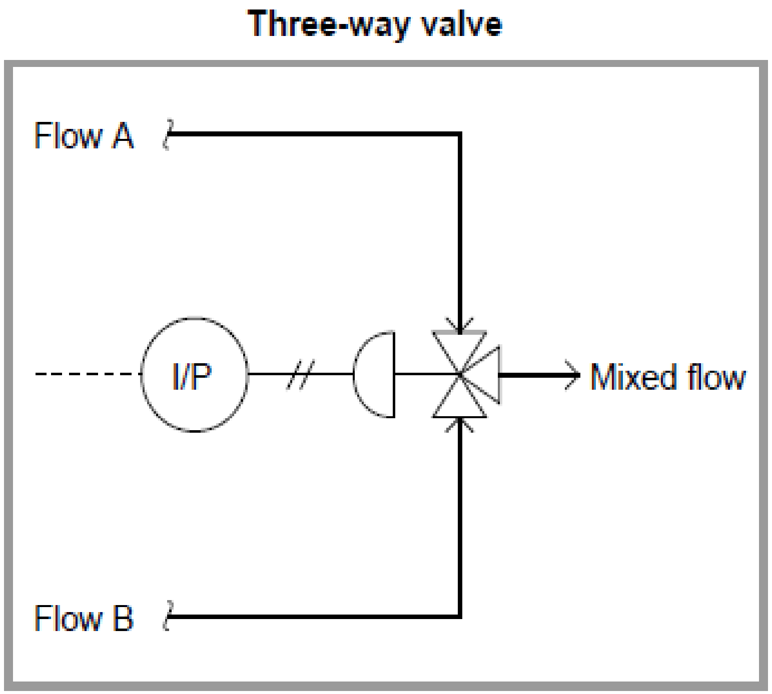
- Both base and pigment valves operate from the same 3 to 15 PSI pneumatic signal output by the I/P transducer (AY), but one of the valves is Air-To-Open while the other is Air-To-Close.



Complementary Valve Sequencing

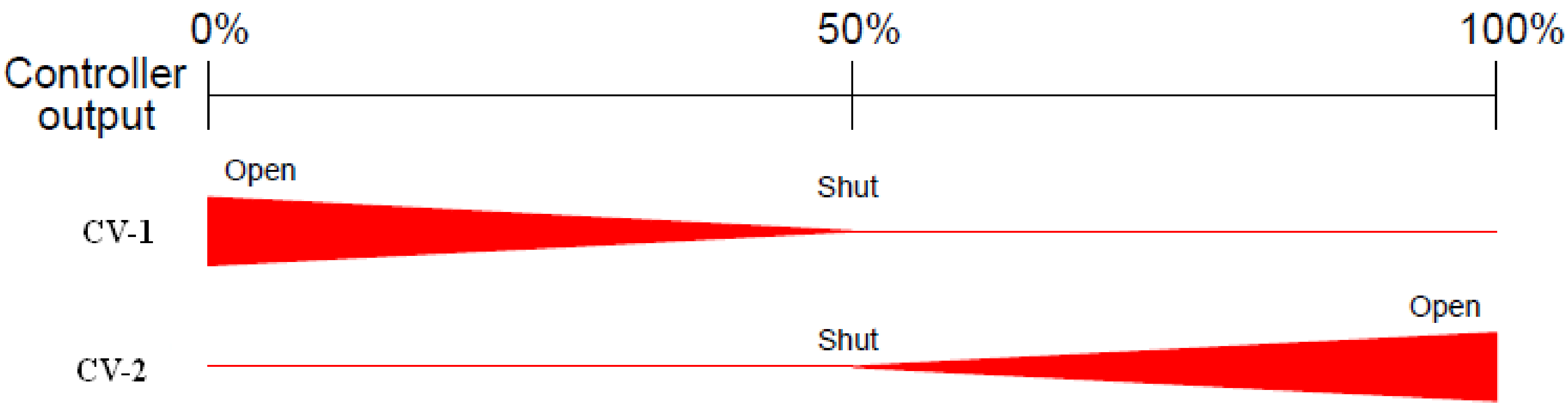
- An alternative to complementary valve sequencing in a process where two fluid streams mix (or diverge) is to use one three-way valve rather than a pair of two-way valves:





Exclusive Valve Sequencing

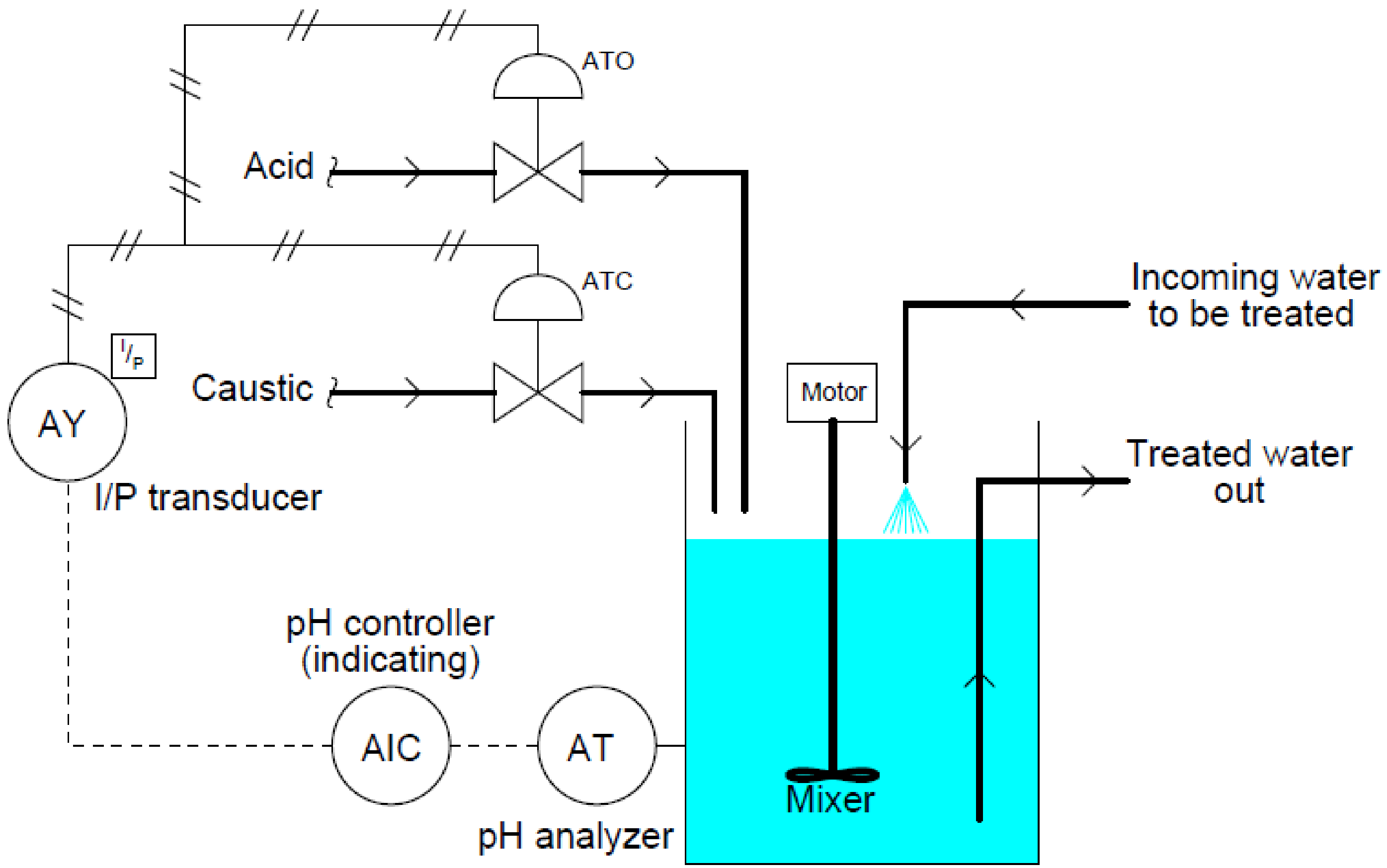
- With this form of valve sequencing, both valves are fully closed at a 50% controller output signal, with one valve opening fully as the controller output drives toward 100% and the other valve opening fully as the controller output goes to 0%.
- The nature of this valve sequencing is to have an "either-or" throttled path for process fluid. That is, either process fluid flows through one valve or through the other, but never through both at the same time.



Controller output (%)	I/P output (PSI)	CV-2 (stem position)	CV-1 (stem position)
0 %	3 PSI	fully shut	fully open
25 %	6 PSI	fully shut	half-open
50 %	9 PSI	fully shut	fully shut
75 %	12 PSI	half-open	fully shut
100 %	15 PSI	fully open	fully shut

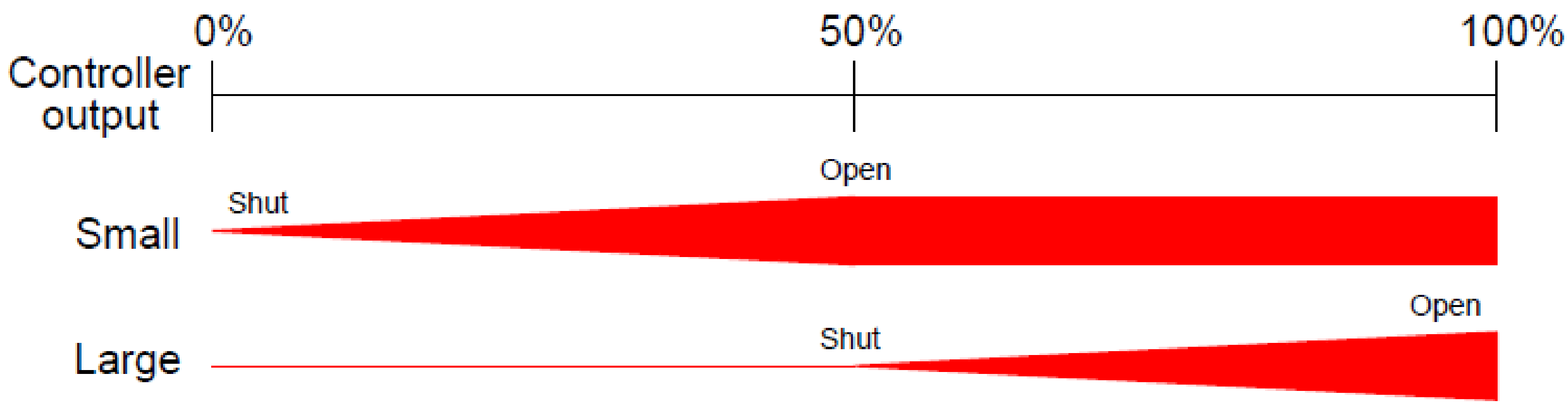
Exclusive Valve Sequencing

- Both reagent control valves operate from the same 3 to 15 PSI pneumatic signal output by the I/P transducer (AY), but the two valves' calibrated ranges are not the same.
- The Air-To-Open acid valve has an operating range of 9 to 15 PSI, while the Air-To-Close caustic valve has an operating range of 9 to 3 PSI.



