Control Valves

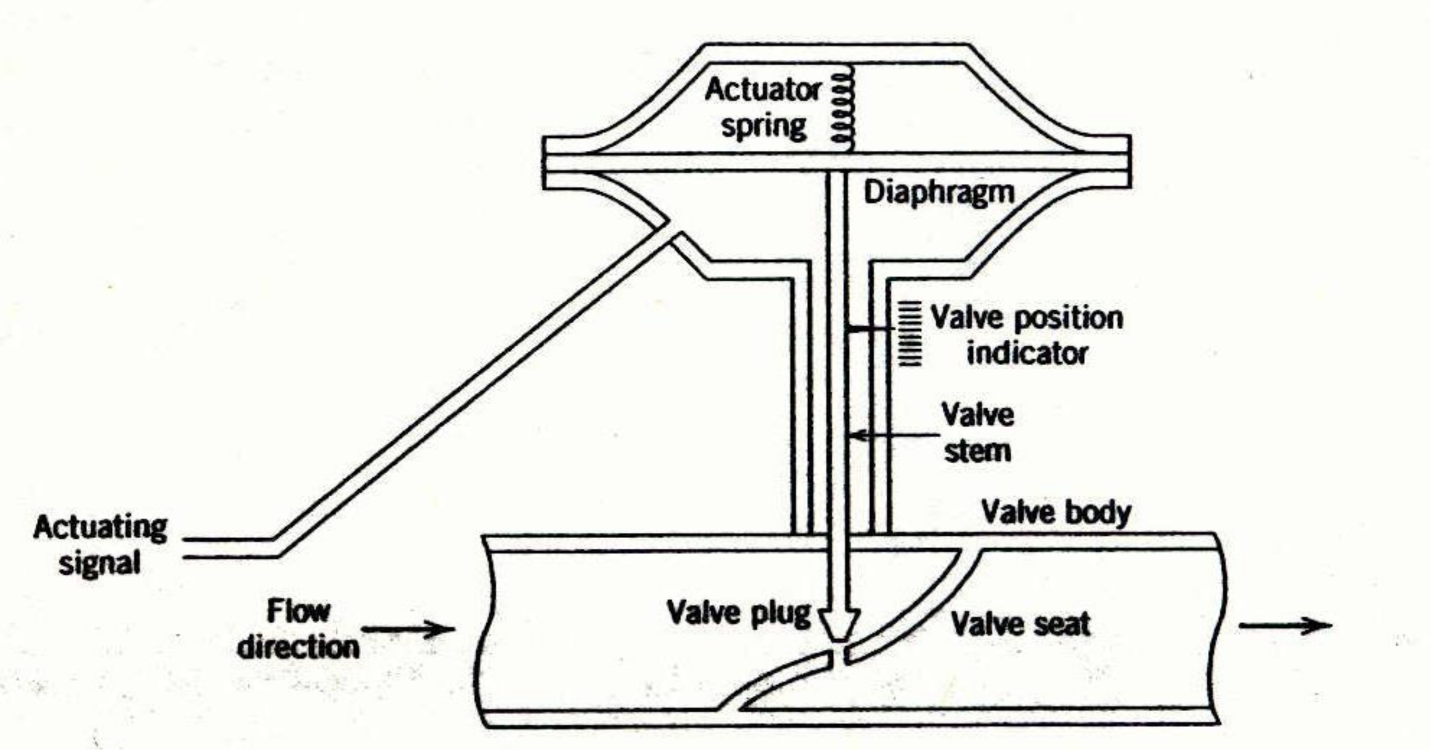
I&CE, MIT, Manipal

Control Valves

- There are many different ways to manipulate the flows of material and energy into and out of a process; for example, the speed of a pump drive, screw conveyer, or blower can be adjusted.
- However, a simple and widely used method of accomplishing this result with fluids is to use a control valve, also called an *automatic control valve*.
- The control valve components include the valve body, trim, seat, and actuator.

Air-to-Open vs. Air-to-Close Control Valves

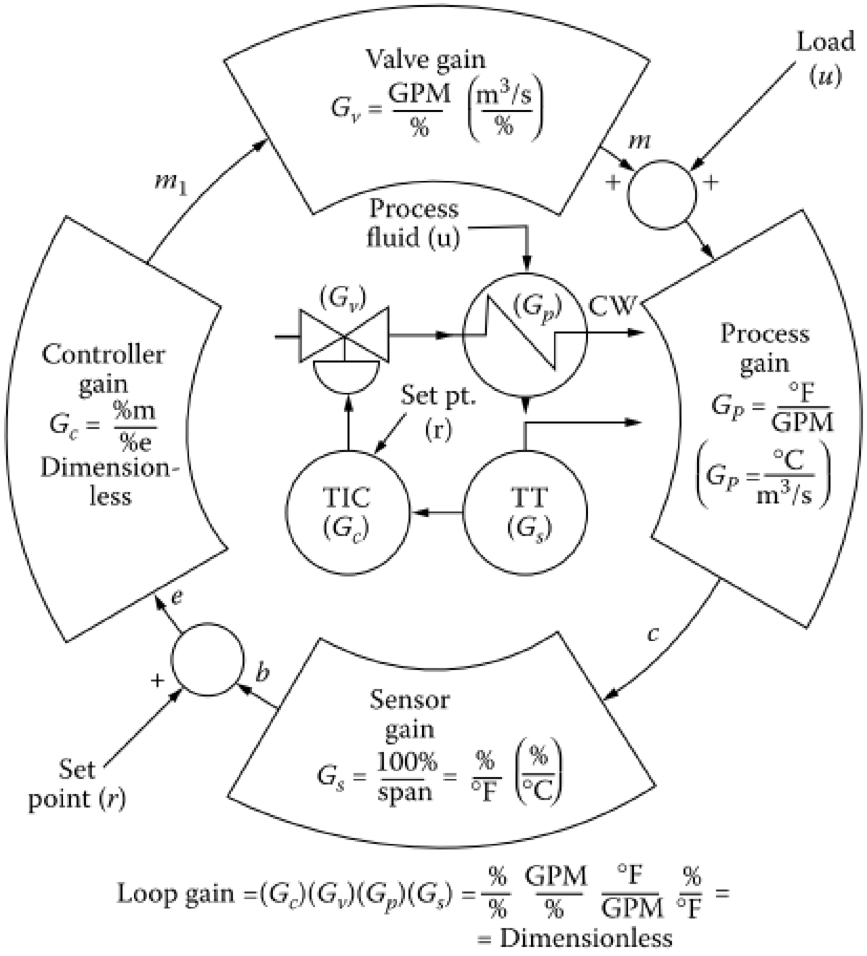
- Normally, the choice of A-O or A-C valve is based on safety considerations.



Characteristics, Gain, and Rangeability

- Good control valve performance usually means that
  - the valve is stable across its full operating range,
  - it is not operating near to one of its extreme positions,
  - it is fast enough to correct for process upsets or disturbances,
  - it will not be necessary to retune the controller every time the process load changes.
- In order to meet the above goals, one must consider such factors as
  1. valve characteristics,
  2. rangeability,
  3. installed gain,
  4. actuator response.

Characteristics - Valve Gain and Loop Gain



Characteristics - Installed Valve Gain

- The inherent valve gain changes after the installation of the valve, if the valve pressure differential varies with load.
- This is the case in all mostly friction pumping systems, because as the load (flow) rises, the pressure drop in the piping system also increases, which leaves less pressure drop for the valve.
- As the valve differential pressure drops with increasing flow rate, the valve gain (Gv) also drops.
- This tends to shift the installed gain of equal-percentage valves towards linear and the installed gain of linear valves towards quick opening.

- All control valves have an inherent flow characteristic that defines the relationship between ‘valve opening’ and flowrate under constant pressure conditions.

- ‘valve opening’ in this context refers to the relative position of the valve plug to its closed position against the valve seat. It does not refer to the orifice pass area.

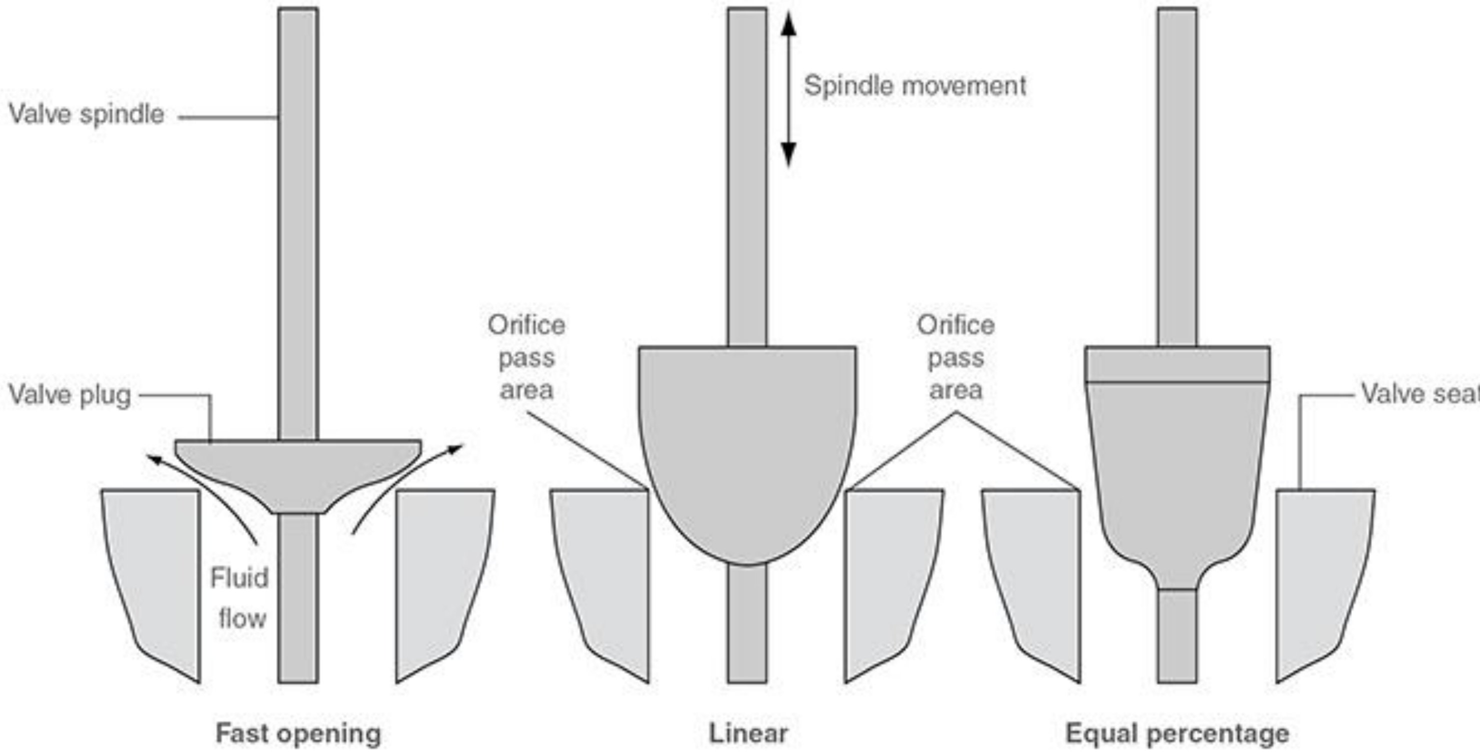
- The orifice pass area is sometimes called the ‘valve throat’ and is the narrowest point between the valve plug and seat through which the fluid passes at any time. For any valve, however it is characterised, the relationship between flowrate and orifice pass area is always directly proportional.

- Valves of any size or inherent flow characteristic which are subjected to the same volumetric flowrate and differential pressure will have exactly the same orifice pass area.

- However, different valve characteristics will give different ‘valve openings’ for the same pass area. Comparing linear and equal percentage valves, a linear valve might have a 25% valve opening for a certain pressure drop and flowrate, whilst an equal percentage valve might have a 65% valve opening for exactly the same conditions. The orifice pass areas will be the same.

- The physical shape of the plug and seat arrangement, sometimes referred to as the valve ‘trim’, causes the difference in valve opening between these valves. Typical trim shapes for spindle operated globe valves are compared in Figure

Valve Characteristics based on the trim shape



Equal percentage characteristic (or logarithmic characteristic)

These valves have a valve plug shaped so that each increment in valve lift increases the flowrate by a certain percentage of the previous flow. The relationship between valve lift and orifice size (and therefore flowrate) is not linear but logarithmic, and is expressed mathematically in Equation 6.5.1:

Equation 6.5.1 $$\dot{V} = \frac{e^x}{\tau}\dot{V}_{max}$$

Where:

$\dot{V}$ = Volumetric flow through the valve at lift H.

e = Exponential constant 2.718 3

x = (ln τ) H **Note:** 'ln' is a mathematical function known as 'natural logarithm'

τ = Valve rangeability (ratio of the maximum to minimum controllable flowrate, typically 50 for a globe type control valve)

H = Valve lift (0 = closed, 1 = fully open)

$\dot{V}_{max}$ = Maximum volumetric flow through the valve

The maximum flowrate through a control valve with an equal percentage characteristic is 10 m³/h. If the valve has a turndown of 50:1, and is subjected to a constant differential pressure, by using Equation 6.5.1 what quantity will pass through the valve with lifts of 40%, 50%, and 60% respectively?

$\dot{V}_{max}$ = Maximum volumetric flow through the valve = 10 m³/h

H = Valve lift (0 closed to 1 fully open) = 0.4; 0.5; 0.6

τ = Valve rangeability = 50

40% open, H = 0.4

$$x = (\ln \tau) \times H$$
$$x = (\ln 50) \times 0.4$$
$$x = 3.912 \times 0.4$$
$$\mathbf{x = 1.564\,8}$$
$$\dot{V} = \frac{e^{1.564\,8}}{\tau} \times 10$$
$$\dot{V} = \frac{4.781\,7}{50} \times 10$$
$$\dot{V} = 0.0956 \times 10$$
$$\mathbf{\dot{V} = 0.956\ m^3/h}$$

50% open, H = 0.5

$$x = (\ln \tau) \times H$$
$$x = (\ln 50) \times 0.5$$
$$x = 3.912 \times 0.5$$
$$\mathbf{x = 1.956}$$
$$\dot{V} = \frac{e^{1.956}}{\tau} \times 10$$
$$\dot{V} = \frac{7.071}{50} \times 10$$
$$\dot{V} = 0.141\,4 \times 10$$
$$\mathbf{\dot{V} = 1.414\ m^3/h}$$

60% open, H = 0.6

$$x = (\ln \tau) \times H$$
$$x = (\ln 50) \times 0.6$$
$$x = 3.912 \times 0.6$$
$$\mathbf{x = 2.347}$$
$$\dot{V} = \frac{e^{2.347}}{\tau} \times 10$$
$$\dot{V} = \frac{10.45}{50} \times 10$$
$$\dot{V} = 0.2091 \times 10$$
$$\mathbf{\dot{V} = 2.091\ m^3/h}$$

Change in flowrate and valve lift for an equal percentage characteristic with constant differential pressure

Valve Lift (H)	Flowrate from ($\dot{V}$ m³/h)	Increase in flow previous increment (%)
0.0	0.20 *	-
0.1	0.30	48%
0.2	0.44	48%
0.3	0.65	48%
0.4	0.96	48%
0.5	1.41	48%
0.6	2.09	48%
0.7	3.09	48%
0.8	4.57	48%
0.9	6.76	48%
1.0	10.00	48%

* Flowrate according to theoretical characteristic due to rangeability. In practice the valve will be fully shut at zero lift.

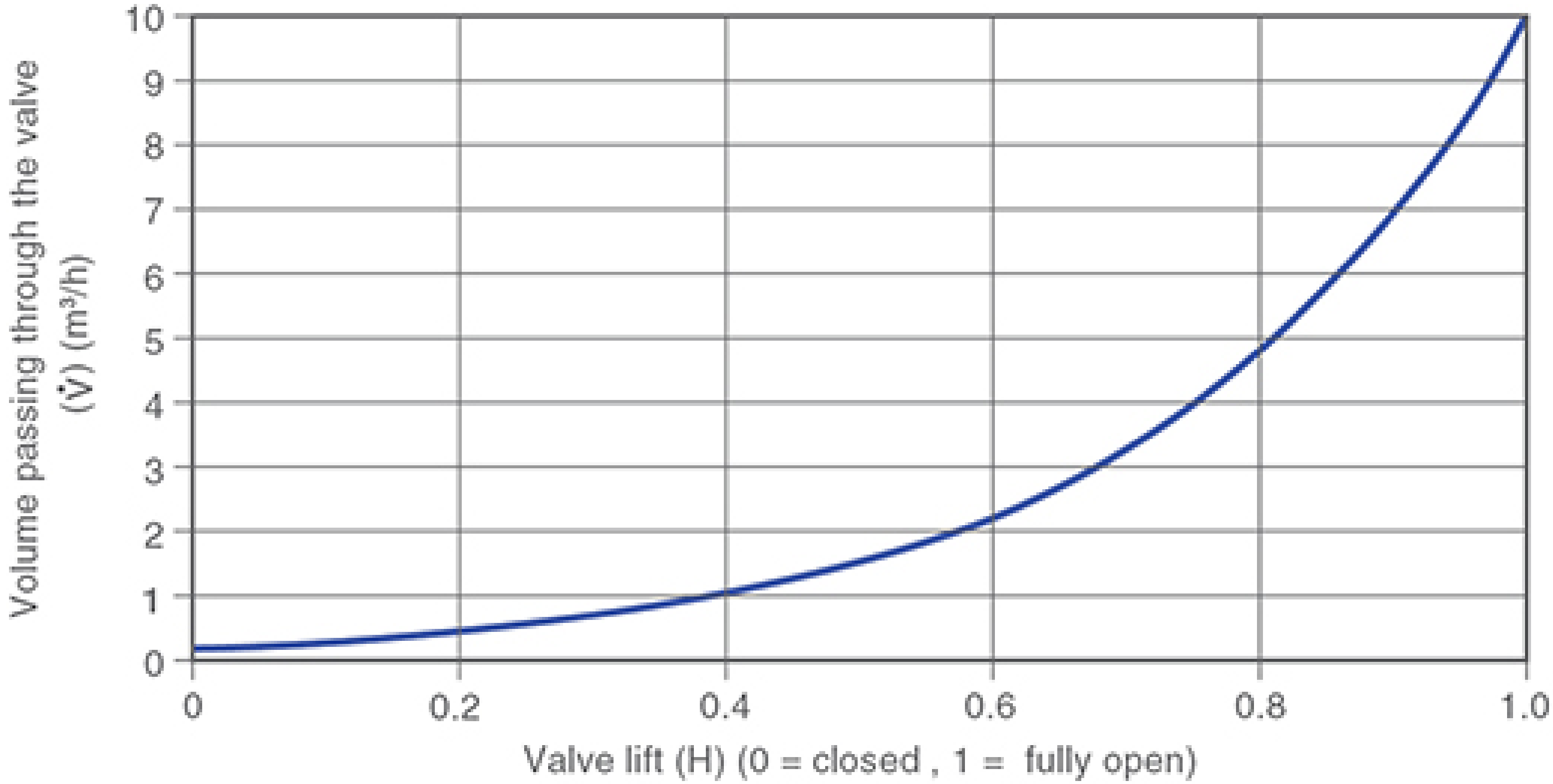


Fig. 6.5.4

Flowrate and valve lift for an equal percentage characteristic with constant differential pressure for Example 6.5.1