Progressive Valve Sequencing

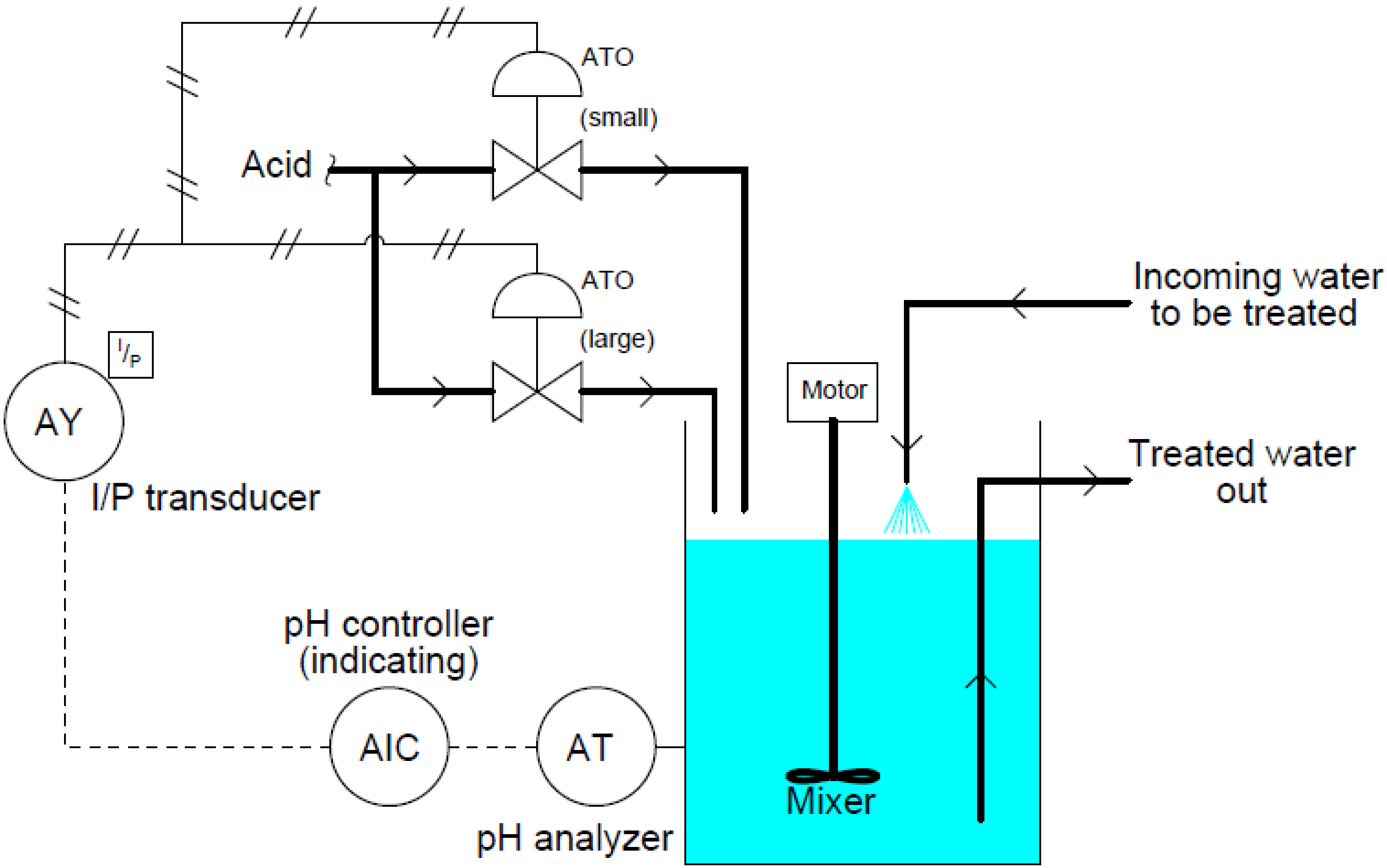
- Some processes demand a greater range of control than any single valve can deliver, and it is within these processes, a pair of progressively-sequenced control valves is a valid solution.
- The combination of two differently-sized (small and large) control valves are used to satisfy the process demand.



Controller output (%)	I/P output (PSI)	Small acid valve (stem position)	Large acid valve (stem position)
0 %	3 PSI	fully shut	fully shut
25 %	6 PSI	half-open	fully shut
50 %	9 PSI	fully open	fully shut
75 %	12 PSI	fully open	half-open
100 %	15 PSI	fully open	fully open

Progressive Valve Sequencing

- A pH control process where the incoming liquid always has a high pH value, and must be neutralized with acid, the progressive valve sequencing may be used.



Flow Capacity or Flow Coefficient (C_v)

- The amount of kinetic energy represented by a volume of moving fluid in turbulent motion with velocity v and is given by

$$E_k = \frac{1}{2}mv^2$$

- Hence

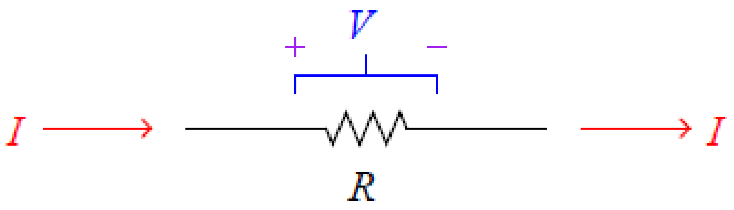
$$\text{Kinetic energy per unit volume} = \frac{1}{2}\rho v^2$$

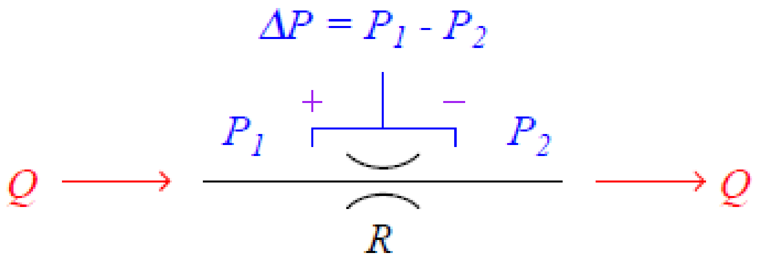
- When a fluid moves turbulently through any restriction, energy is inevitably dissipated in that turbulence. The amount of energy dissipated is proportional to the kinetic energy of the turbulent motion. i.e. the amount of energy dissipated by turbulence in such a fluid stream will be some proportion (k) of the total kinetic energy, so:

$$\text{Energy dissipated per unit volume} = \frac{1}{2}k\rho v^2$$

- Any energy lost in turbulence eventually manifests as a loss in fluid pressure downstream of that turbulence. Thus, a control valve throttling a fluid flowstream will have a greater upstream pressure than downstream pressure.

Flow Capacity or Flow Coefficient (C_v)





- This pressure drop (P1 − P2, or ΔP) is equivalent to dissipated energy per unit volume.
- With ***Q = Av*, solving for a quotient with pressure drop (P1 − P2) in the numerator and flow rate Q in the denominator so the equation bears a resemblance to Ohm's Law (R = V/I):**

$$P_1 - P_2 = \frac{1}{2} k \rho \frac{Q^2}{A^2}$$

$$\frac{P_1 - P_2}{Q^2} = \frac{k\rho}{2A^2}$$

$$\frac{\sqrt{P_1 - P_2}}{Q} = \sqrt{\frac{k\rho}{2A^2}}$$

Flow Capacity or Flow Coefficient (C_v)

- Either side of the last equation represents a sort of "Ohm's Law" for turbulent liquid restrictions.
- The left-hand side expressing fluid "resistance" in the state variables of pressure drop and volumetric flow.
- The right-hand term expressing fluid "resistance" as a function of fluid density and restriction geometry.
- We can see how pressure drop (P1 − P2) and volumetric flow rate (Q) are not linearly related as voltage and current are for resistors, but that nevertheless we still have a quantity that acts like a "resistance" term:

$$R = \frac{\sqrt{P_1 - P_2}}{Q} \qquad\qquad R = \sqrt{\frac{k\rho}{2A^2}}$$

Where,

R = Fluid "resistance"

P1 = Upstream fluid pressure

P2 = Downstream fluid pressure

Q = Volumetric fluid flow rate

k = Turbulent energy dissipation factor

ρ = Mass density of fluid

A = Cross-sectional area of restriction

Flow Capacity or Flow Coefficient (C_v)

- The fluid "resistance" of a restriction depends on several variables: the proportion of kinetic energy lost due to turbulence (k), the density of the fluid **(ρ)**, and the cross-sectional area of the restriction (A).
- In a control valve throttling a liquid flow stream, only k and A are subject to change with stem position, fluid density remaining relatively constant.
- It is customary in control valve engineering to express the "restrictiveness" of any valve in terms of how much flow it will pass given a certain pressure drop and fluid specific gravity (G_f). This measure of valve performance is called flow capacity or flow coefficient, symbolized as C_v.
- A greater flow capacity value represents a less restrictive (less "resistive") valve, able to pass greater rates of flow for the same pressure drop.

Flow Capacity or Flow Coefficient (C_v)

$$G_f = \frac{\rho}{\rho_{water}}$$

$$\rho_{water} G_f = \rho$$

$$P_1 - P_2 = \frac{1}{2} k \rho \frac{Q^2}{A^2}$$

$$P_1 - P_2 = \frac{1}{2} k \rho_{water} G_f \frac{Q^2}{A^2}$$

$$\frac{P_1 - P_2}{G_f} = \frac{1}{2} k \rho_{water} \frac{Q^2}{A^2}$$

$$\left(\frac{2A^2}{k\rho_{water}}\right)\left(\frac{P_1 - P_2}{G_f}\right) = Q^2$$

$$Q = \sqrt{\frac{2A^2}{k\rho_{water}}} \sqrt{\frac{P_1 - P_2}{G_f}}$$

- The first square-rooted term in the equation, $\sqrt{\frac{2A^2}{k\rho_{water}}}$; is the Valve Capacity or C_v factor.