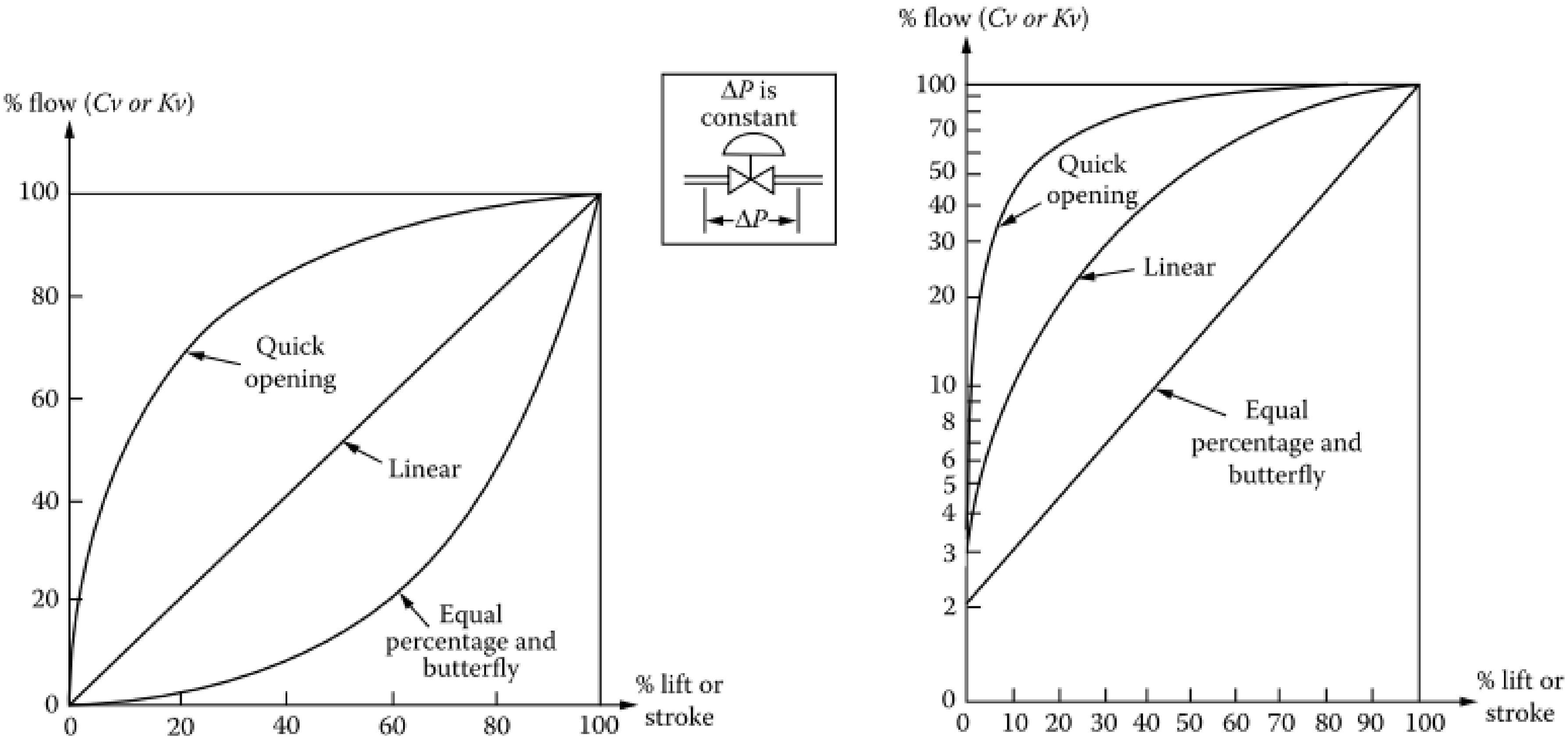
Characteristics - Installed Valve Gain

- The inherent characteristics of a control valve describes the relationship between the controller output signal received by the valve actuator and the flow through that valve, assuming that:

1. The actuator is linear (valve travel is proportional with controller output).
2. The pressure difference across the valve is constant.
3. The process fluid is not flashing, cavitating, or approaching sonic velocity (choked flow).

- Some of the widely used inherent lift to flow rate relationships are illustrated in Figure next slide.

Characteristics - Installed Valve Gain



Selecting the Valve Characteristics:

- Different engineers began to develop different rules of thumb to be used in selecting valve characteristics for the various types of control loops. These recommendations vary in complexity.
- Shinskey, for example, recommends equal percentage for temperature control and the use of linear valves for all flow, level, and pressure control applications (except vapour pressure, for which he recommends equal percentage).
- According to Driskell, one can avoid a detailed dynamic analysis by just considering the ratio of the maximum and minimum valve pressure drops (Δp max / Δp min) and follow the rule of thumbs listed for the most common applications in Table.

Selecting the Valve Characteristics:

Valve Characteristics Selection Guide

Service	*Valve* ($\Delta p_{max}/\Delta p_{min}$) *Under 2:1*	*Valve* ($\Delta p_{max}/\Delta p_{min}$) *Over 2:1 but Under 5:1*
Orifice-type flow	Quick-opening	Linear
Flow	Linear	Equal %
Level	Linear	Equal %
Gas pressure	Linear	Equal %
Liquid pressure	Equal %	Equal %

Selecting the Valve Characteristics:

Recommendations on Selecting Control Valve Characteristics for Flow, Level, and Pressure Control Loops‡

LIQUID LEVEL SYSTEMS	
Control Valve Pressure Drop	*Best Inherent Characteristic*
Constant ΔP	Linear
Decreasing ΔP with increasing load, ΔP at maximum load > 20% of minimum load ΔP	Linear†
Decreasing ΔP with increasing load, ΔP at maximum load < 20% of minimum load ΔP	Equal-percentage
Increasing ΔP with increasing load, ΔP at maximum load < 200% of minimum load ΔP	Linear
Increasing ΔP with increasing load, ΔP at maximum load > 200% of minimum load ΔP	Quick-opening

PRESSURE CONTROL SYSTEMS	
Application	*Best Inherent Characteristic*
Liquid process	Equal-percentage†
Gas process, small volume, less than 10 ft of pipe between control valve and load valve	Equal-percentage
Gas process, large volume (process has a receiver, distribution system, or transmission line exceeding 100 ft of nominal pipe volume), decreasing ΔP with increasing load, ΔP at maximum load > 20% of minimum load ΔP	Linear†
Gas process, large volume, decreasing ΔP with increasing load ΔP at maximum load < 20% of minimum load ΔP	Equal-percentage

Selecting the Valve Characteristics:

FLOW CONTROL PROCESSES

		Best Inherent Characteristic	
Flow Measurement Signal to Controller	*Location of Control Valve Relation to Measuring Element*	*Wide Range of Flow Setpoint*	*Small Range of Flow but Large ΔP Change at Valve with Increasing Load*
Proportional to Q	In series	Linear	Equal-percentage†
Proportional to Q	In bypass*	Linear	Equal-percentage
Proportional to Q^2 (orifice)	In series	Linear†	Equal-percentage
Proportional to Q^2 (orifice)	In bypass*	Equal-percentage	Equal-percentage

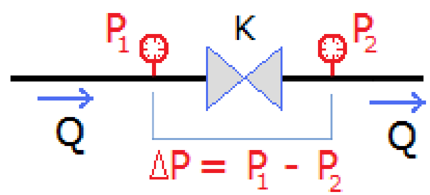
Flow Coefficient Definition

- When flow goes through a valve or any other restricting device it loses some energy. The **flow coefficient** is a designing factor which relates head drop (Δh) or pressure drop (ΔP) across the valve with the flow rate (Q).

$$Q = K \cdot \sqrt{\frac{\Delta P}{SG}}$$

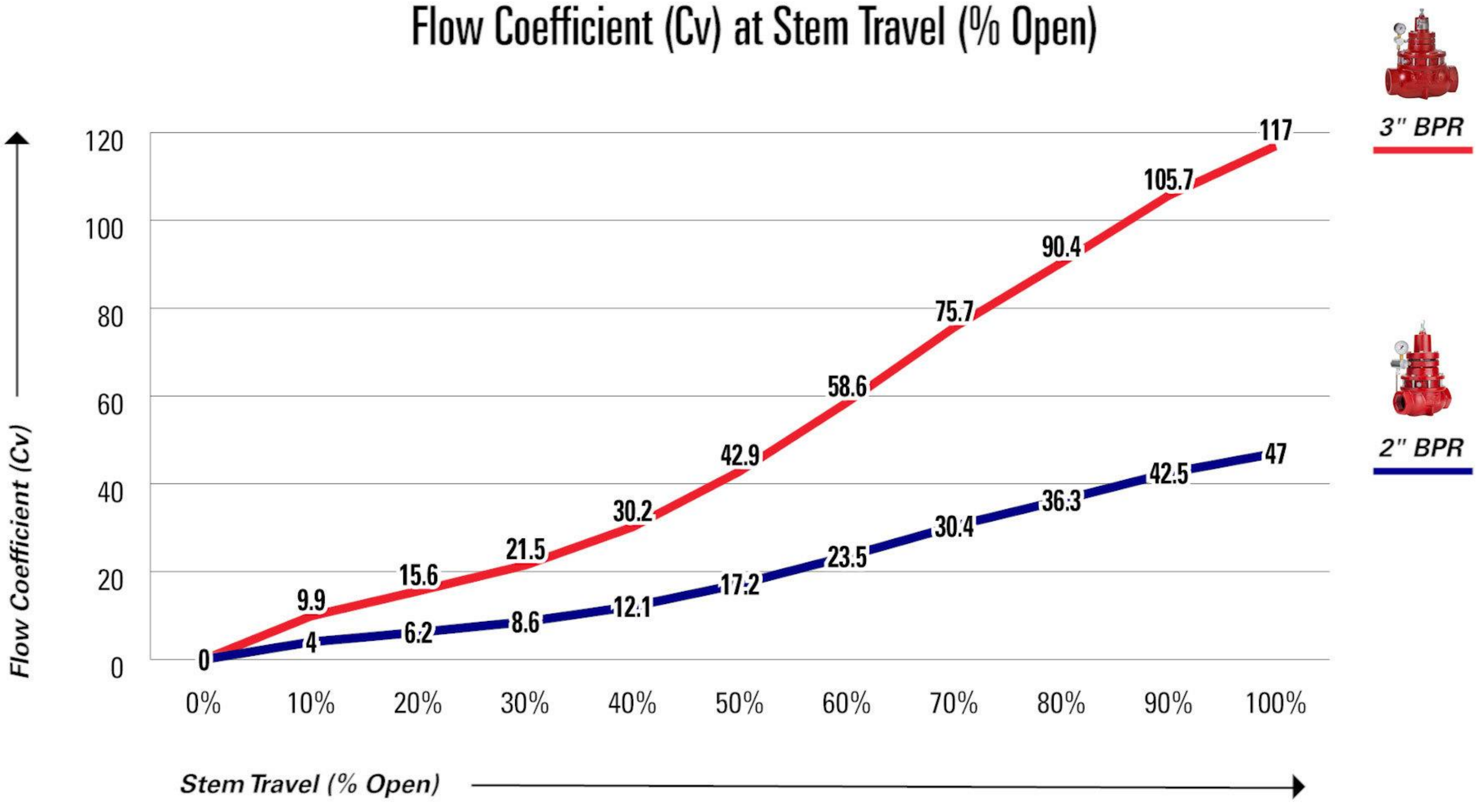
(liquids)

Q: Flow rate
ΔP: Pressure Drop
Sg: Specific gravity (1 for water)
K: Flow coefficient Kv or Cv



- **Kv** is the flow coefficient in metric units. It is defined as the flow rate in cubic meters per hour [m^3/h] of water at a temperature of 16º celsius with a pressure drop across the valve of 1 bar.
- **Cv** is the flow coefficient in imperial units. It is defined as the flow rate in US Gallons per minute [gpm] of water at a temperature of 60º fahrenheit with a pressure drop across the valve of 1 psi.
- Kv = 0.865 · Cv
  Cv = 1,156 · Kv

Flow Coefficient Definition



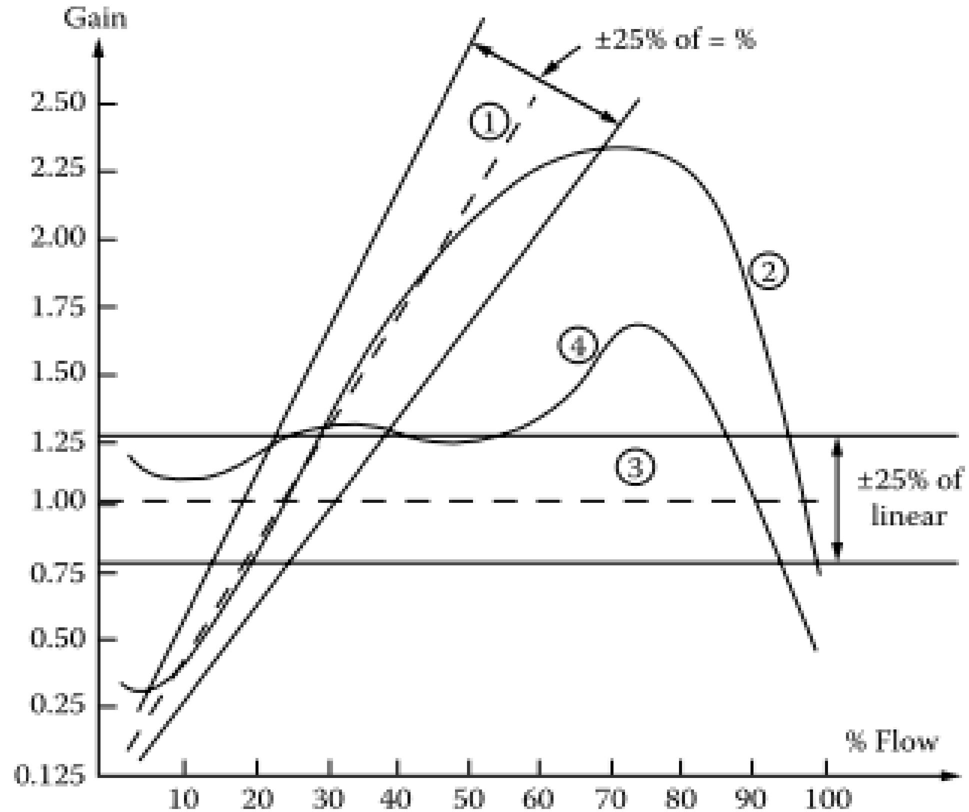
Rangeability:

- The conventional definition of rangeability is the ratio between maximum and minimum “controllable” flow through the valve.
- Minimum controllable flow (Fmin) is defined as the flow below which the valve tends to close completely.
- In other words, this widely held definition of Fmin refers not to the leakage flow (which occurs when the valve is closed), but to the minimum flow that is controllable in the sense that it can be changed up or down as the valve stroke is changed.
- Using this definition, manufacturers usually claim a 50:1 rangeability for equal-percentage valves, 33:1 for linear valves, and about 20:1 for quick-opening valves.

Rangeability:

- These claims suggest that the flow through these valves can be controlled down to 2, 3, and 5% of the flow corresponding to their rated Cv (Kv).
- The acceptable flow range within which the valve can safely be used for closed-loop control must be based on a relationship between the theoretical and the actual valve gain.
- The valve rangeability should therefore be defined as the flow range over which the theoretical (inherent) valve gain and the actual installed valve gain will stay within preset limits.
- Therefore, the rangeability of the valve can be defined as the ratio of the minimum and maximum Cv s (Kv s) bordering the region within which the actual valve gain is within ± 25% of the theoretical valve gain.

Rangeability:



(1) Theoretical gain characteristics of equal % valve

(2) Actual, inherent gain characteristics of equal % valve

(3) Theoretical gain characteristics of linear valve

(4) Actual, inherent gain characteristics of linear valve

FIG. 6.7e

The theoretical vs. the actual characteristics of a 2 in. (50 mm) cage-guided globe valve, according to Driskell.

Valve Positioners

- The positioner is a high-gain plain proportional controller that measures the valve stem position (to within 0.1 mm), compares that measurement to its set point (the controller output signal), and, if there is a difference, corrects the error.
- The open-loop gain of positioners ranges from 10 to 200 (proportional band of 10–0.5%), and their periods of oscillation range between 0.3 and 10 sec (frequency response of 3–0.1 Hz). In other words, the positioner is a very sensitively tuned, proportional-only controller.
- The main purpose of having a positioner is to guarantee that the valve does, in fact, move to the position where the controller wants it to be.

Valve Positioners

- When the valve is under automatic (closed loop) control, the positioner will be helpful in most slow loops, which control analytical properties, temperature, liquid level, blending, slow flow, and large volume gas flow.

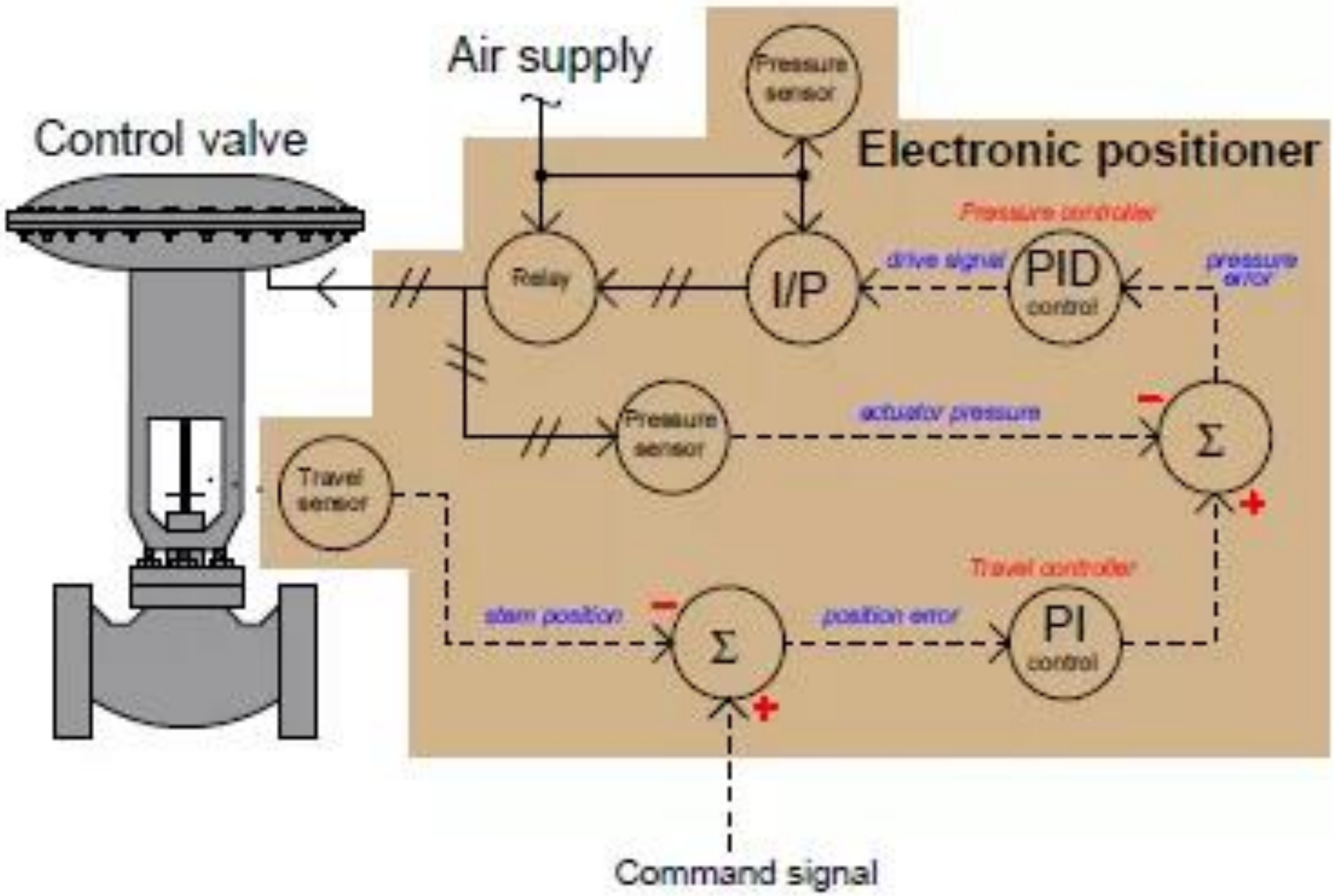
Limitations:

- The positioner’s function as a cascade slave, can cause oscillation and cycling on fast loops if the controller cannot be sufficiently detuned.
- Similarly, negative force reactions on the plug require an increase in actuator stiffness and not the addition of a positioner.
- Actuator stiffness can be improved by increasing the operating air pressure or by using hydraulic actuators.

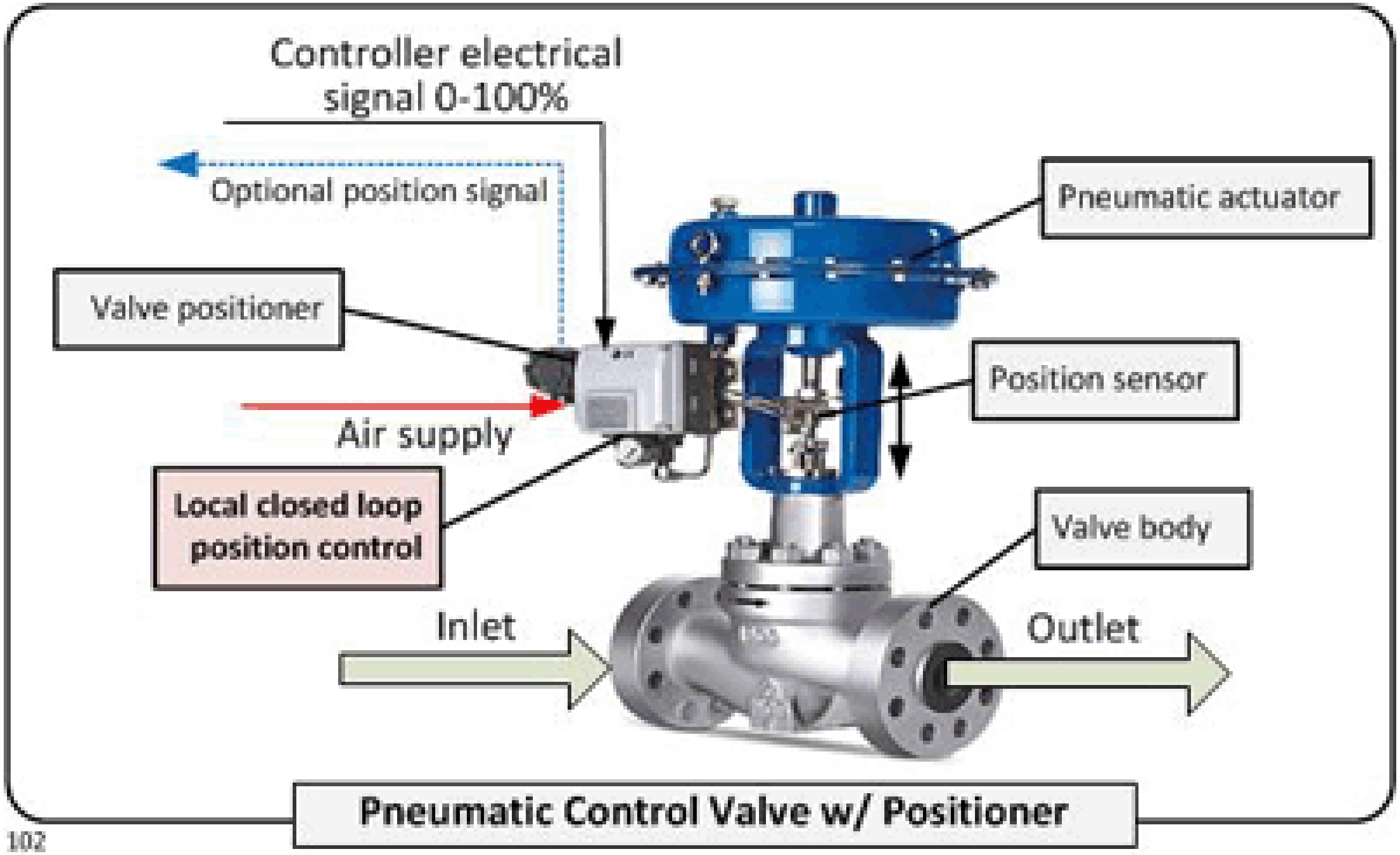
Valve Positioners

- The positioner in effect is the cascade slave of the loop controller.
- In order for a cascade slave to be effective, it must be faster than the speed at which its set point, the master output signal, can change.
- The rules of thumb used in this respect suggest that the time constant of the slave should be ten times shorter (open-loop gain ten times higher) than that of the master and the period of oscillation of the slave should be three times shorter (frequency response three times higher) than that of the primary.
- The criteria for positioners need not be this stringent, but still, it is recommended not to use positioners if the positioned valve is slower than the process variable it is assigned to control.