Flow Capacity or Flow Coefficient (C_v)

- Substituting C_v for this term results in the simplest form of valve sizing equation (for incompressible fluids):

$$Q = C_v \sqrt{\frac{P_1 - P_2}{G_f}}$$

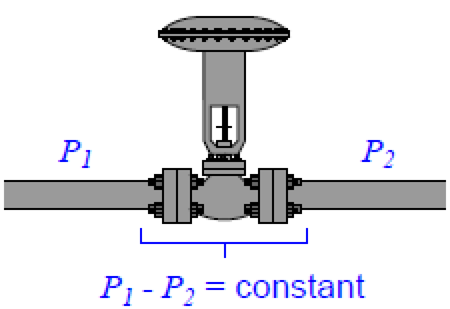
- C_v is defined as the number of US gallons of water at 60^0 F that will flow per minute through a valve with 1 PSI of pressure drop.

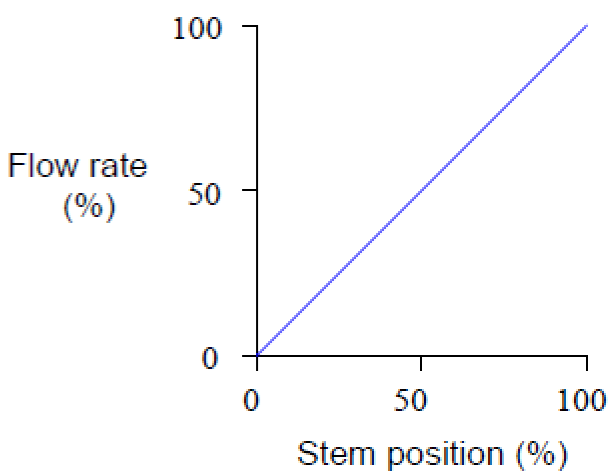
- A similar valve capacity expression K_v used elsewhere in the world expressed as number of cubic meters of water will flow per hour through a valve with a pressure drop of 1 bar.

Control Valve Characterization

Inherent Characteristics

- When control valves are tested in a laboratory setting, they are connected to a piping system that is able to provide a nearly constant pressure difference between upstream and downstream (P1 − P2).
- With a fluid of constant density and a constant pressure drop across the valve, flow rate becomes a direct function of flow coefficient (C_v).
- The amount of "resistance" offered by a restriction of any kind to a turbulent fluid depends on the cross-sectional area of that restriction and also the proportion of fluid kinetic energy dissipated in turbulence.
- If a control valve is designed such that the combined effect of these two parameters vary linearly with stem motion, the Cv of the valve will likewise be proportional to stem position.

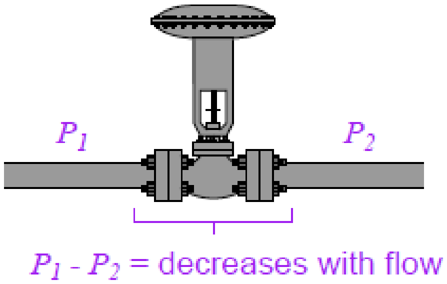


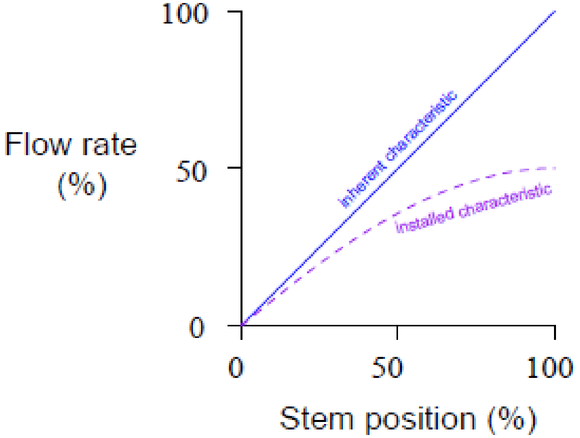


Control Valve Characterization

Installed Characteristics

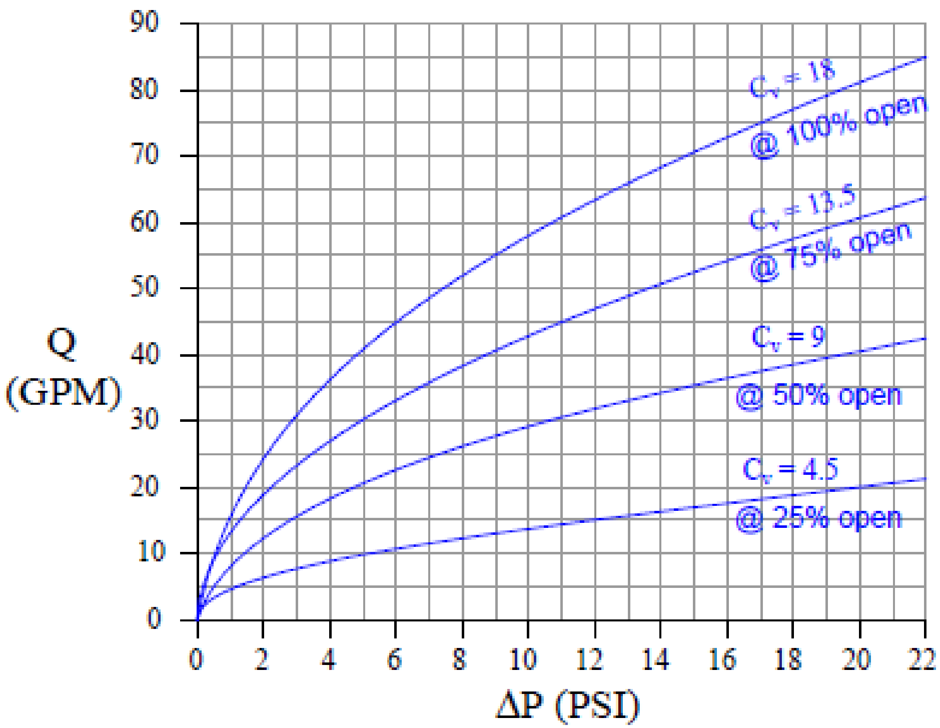
- Most real valve installations do not place the control valve under a condition of constant pressure drop.
- Due to frictional pressure losses in piping and changes in supply/demand pressures that vary with flow rate, a typical control valve “sees” substantial changes in differential pressure as its controlled flow rate changes.
- Generally speaking, the pressure drop available to the control valve will decrease as flow rate increases.
- The result of this pressure drop versus flow relationship is that the actual flow rate of the same valve installed in a real process will not linearly track valve stem position. Instead, it will “droop” as the valve is further opened . This “drooping” graph is called the valve’s installed characteristic.





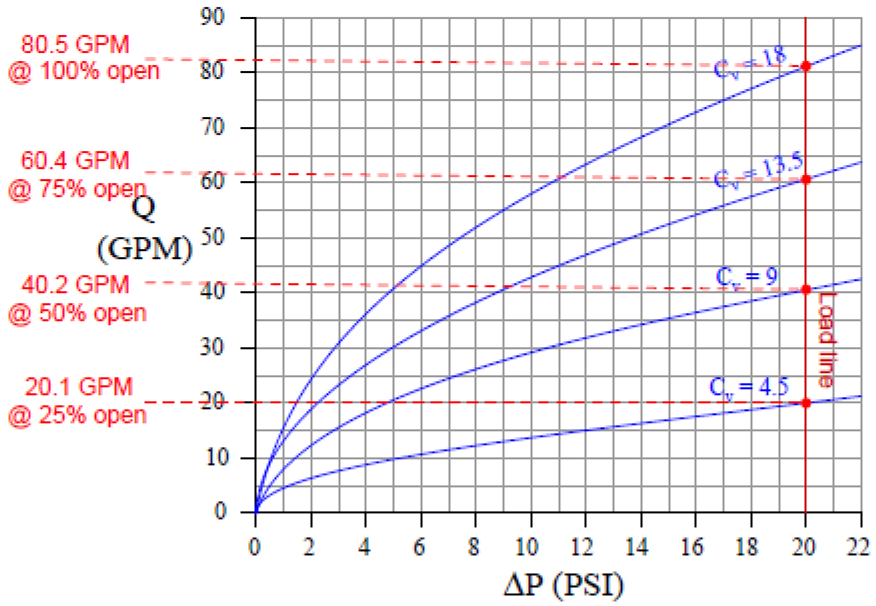
Control Valve Characterization

- Let us assume the control valve has a "linear" inherent characteristic and a maximum flow capacity (Cv rating) of 18.
- This means the valve's Cv will be 18 at 100% open, 13.5 at 75% open, 9 at 50% open, 4.5 at 25% open, and 0 at fully closed (0% open).
- We may plot the behavior of this control valve at these four stem positions by graphing the amount of flow through the valve for varying degrees of pressure drop across the valve. The result is a set of characteristic curves for our hypothetical control valve.



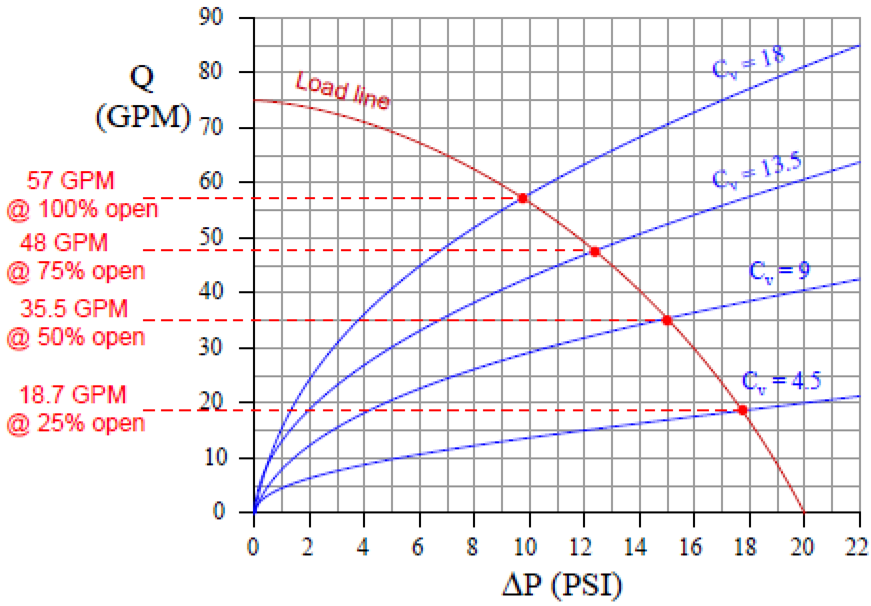
Control Valve Characterization

Inherent



Opening (%)	C_v	Flow rate (GPM)
0	0	0
25	4.5	20.1
50	9	40.2
75	13.5	60.4
100	18	80.5

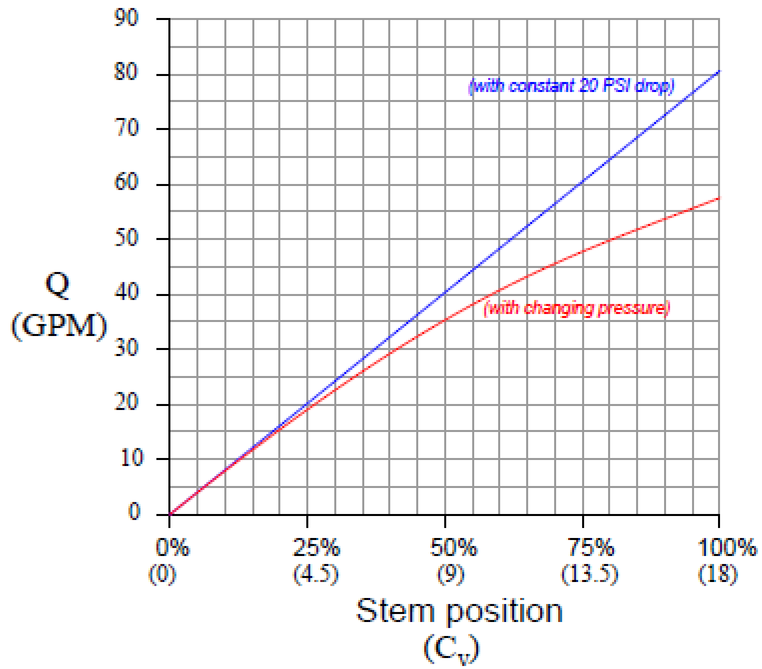
Installed



Opening (%)	C_v	Flow rate (GPM)
0	0	0
25	4.5	18.7
50	9	35.5
75	13.5	48
100	18	57

Control Valve Characterization

- If we plot the valve's performance in both scenarios we see the difference very clearly.



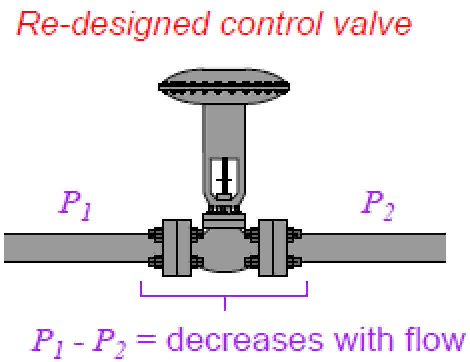
- The "drooping" graph shows how the valve responds when it does not receive a constant pressure drop throughout the flow range. This is how the valve responds when installed in a non-ideal process, compared to the straight-line response it exhibits under ideal conditions of constant pressure.
- Any piping system that fails to provide constant pressure across a control valve will "distort" the valve's inherent characteristic in the same "drooping" manner, and this must be compensated in some way if we desire linear response from the valve.

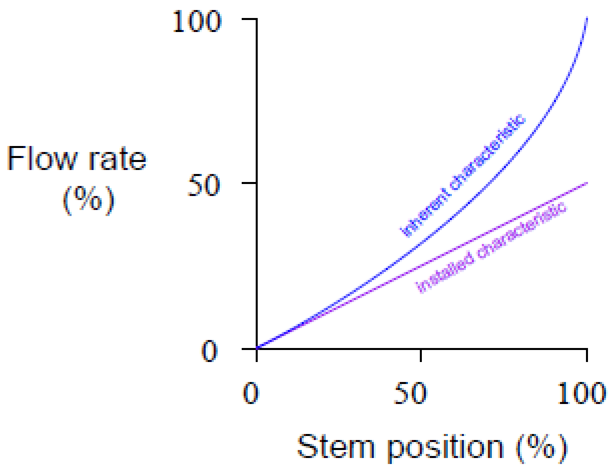
Control Valve Characterization

- Note how the installed characteristic graph is relatively steep at the beginning where the valve is nearly closed, and how the graph grows "flatter" at the end where the valve is nearly full-open. The rate of response (rate-of-change of flow Q compared to stem position x, which may be expressed as the derivative (dQ/dx) is much greater at low flow rates than it is at high flow rates, all due to diminished pressure drop at higher flow rates.
- This means the valve will respond more "sensitively" at the low end of its travel and more "sluggishly" at the high end of its travel.
- From the perspective of a flow control system, this varying valve responsiveness means the system will be unstable at low flow rates and unresponsive at high flow rates.
- At low flow rates, there the valve is nearly closed, any small movement of the valve stem will have a relatively large effect on flow. However, at high flow rates, a much greater stem motion will be required to effect the same change in flow.
- Thus, the control system will tend to over-react at low flow rates and under-react at high flow rates, simply because the control valve fails to exert the same degree of control over process flow at different flow rates.

Characterized Valve Trim

- The root cause of the problem – a varying pressure drop caused by frictional losses in the piping and other factors – generally cannot be eliminated.
- However, there is a clever way to to purposely design the valve such that its inherent characteristic complements the process "distortion" caused by changing pressure drop.
- In other words, we design the control valve trim so it opens up gradually during the initial stem travel (near the closed position), then opens up more rapidly during the final stages of stem travel (near the full-open position).
- With the valve made to open up in a nonlinear fashion inverse to the "droop" caused by the installed pressure changes, the two non-linearities should cancel each other and yield a more linear response.
- This re-design will give the valve a nonlinear characteristic when tested in the laboratory with constant pressure drop, but the installed behavior should be more linear.





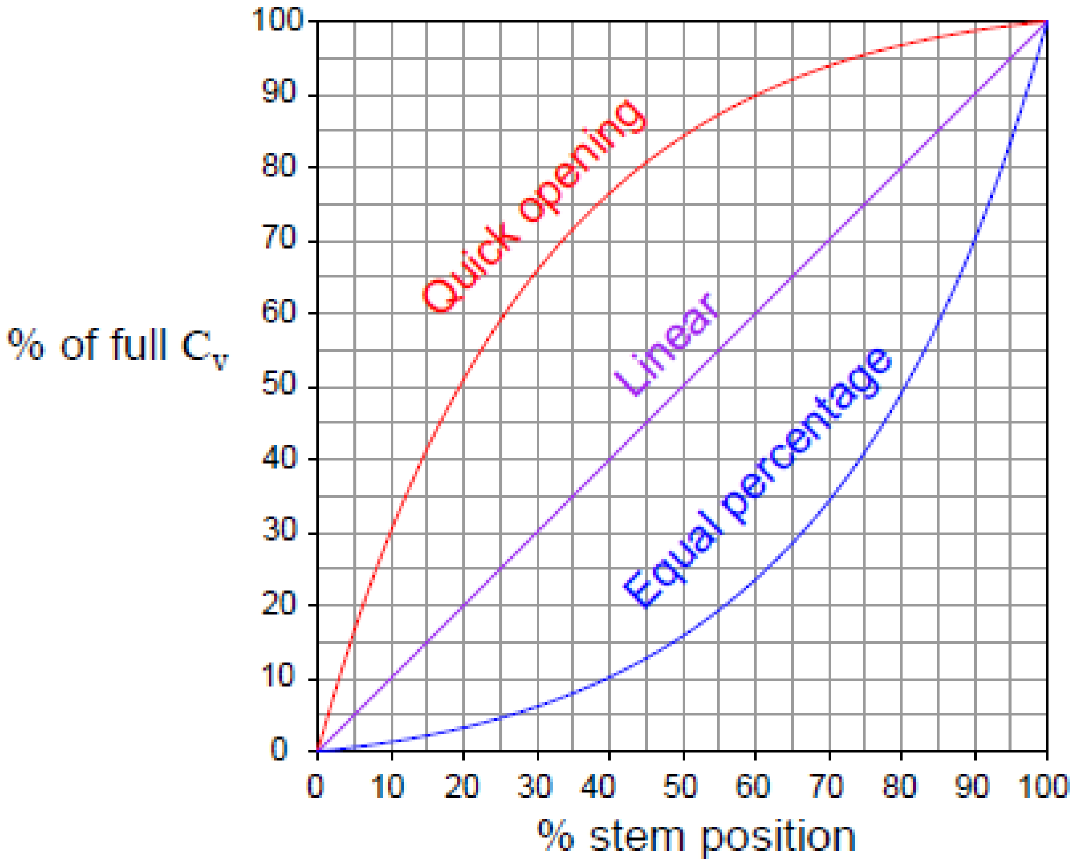
Valve Trim Characteristics

➢ Control valve trim is manufactured in a variety of different inherent “characteristics” to provide the desired installed behavior.

❖ Quick-opening

❖ Linear

❖ Equal percentage



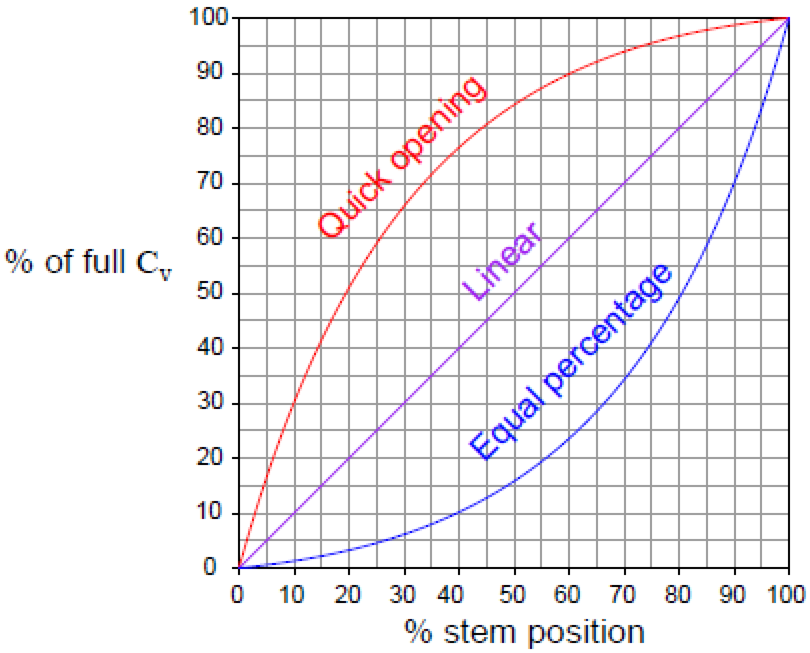
Valve Trim Characteristics

❖ Quick-opening

The quick–**opening** flow characteristic provides for maximum change in flow rate at low valve travels with a nearly linear relationship. Additional increases in valve travel give sharply reduced changes in flow rate, and when the valve plug nears the wide open position, the change in flow rate approaches zero.