Valve Positioners



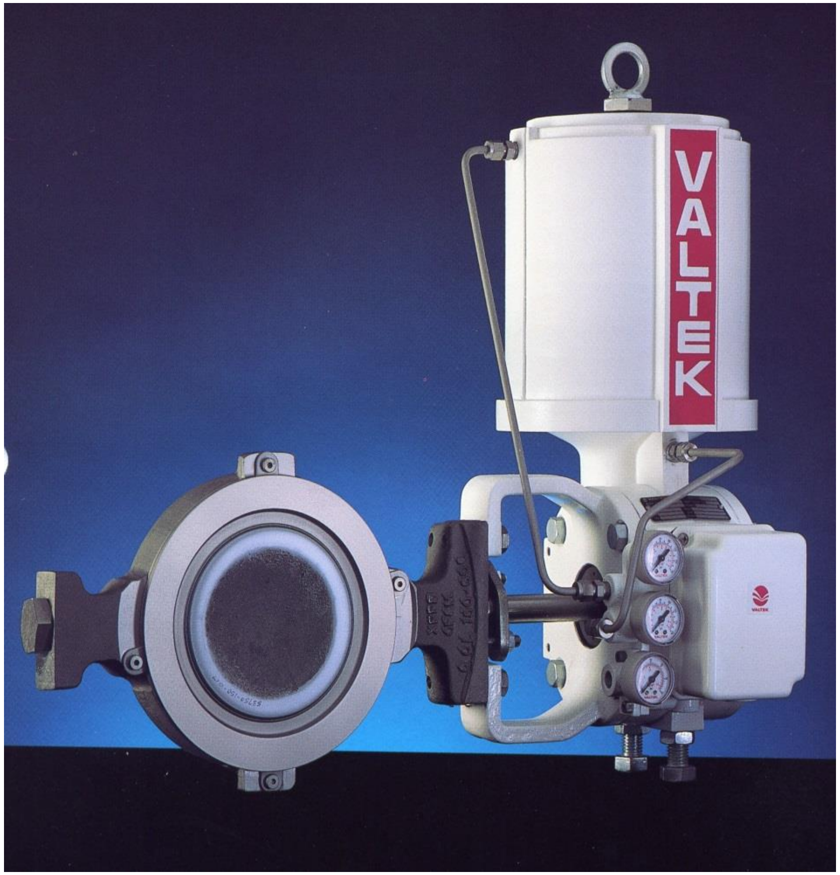
Valve Positioners

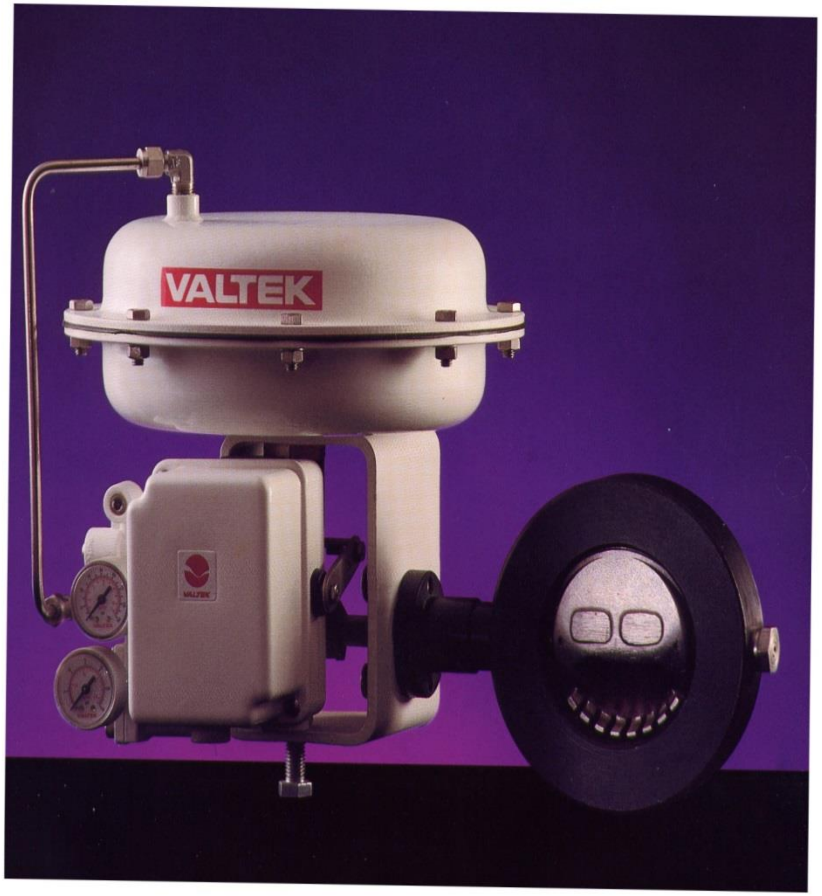


Valve Positioners

Valves

Valves

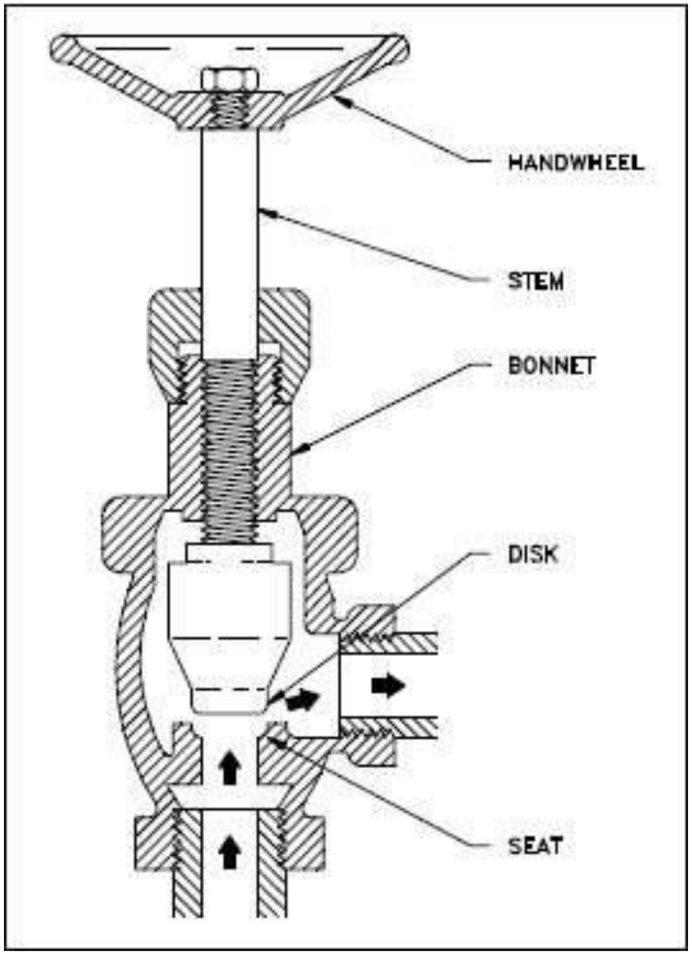




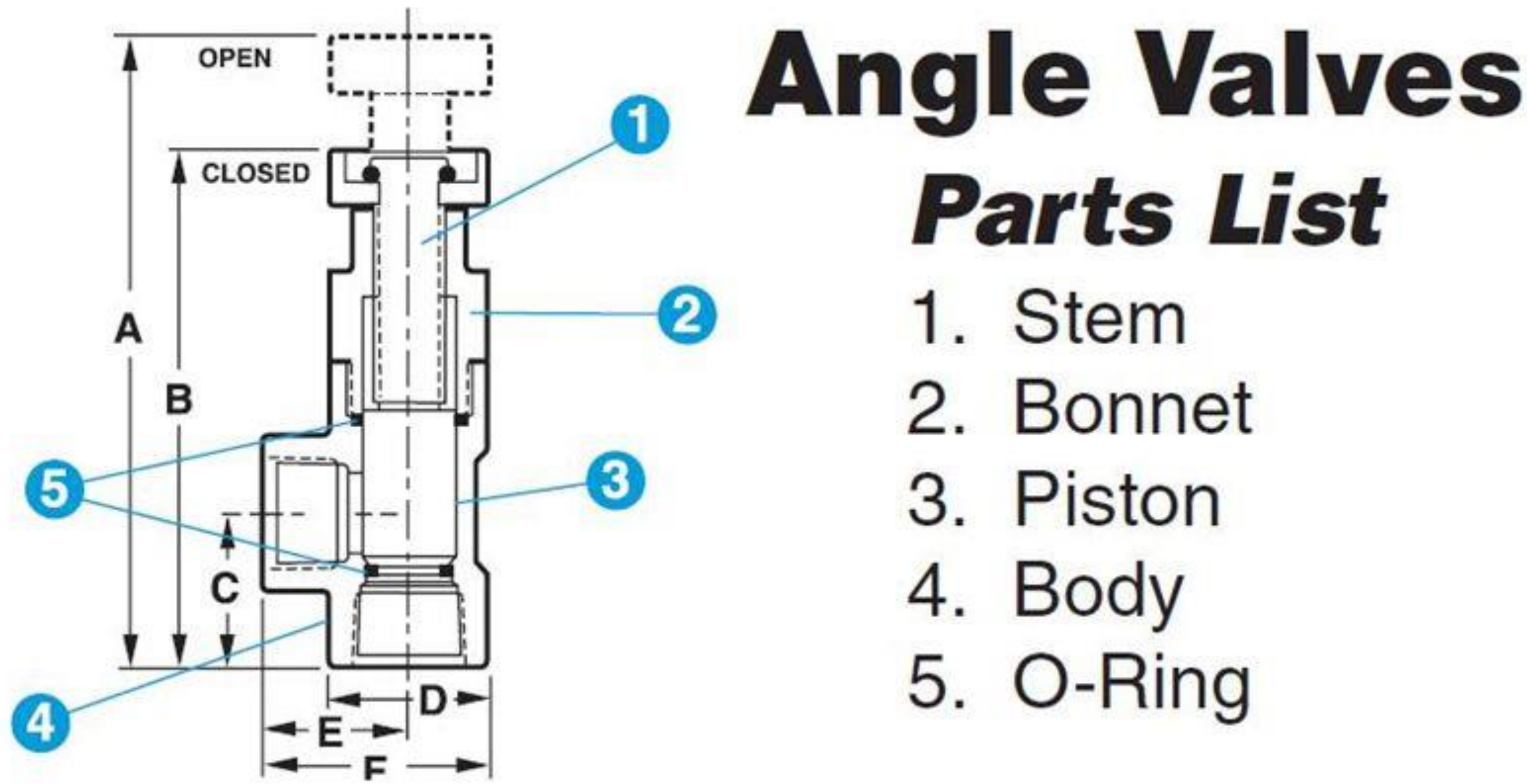
Valves

- Linear Type
- Rotary Type