Applications:

- On/off applications where significant flow rate must be established quickly as the valve begins to open. consequently, they are often used in relief valve applications.



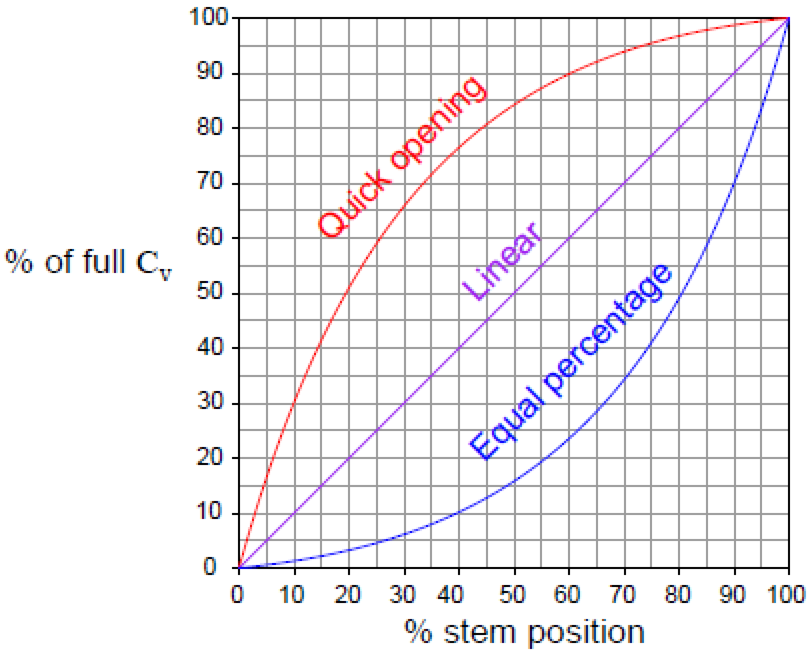
Valve Trim Characteristics

❖ Linear

The linear flow characteristic curve shows that the flow rate is directly proportional to the valve travel. This proportional relationship produces a characteristic with a constant slope so that with constant pressure drop, the valve gain will be the same at all flows throughout the travel range.

Applications:

- Valves with a linear characteristic are often specified for liquid level control and for flow control applications requiring constant gain.



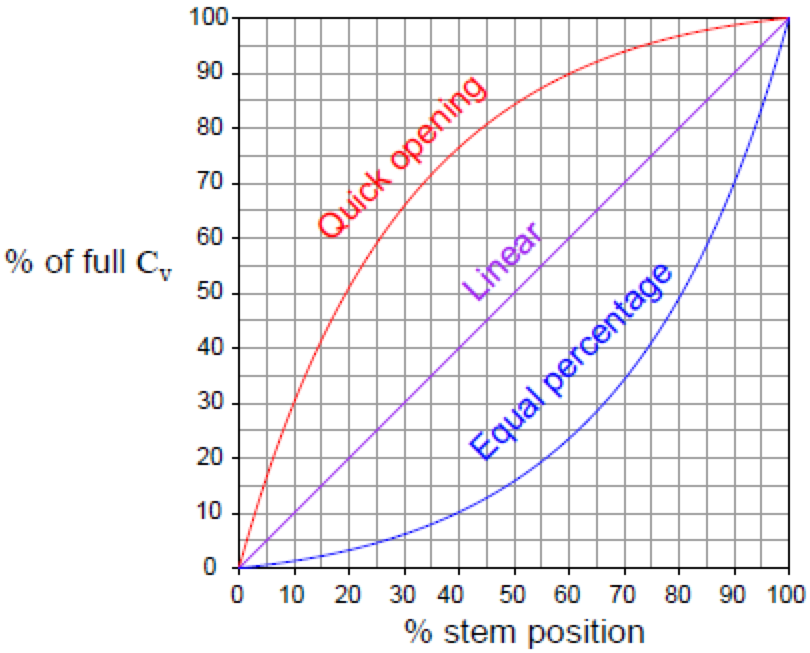
Valve Trim Characteristics

❖ Equal Percentage

Ideally, for equal increments of valve plug travel, the change in flow rate regarding travel may be expressed as a constant percent of the flow rate at the time of the change.

Applications:

- ➢ Pressure control applications, on applications where a large percentage of the pressure drop is normally absorbed by the system itself with only a relatively small percentage available at the control valve and on applications where highly varying pressure drop conditions can be expected.



Valve Trim Characteristics

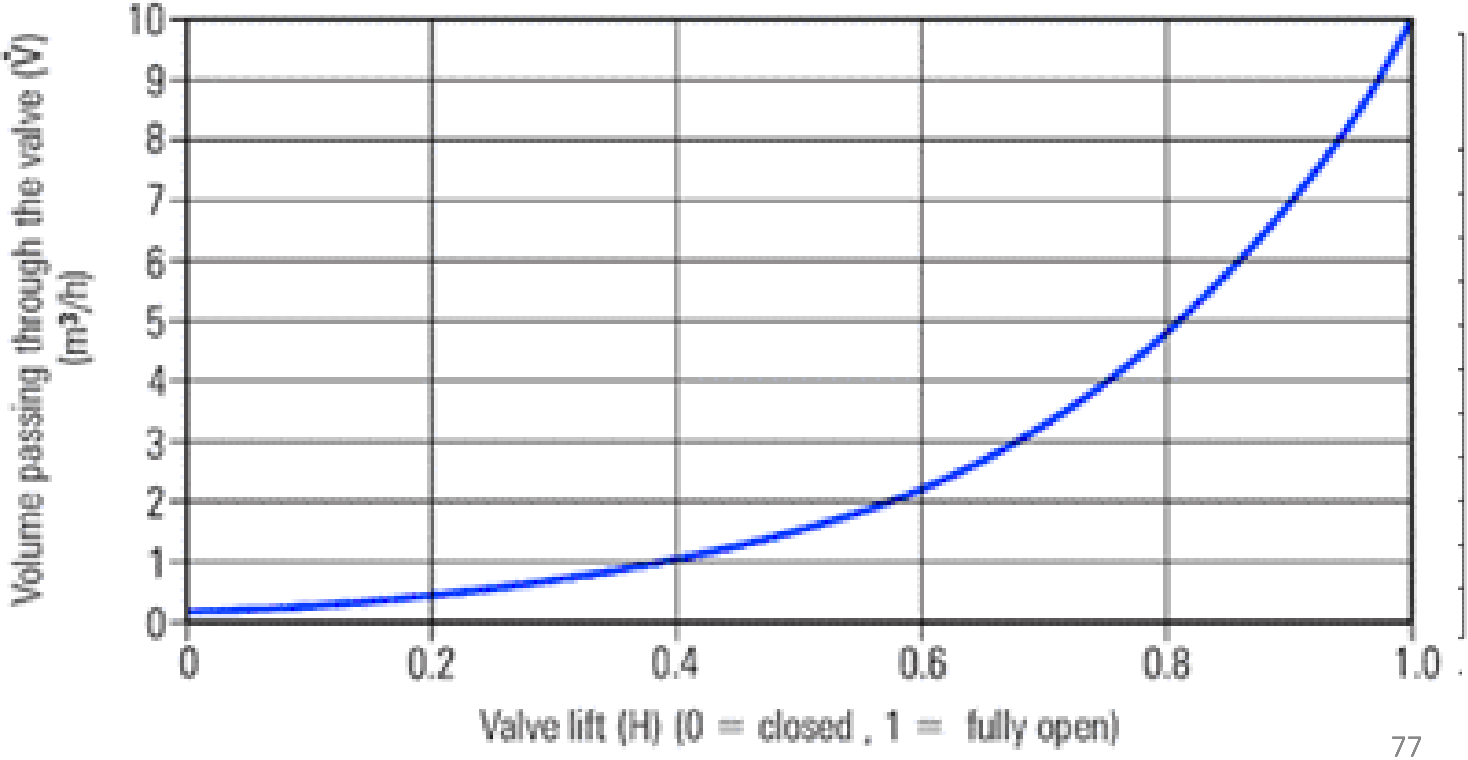
❖ Equal Percentage

$$Q = \frac{e^{(\ln\tau)H}}{\tau} Q_{\max} \; ; where, \tau = Valve Rangeability \left(\frac{Q_{\max\, controllable}}{Q_{\min\, controllable}} \right),$$

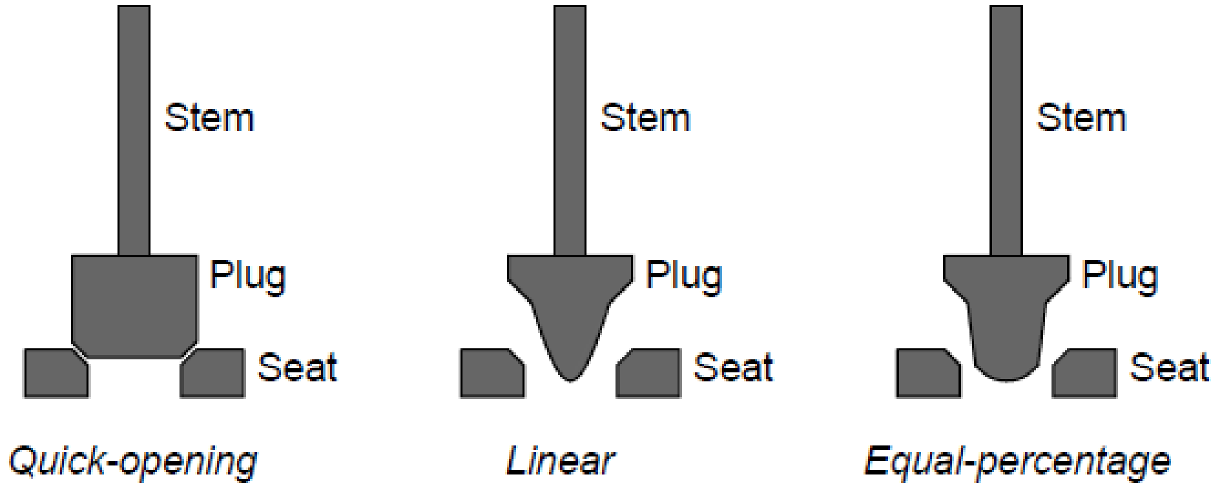
$$H = Valve\, Lift\, (0 = close, 1 = fully\, open); Q_{\max} = Max.\ vol.\ flow\ through\ valve.$$

Q_{max} = 10 m^3/h

τ=50



Valve Trim Characteristics



Plug Profiles Of A Single-ported, Stem-guided Globe Valve

Characterized Cages for Globe-Style Valve Bodies

Valve Sizing

❖ STEP 1: Define the system

The system is pumping water from one tank to another through a piping system with a total pressure drop of 150 psi. The fluid is water at 70 ^{0}F.   Design (maximum) flowrate of 150 gpm, operating flowrate of 110 gpm, and a minimum flowrate of 25 gpm. The pipe diameter is 3 inches. At 70 ^{0}F, water has a specific gravity of 1.0.

Key Variables: Total pressure drop, design flow, operating flow, minimum flow, pipe diameter, specific gravity

Valve Sizing

- STEP 2: Define a maximum allowable pressure drop for the valve

  The usual rule of thumb is that a valve should be designed to use 10-15% of the total pressure drop or 10 psi, whichever is greater.

  For our system, 10% of the total pressure drop is 15 psi which is what we'll use as our allowable pressure drop when the valve is wide open.

- STEP 3: Calculate the valve characteristic

$$C_v = Q\sqrt{\frac{G}{\Delta P}}$$

where:

$Q =$ design flowrate (gpm)

$G =$ specific gravity relative to water

$\Delta P =$ allowable pressure drop across wide open valve

For our system,

$$C_v = 150\sqrt{\frac{1}{15}} = 38.7 \cong 39$$

Valve Sizing

- STEP 4: Preliminary valve selection
  - Don't make the mistake of trying to match a valve with your calculated Cv value. The Cv value should be used as a guide in the valve selection, not a hard and fast rule.
  - Some other considerations are:
    - ✓ Never use a valve that is less than half the pipe size,
    - ✓ Avoid using the lower 10% and upper 20% of the valve stroke. The valve is much easier to control in the 10-80% stroke range.

Before a valve can be selected, decide what type of valve will be used.

For our case, we'll assume we're using an equal percentage, globe valve. The valve chart for this type of valve is shown below.

Valve Sizing

❖ STEP 4: Preliminary valve selection

FLOW CHARAC-TERISTIC	VALVE SIZE		MAXI-MUM TRAVEL	PORT DIA.	DESIGNS ED AND ET (FLOW DOWN)					DESIGN ES (FLOW UP)				
					Valve Opening, Percent of Total Travel									
					10	30	70	100	100	10	30	70	100	100
	DIN	Inches	mm	mm	C_v				F_L	C_v				F_L
Equal Percentage	DN 25	1, 1-1/4	19	33.3	.783	2.20	7.83	17.2	.88	.783	1.86	9.54	17.4	.95
	DN 40	1-1/2	19	47.6	1.52	3.87	17.4	35.8	.84	1.54	3.57	17.2	33.4	.94
	DN 50	2	29	58.7	1.66	4.66	25.4	59.7	.85	1.74	4.72	25.0	56.2	.92
	DN 65	2-1/2	38	73.0	3.43	10.8	49.2	99.4	.84	4.05	10.6	45.5	82.7	.93
	DN 80	3	38	87.3	4.32	10.9	66.0	136	.82	4.05	10.0	59.0	121	.89
	DN 100	4	51	111.1	5.85	18.3	125	224	.82	6.56	17.3	103	203	.91
	DN 150	6	51	177.8	12.9	43.3	239	394	.85	13.2	41.1	223	357	.86
	DN 200	8	76	203.2	27.0	105	605	818	.96	25.9	97.8	618	808	.85
					X_T				---	X_T				---
	DN 25	1, 1-1/4	19	33.3	.766	.587	.743	.667	---	.754	.763	.630	.721	---
	DN 40	1-1/2	19	47.6	.780	.716	.690	.679	---	.674	.694	.698	.793	---
	DN 50	2	29	58.7	.827	.774	.702	.687	---	.863	.849	.792	.848	---
	DN 65	2-1/2	38	73.0	.778	.678	.661	.660	---	.747	.745	.783	.878	---
	DN 80	3	38	87.3	.774	.682	.663	.675	---	.768	.761	.754	.757	---
	DN 100	4	51	111.1	.731	.643	.672	.716	---	.722	.739	.718	.822	---
	DN 150	6	51	177.8	.688	.682	.736	.778	---	.723	.767	.808	.816	---
	DN 200	8	76	203.2	.644	.636	.725	.807	---	.825	.681	.735	.827	

For our case, it appears the 2 inch valve will work well for our Cv value at about 80-85% of the stroke range. Notice that we're not trying to squeeze our Cv into the 1 1/2 valve which would need to be at 100% stroke to handle our maximum flow.

Valve Sizing

❖ STEP 5: Check the Cv and stroke percentage at the minimum flow

Cv at minimum flowrate:

$$C_v = 25\sqrt{\frac{1}{15}} = 6.5$$

Referring back to our valve chart, we see that a Cv of 6.5 would correspond to a stroke percentage of around 35-40% which is certainly acceptable.

Notice that we used the maximum pressure drop of 15 psi once again in our calculation. Although the pressure drop across the valve will be lower at smaller flowrates, using the maximum value gives us a "worst case" scenario. If our Cv at the minimum flow would have been around 1.5, there would not really be a problem because the valve has a Cv of 1.66 at 10% stroke and since we use the maximum pressure drop, our estimate is conservative. Essentially, at lower pressure drops, Cv would only increase which in this case would be advantageous.

Valve Sizing

❖ STEP 6: Check the gain across applicable flow rates

Gain is defined as:

$$\text{Gain} = \frac{\Delta\,\text{Flow}}{\Delta\,\text{Stroke or Travel}}$$

Now, at our three flow rates:

Qmin = 25 gpm
Qop = 110 gpm
Qdes = 150 gpm

We have corresponding Cv values of 6.5, 28, and 39. The corresponding stroke percentages are 35%, 73%, and 85% respectively. Now we construct the following table:

<table>
<tr><th>Flow (gpm)</th><th>Stroke (%)</th><th>Change in flow (gpm)</th><th>Change in Stroke (%)</th></tr>
<tr><td>25</td><td>35</td><td rowspan="2">110-25 = 85</td><td rowspan="2">73-35 = 38</td></tr>
<tr><td>110</td><td>73</td></tr>
<tr><td>150</td><td>85</td><td rowspan="2">150-110 = 40</td><td rowspan="2">85-73 = 12</td></tr>
<tr><td colspan="2"></td></tr>
</table>

Gain #1 = 85/38 = 2.2
Gain #2 = 40/12 = 3.3

The difference between these values should be less than 50% of the higher value.

0.5 of 3.3 = 1.65 and 3.3 - 2.2 = 1.10.

Since 1.10 is less than 1.65, there should be no problem in controlling the valve. Also note that the gain should never be less than 0.50. So for our case, our selected valve will do nicely!

Valve Selection

- Equal Percentage: equal increments of valve travel produce an equal percentage in flow change.
  Linear: valve travel is directly proportional to the valve stoke.
  Quick opening: large increase in flow with a small change in valve stroke.

- So how do you decide which valve control to use? Here are some rules of thumb for each one:

  1. Equal Percentage (most commonly used valve control)
     a. Used in processes where large changes in pressure drop are expected
     b. Used in processes where a small percentage of the total pressure drop is permitted by the valve
     c. Used in temperature and pressure control loops

  2. Linear
     a. Used in liquid level or flow loops
     b. Used in systems where the pressure drop across the valve is expected to remain fairly constant (ie. steady state systems)

  3. Quick Opening
     a. Used for frequent on-off service.
     b. Used for processes where "instantly" large flow is needed (ie. safety systems or cooling water systems.)

Control Valve Problems

- Mechanical Friction
- Flashing
- Cavitation
- Choked flow
- Valve noise
- Erosion
- Chemical Attack