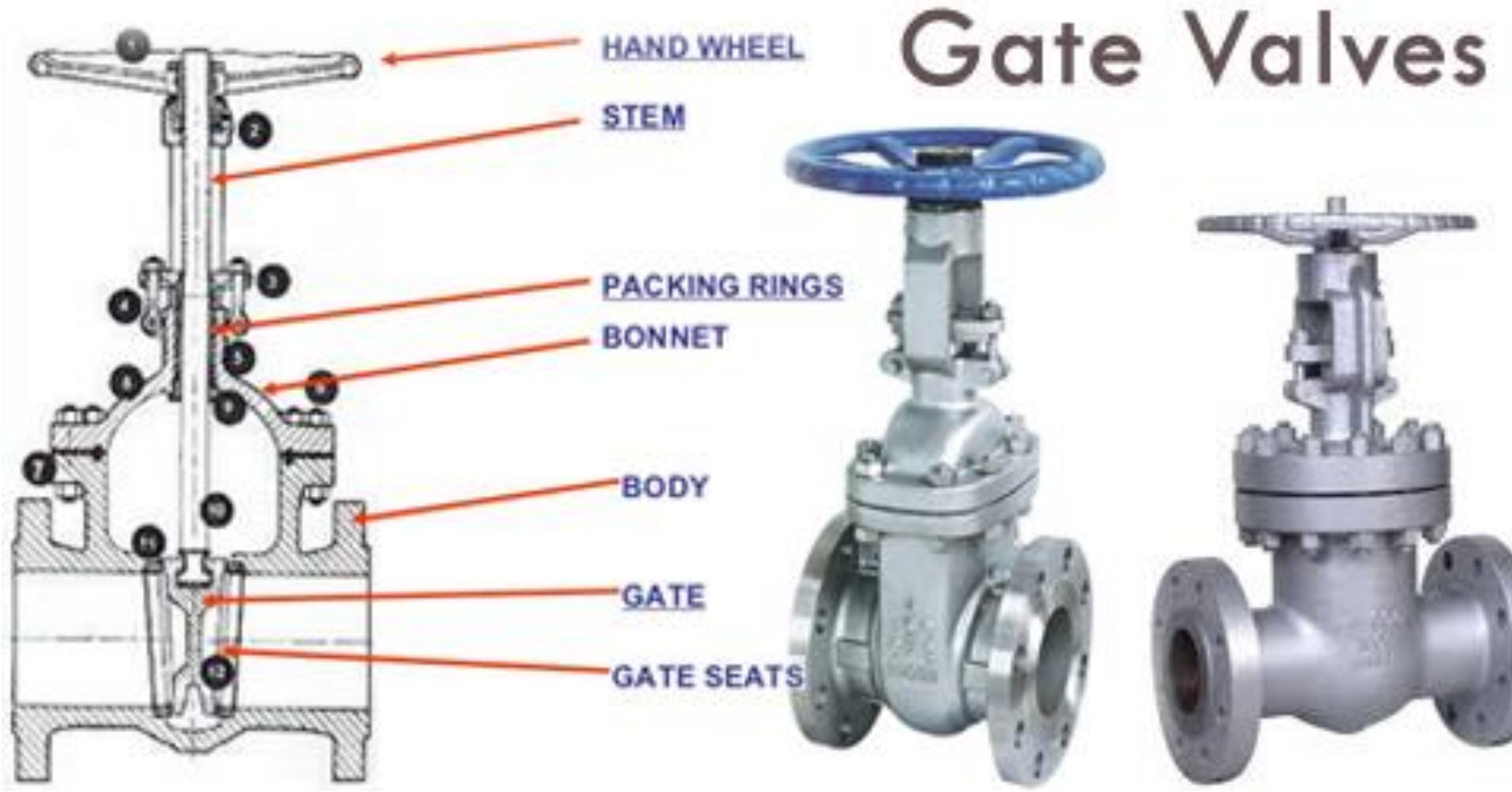
Angle Valves



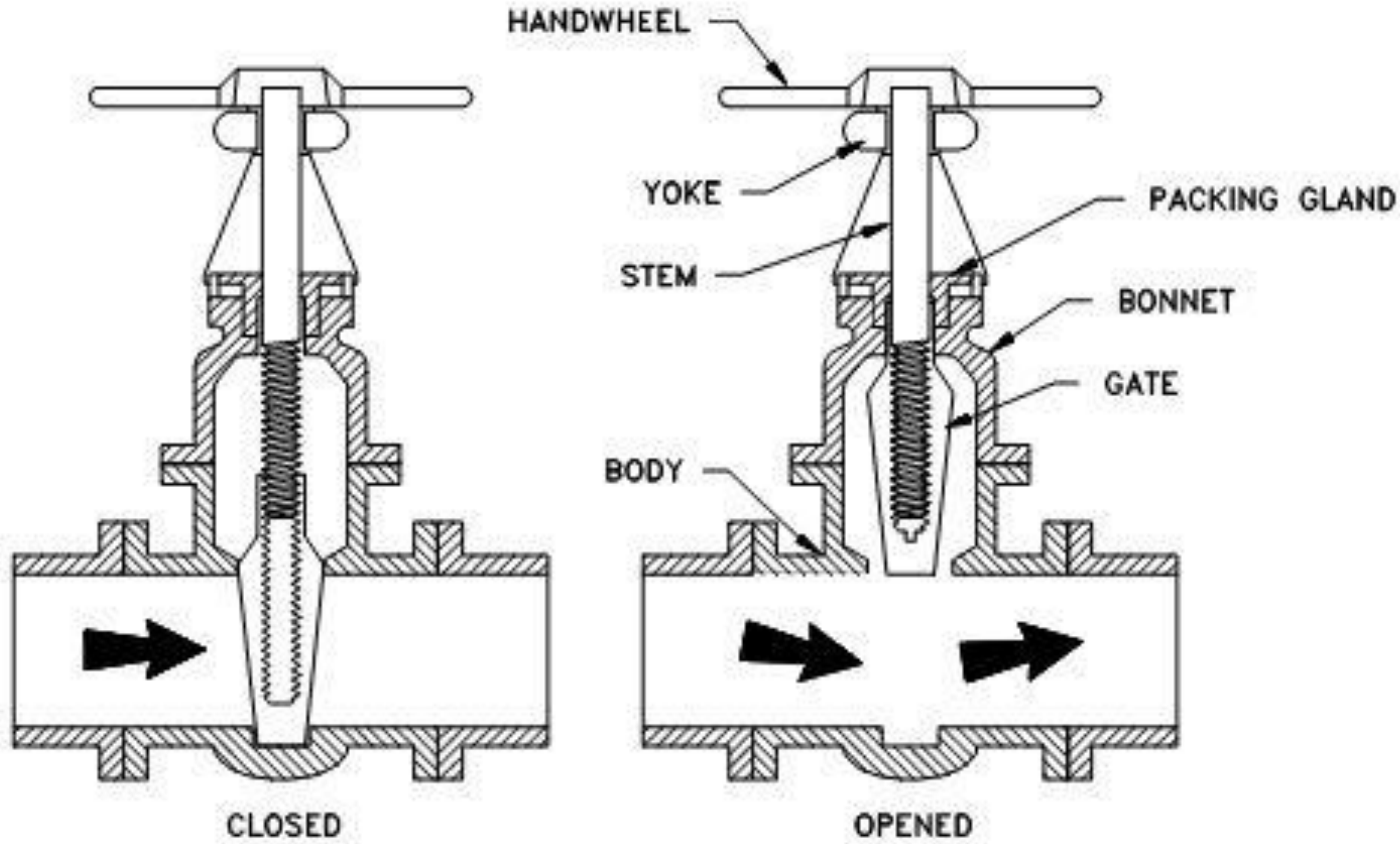
Angle Valves



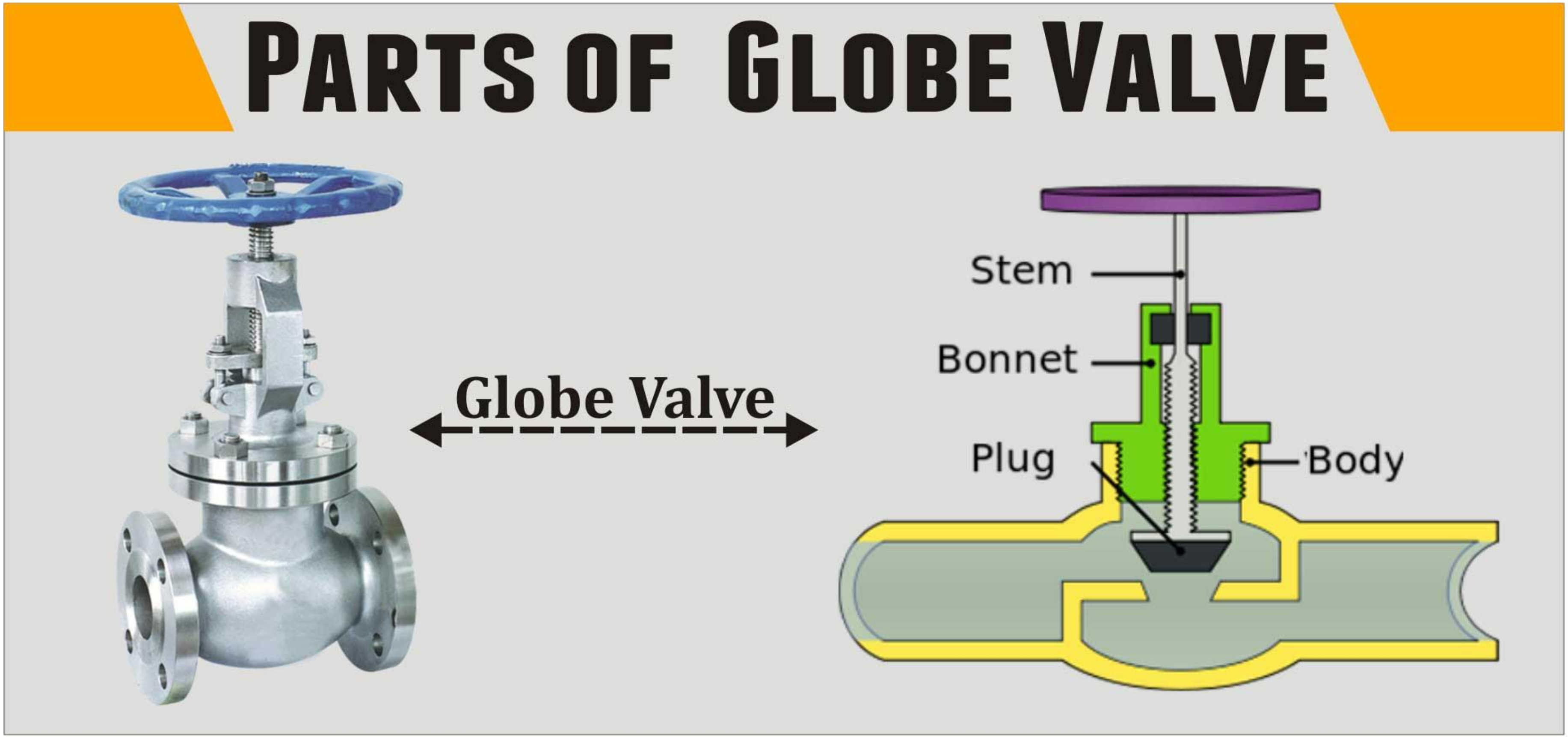
Gate Valves


HAND WHEEL
STEM
PACKING RINGS
BONNET
BODY
GATE
GATE SEATS
Gate Valves

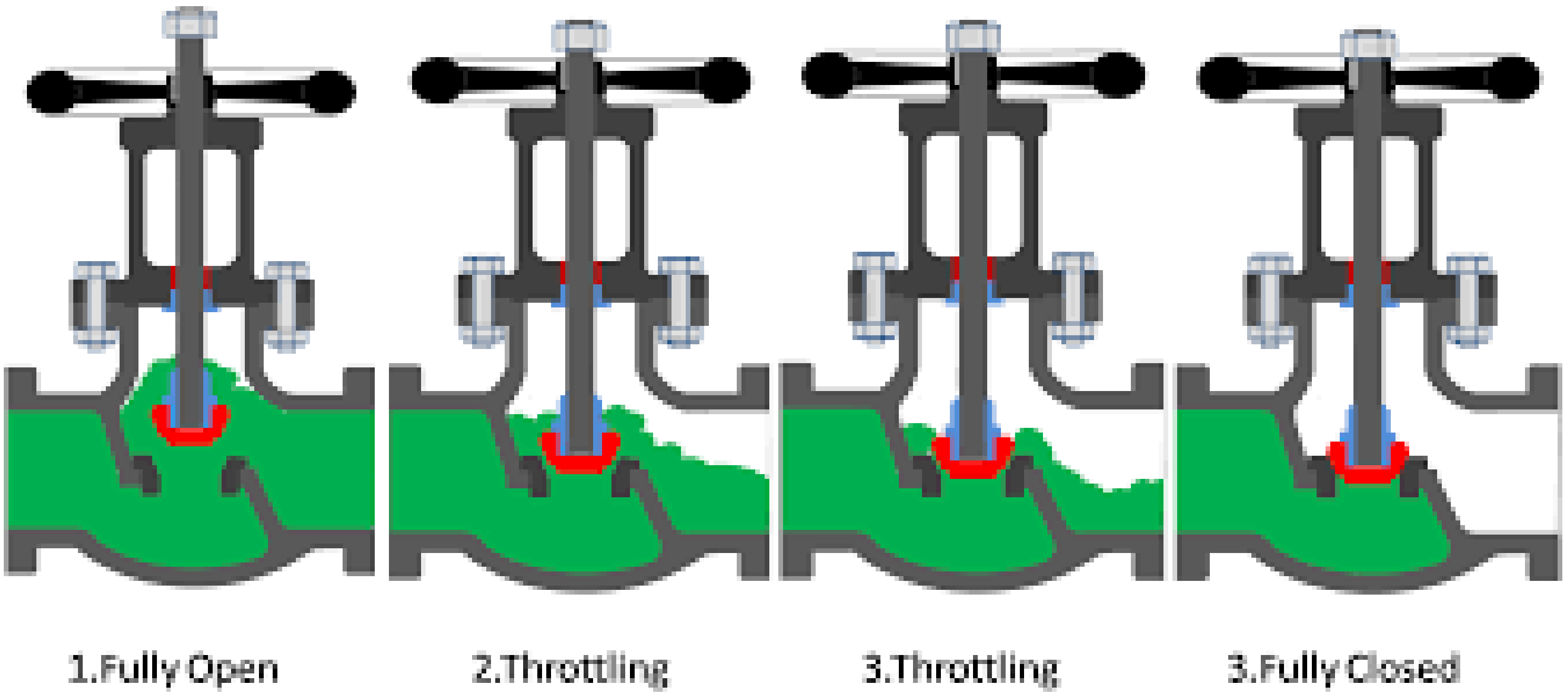
Gate Valves