Control Valve Problems

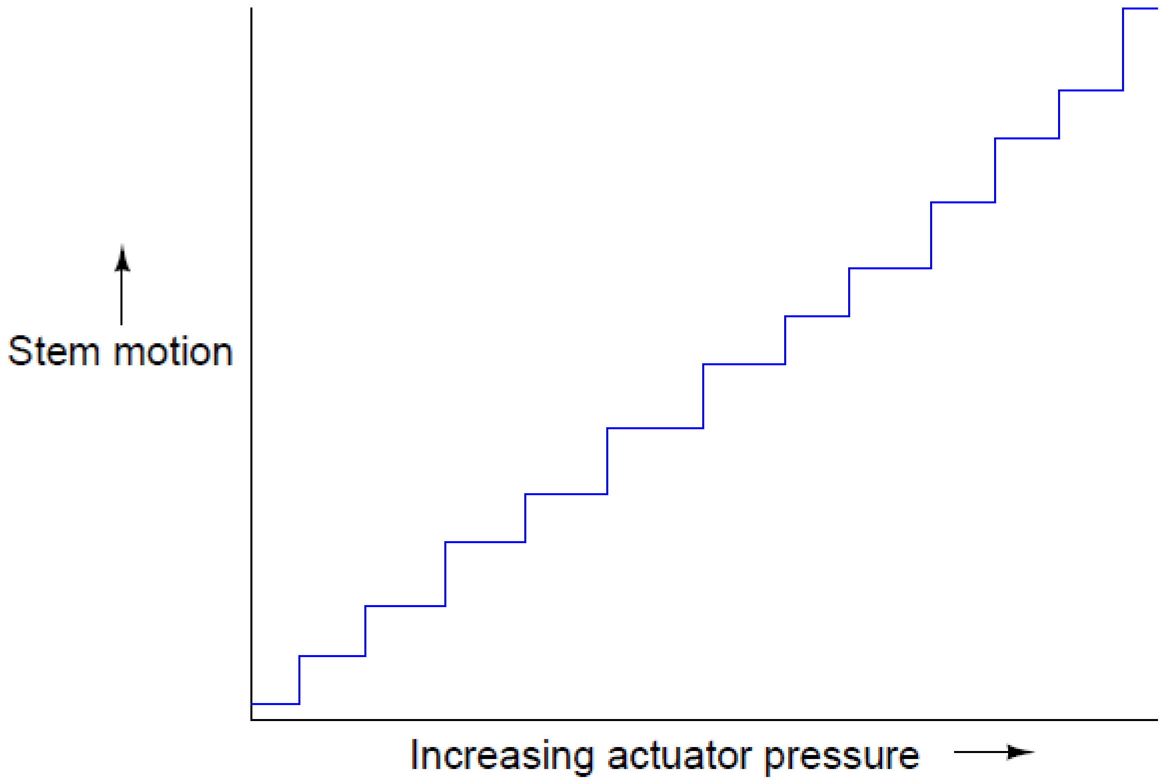
Mechanical Friction

- ✓ Control valves are mechanical devices having moving parts, and as such they are subject to friction (static or dynamic), primarily between the valve stem and the stem packing.
- ✓ The presence of packing friction in a control valve increases the force necessary from the actuator to cause valve movement.
- ✓ Instead of the stem smoothly lifting immediately as pressure exceeds the bench-set value, the valve will remain fully closed until enough extra pressure has accumulated in the actuator to generate a force large enough to overcome spring tension plus packing friction.
- ✓ Effect of static and dynamic friction induces "slip-stick" response of the stem motion.
- ✓ In order to reverse the direction of stem motion, not only does the static friction have to be "relaxed" from the last movement, but additional static friction must be overcome in the opposite direction before the stem is able to move that way.

Control Valve Problems

Mechanical Friction

- ✓ To use numerical quantities, if pressure increments of 0.5 PSI are required to repeatedly overcome static friction in the upward (opening) direction, a pressure decrement of approximately twice that (1.0 PSI) will be required to make the stem go downward even just a bit.



Control Valve Problems

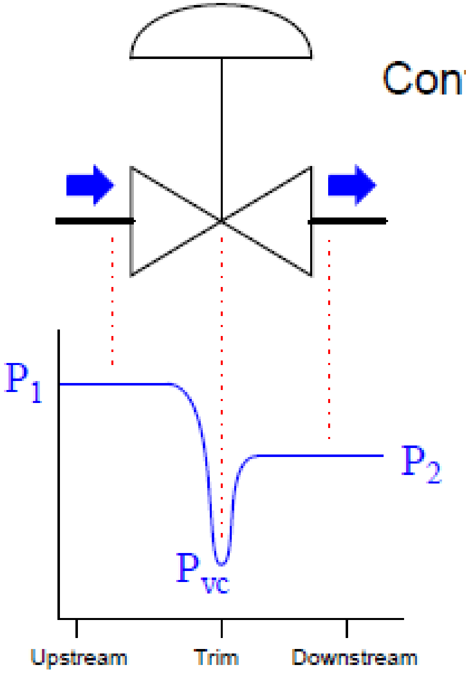
Mechanical Friction

Control Valve Problems

Flashing

- ✓ If the fluid being throttled by the valve is a liquid and its absolute pressure ever falls below the vapor pressure of that substance, the liquid will begin to boil. This phenomenon, when it happens inside a control valve, is called Flashing.

- ✓ As the graph shows, the point of lowest pressure inside the valve (called the vena contracta pressure, or Pvc) is the location where flashing will first occur, if it occurs at all.



Control Valve Problems

Flashing

- ✓ The effect of boiling liquid at the point of maximum constriction is that flow through the valve becomes "choked" by the rapid expansion of liquid to vapor as it boils, severely inhibiting the total flow rate allowed through the valve.
- ✓ Flashing is also destructive to the valve trim, as boiling action propels tiny droplets of liquid at extremely high velocities past the plug and seat faces, eroding the metal over time.
- ✓ Pressure recovery is the amount that fluid pressure increases from the minimum pressure at the vena contracta to the downstream pressure:

  P2 − Pvc.
- ✓ Pressure Recovery Factor

$$F_L = \sqrt{\frac{P_1 - P_2}{P_1 - P_{vc}}}$$

Where,

FL = Pressure recovery factor (unit less)

P1 = Absolute fluid pressure upstream of the valve

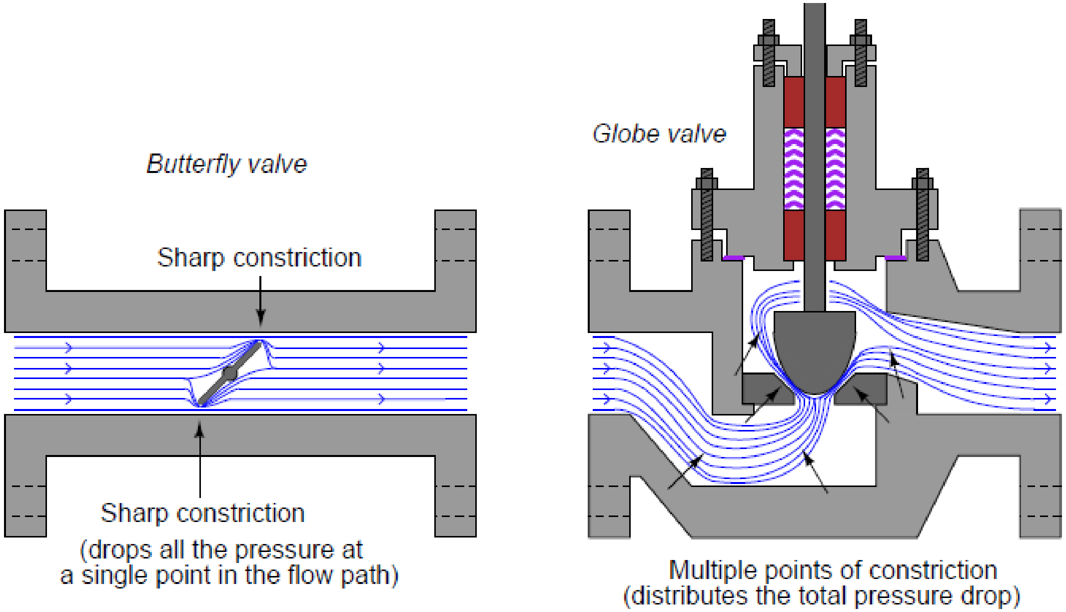
P2 = Absolute fluid pressure downstream of the valve

Pvc = Absolute fluid pressure at the vena contracta (point of minimum fluid pressure within the valve)

Control Valve Problems

Flashing

- ✓ The style of valve (ball, butterfly, globe, etc.) is very influential on pressure recovery factor.



- ✓ The globe valve does a better job of evenly distributing pressure losses throughout the path of flow. By contrast, the butterfly valve can only drop pressure at the points of constriction between the disk and the valve body, because the rest of the valve body is a straight-through path for fluid offering little restriction at all. As a consequence, the butterfly valve experiences a much lower vena contracta pressure (i.e. greater pressure recovery, and a lower FL value) than the globe valve for any given amount of permanent pressure loss, making the butterfly valve more prone to flashing than the globe valve with all other factors being equal.

Control Valve Problems

Cavitation

- ✓ If, the pressure recovers to a point greater than the vapor pressure of the liquid, the vapor will re-condense back into liquid again. This is called Cavitation.
- ✓ When vapor bubbles re-condense into liquid they often do so asymmetrically, one side of the bubble collapsing before the rest of the bubble. This has the effect of translating the kinetic energy of the bubble's collapse into a high-speed "jet" of liquid in the direction of the asymmetrical collapse.
- ✓ These liquid "microjets" have been experimentally measured at speeds up to 100 meters per second (over 320 feet per second).
- ✓ Each microjet strikes the valve component surface over a very small surface area, resulting in a very high pressure ($P = F/A$) applied to that small area.
- ✓ The effect of each microjet impinging on a metal surface is to carve out a small pocket in that metal surface. Over time, the metal will begin to take on a "pock-marked" look over the area where cavitation occurs.

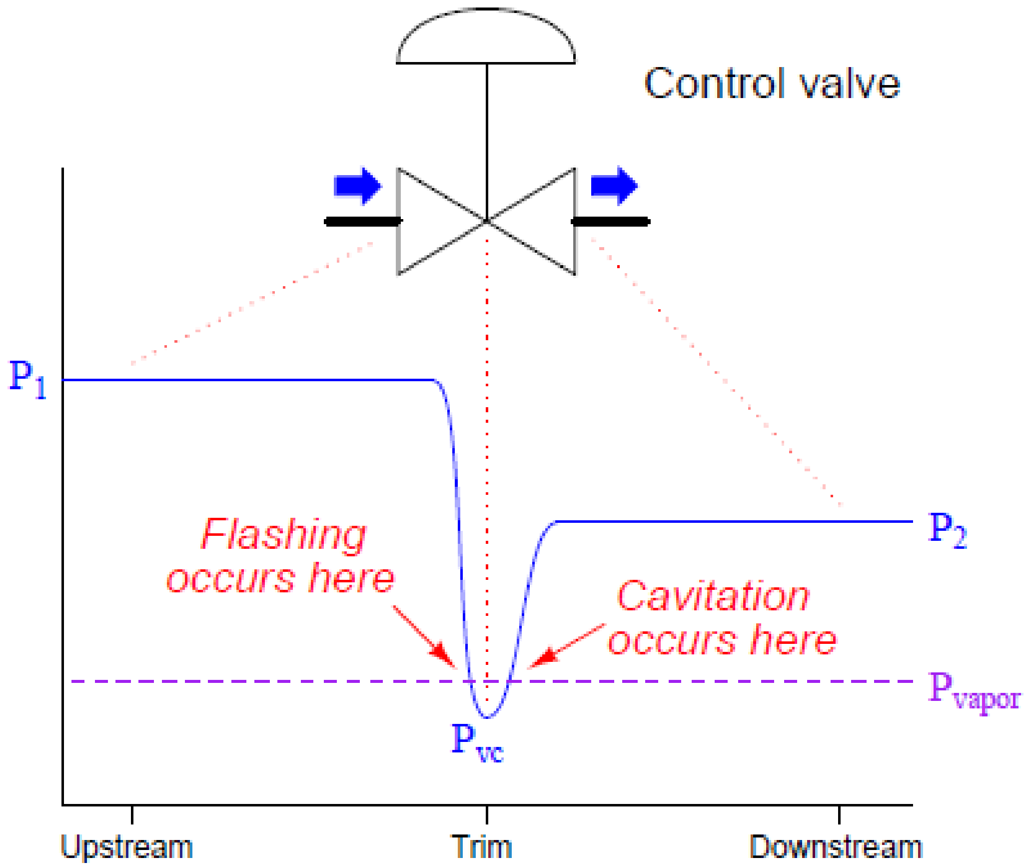
Control Valve Problems

Photographs of a fluted valve plug and its matching seat are shown here as evidence of flashing and cavitation damage, respectively:

- ✓ The flashing damage is responsible for the relatively smooth wear areas seen on the plug.
- ✓ Cavitation damage is most prominent inside the seat, where almost all the damage is in the form of pitting.
- ✓ The mouth of the seat exhibits smooth wear caused by flashing, but deeper inside you can see the pock-marked surface characteristic of cavitation, where liquid microjets literally blasted away pieces of metal.

Control Valve Problems

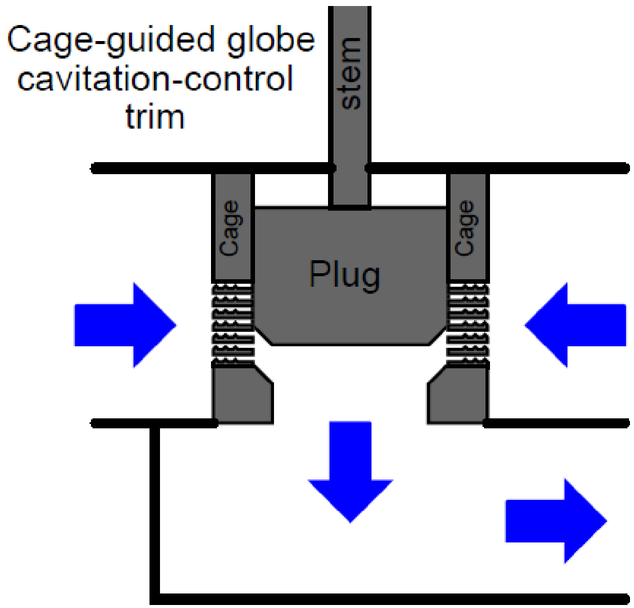
- ✓ Flashing sounds as though sand were flowing through the valve, cavitation produces a much louder "crackling" sound comprised of distinct impact pulses, reminiscent of what gravel or rocks might sound like if they were somehow forced to flow through the valve.

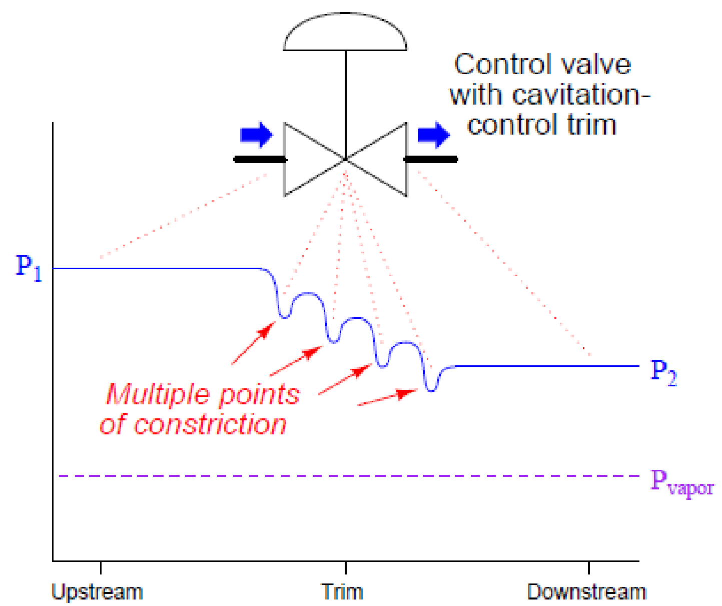


Control Valve Problems

Cavitation-control valve trim:

- ✓ Valve trim may be specially designed for cavitation abatement by providing multiple stages of pressure drop for the fluid as it passes through the trim.
- ✓ A valve equipped with cavitation-control trim will have a different pressure profile, with multiple vena contracta points where the fluid passes through a series of constrictions within the trim itself.
- ✓ This way, the same final permanent pressure drop (P1 **−P**2) may be achieved without the lowest pressure ever falling below the liquid's vapor pressure limit.





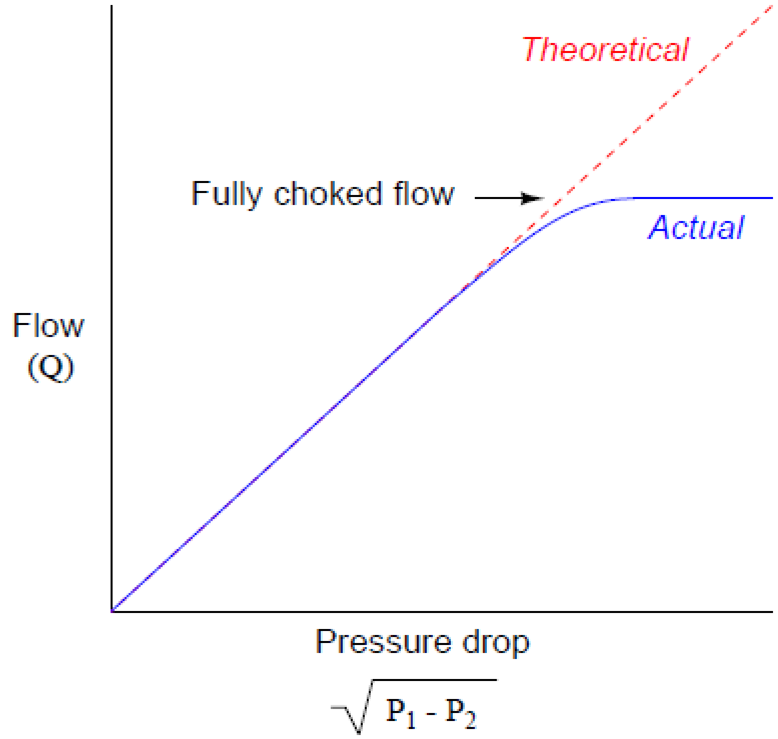
Control Valve Problems

Choked Flow

- ✓ "Choked flow" is a condition where the rate of flow through a valve does not change substantially as downstream pressure is reduced.
- ✓ Choking occurs when the velocity of the fluid reaches the speed of sound for that fluid.
- ✓ Pressure changes propagate through any fluid at the speed of sound within that fluid.
- ✓ If a fluid stream happens to move at or above the speed of sound, pressure changes downstream are simply not able to overcome the stream's velocity to affect anything upstream, which explains why the flow rate through a control valve experiencing sonic (critical) flow velocities does not change with changes in downstream pressure: those downstream pressure changes cannot propagate upstream against the fast-moving flow, and so will have no effect on the flow as it accelerates to sonic velocity at the point(s) of constriction.

Control Valve Problems

Choked Flow

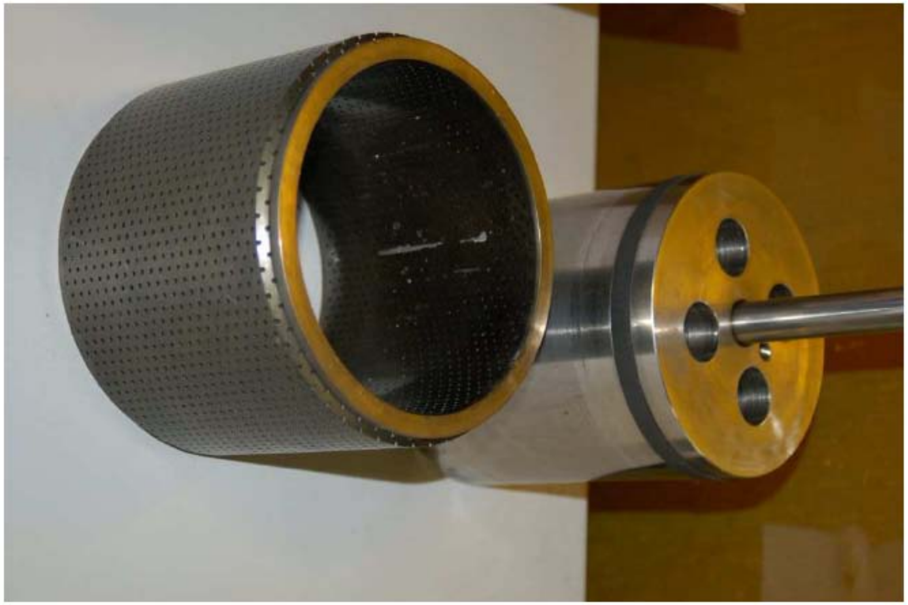


- ✓ In a choked flow condition, further reductions in downstream pressure achieve no greater flow of liquid through the valve. This is not to say that the valve has reached a maximum flow – we may still increase flow rate through a choked valve by increasing its upstream pressure. We simply cannot coax more flow through a choked valve by decreasing its downstream pressure.

Control Valve Problems

Valve Noise

- ✓ Noise produced due to the phenomenon of flashing, cavitation and sonic flow.
- ✓ One way to reduce noise output is to use special valve trim resembling the trim used to mitigate cavitation.
- ✓ A common cage-guided globe valve trim design for noise reduction uses a special cage designed with numerous, small holes for process gas to flow through. These small holes shift the frequency of that noise up above the human hearing range.



Control Valve Problems

Erosion

A problem common to control valves used in slurry service (where the process fluid is a liquid containing a substantial quantity of hard, solid particles) is erosion, where the valve trim and body are worn by the passage of solid particles.

Chemical attack

Corrosive chemicals may attack the metal components of control valves if those components are not carefully selected for the proper service.

References

- R. Kuphaldt, “Lessons In Industrial Instrumentation”, Version 1.14, January 11, 2011.
- Control Valve Handbook, Fourth Edition, Fisher Controls International , 2005.
- Classification Of Valves, PPT, M. Ganesh Murugan.

Thank You