HANDWHEEL
YOKE
PACKING GLAND
STEM
BONNET
GATE
BODY
CLOSED
OPENED

Globe Valves



Globe Valves



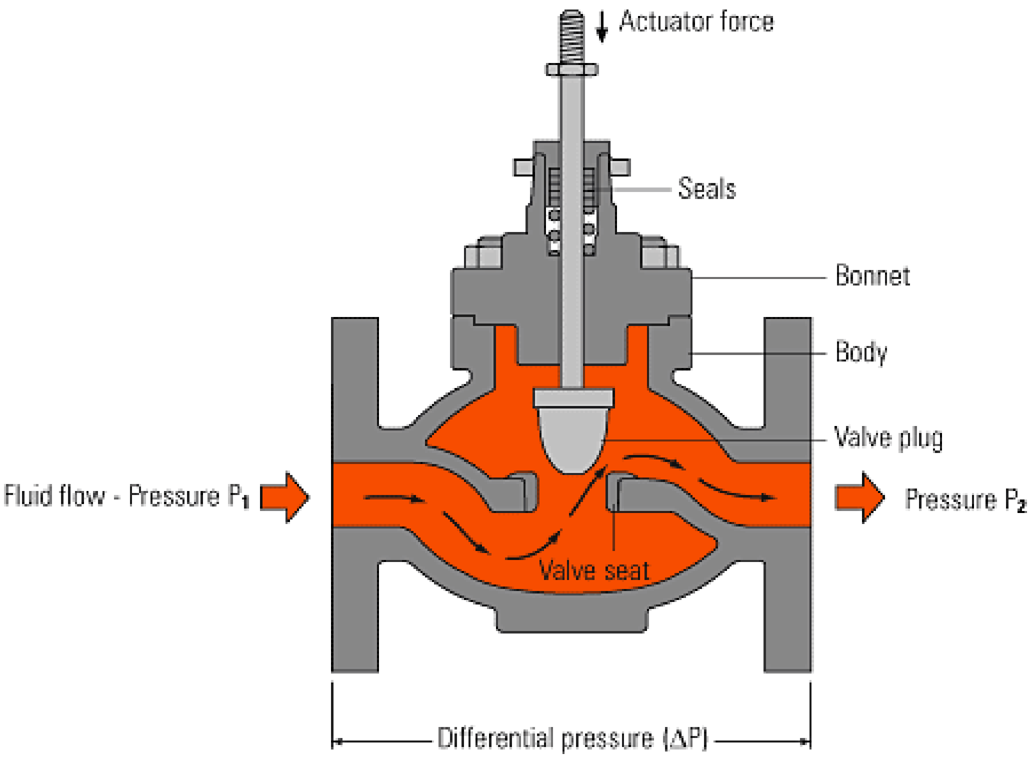
Globe Valves – Single Seat, two port

(A x ΔP) + Friction allowance = F

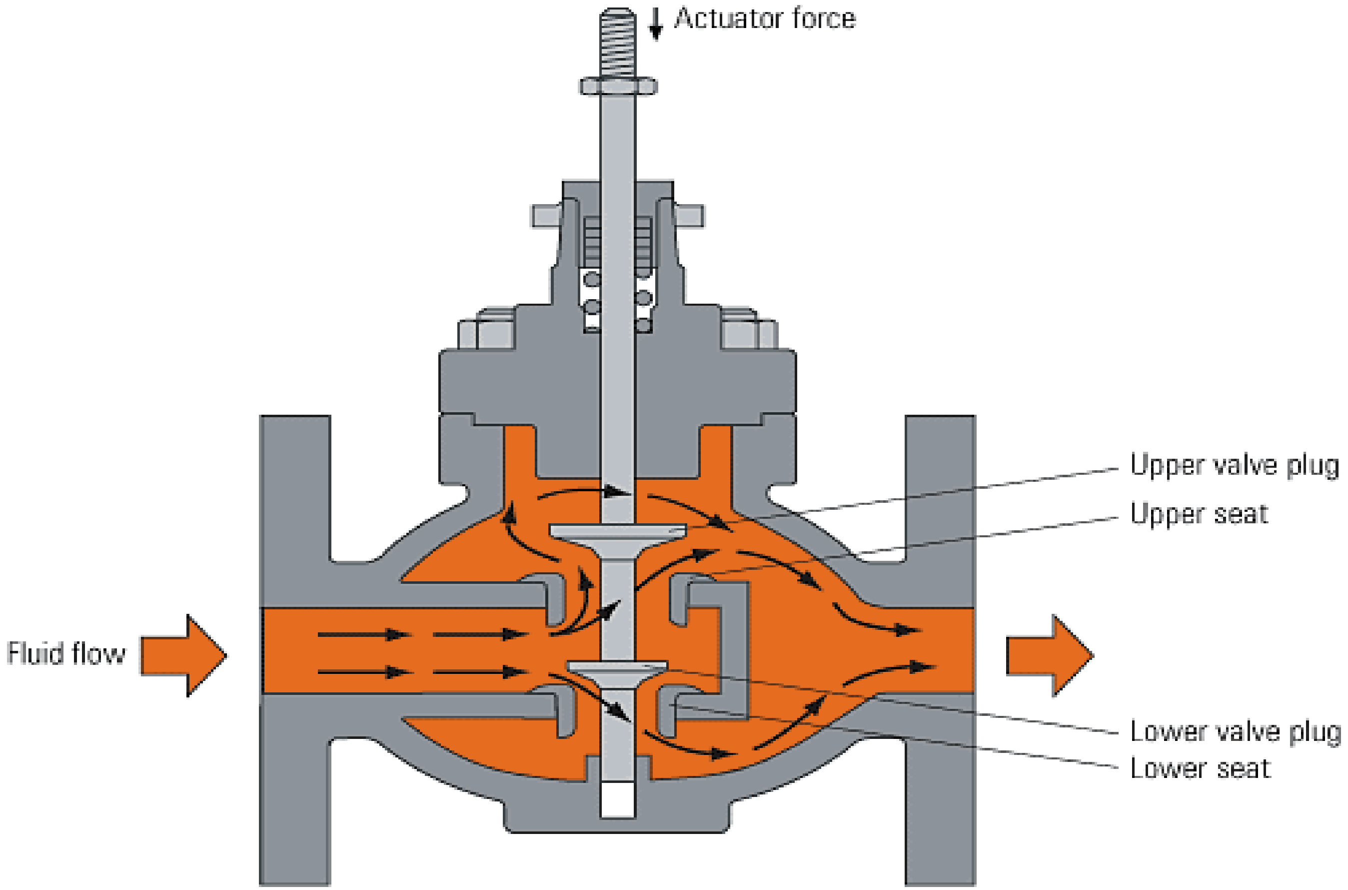
A = Valve seating area (m²)

DP = Differential pressure (kPa)

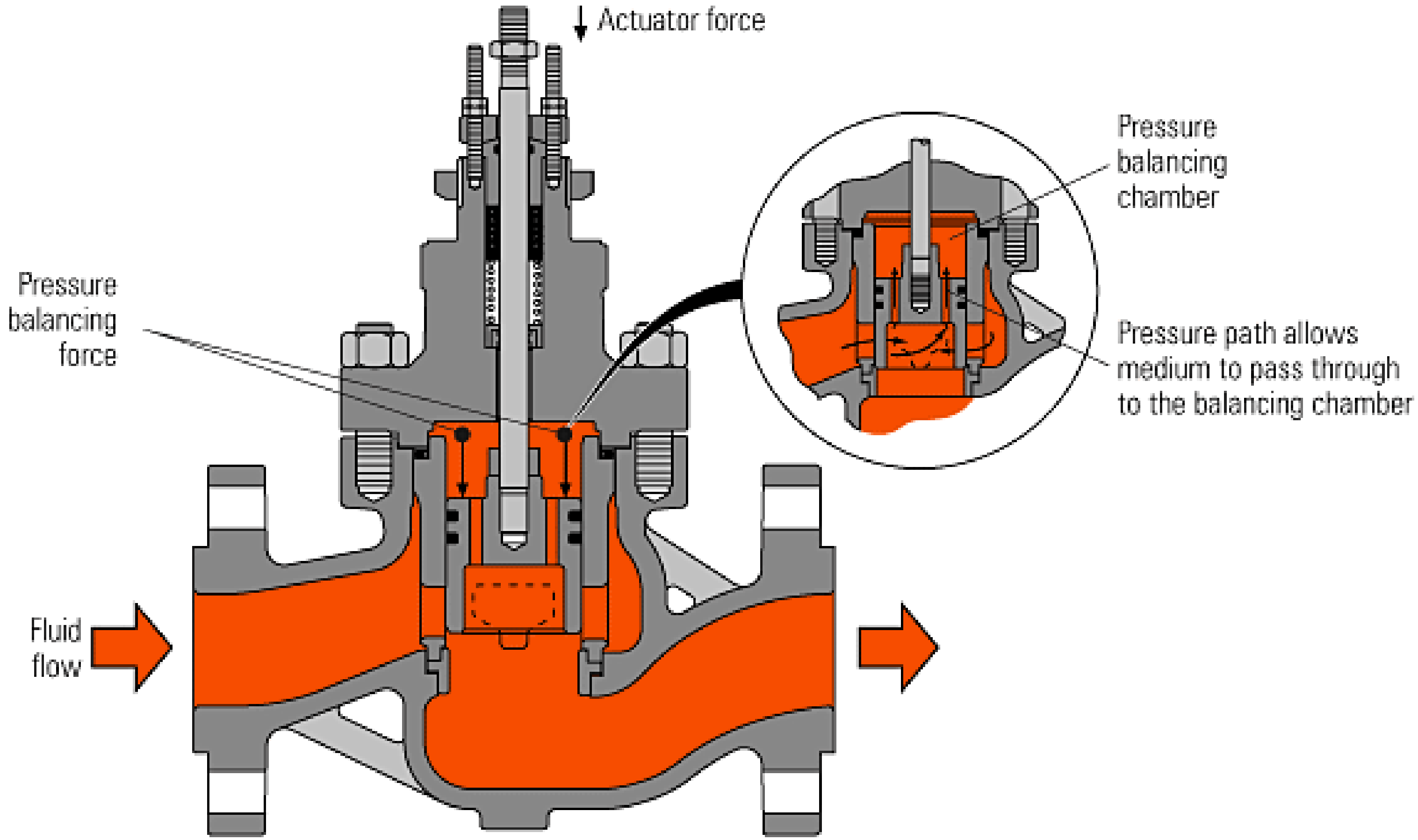
F = Closing force required (kN)



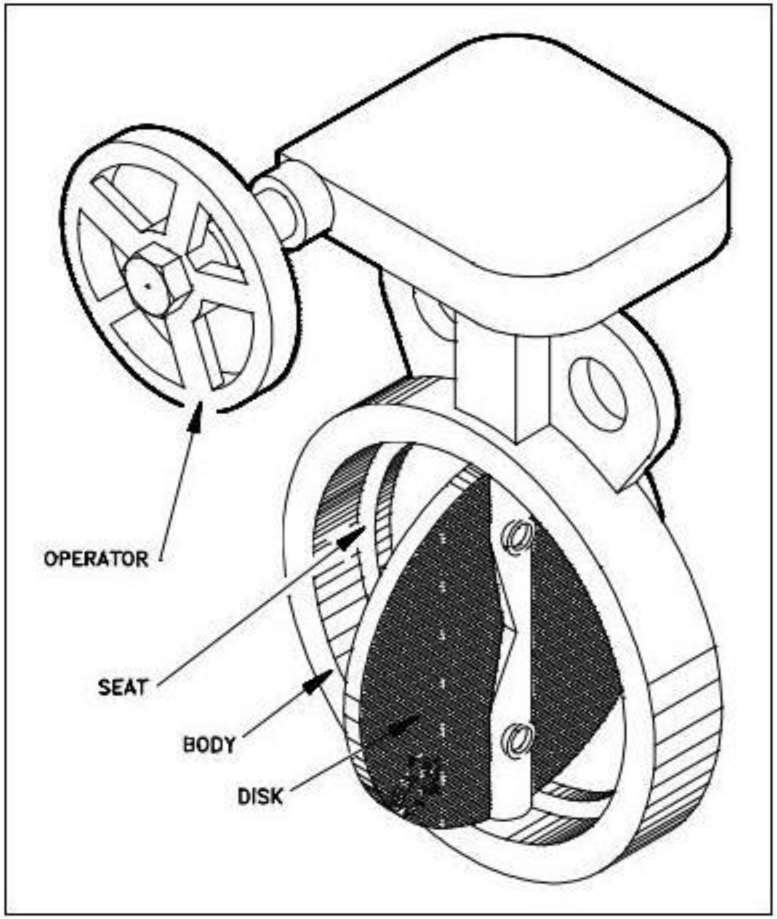
Globe Valves – Double Seat, two Port



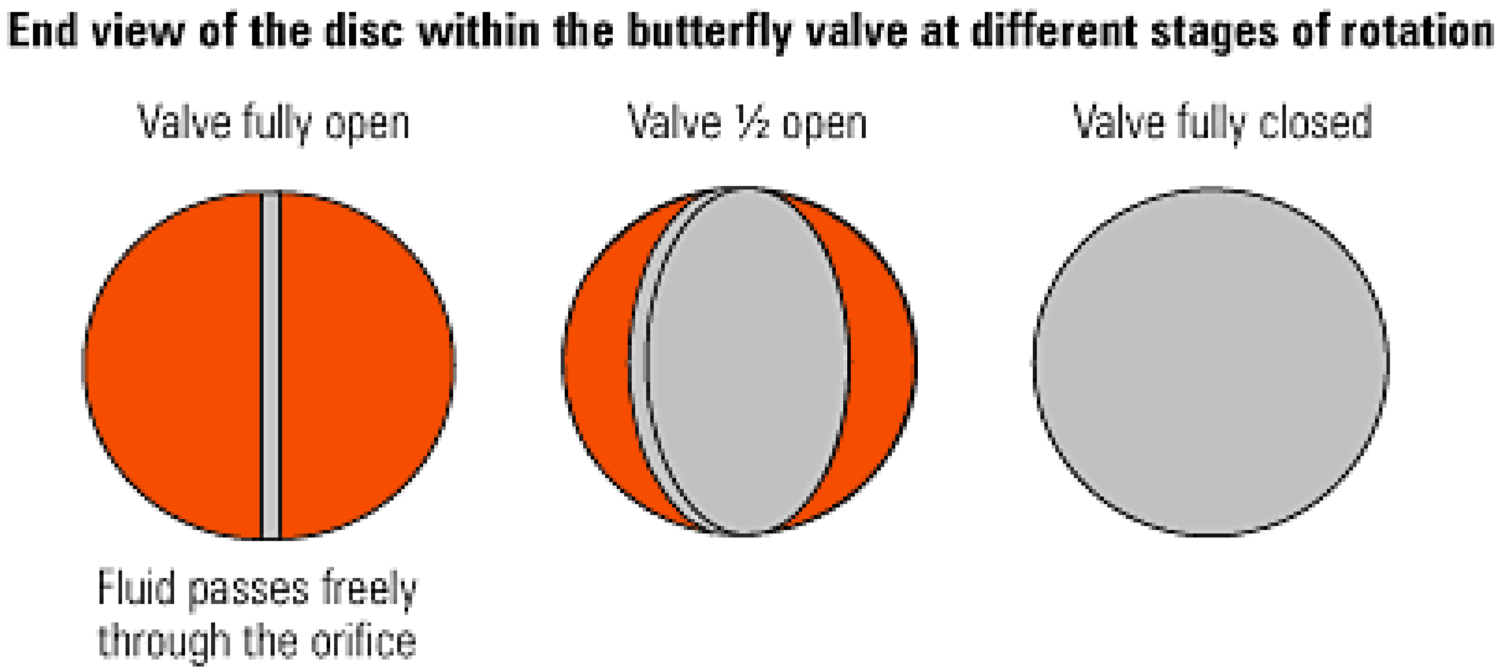
Globe Valves



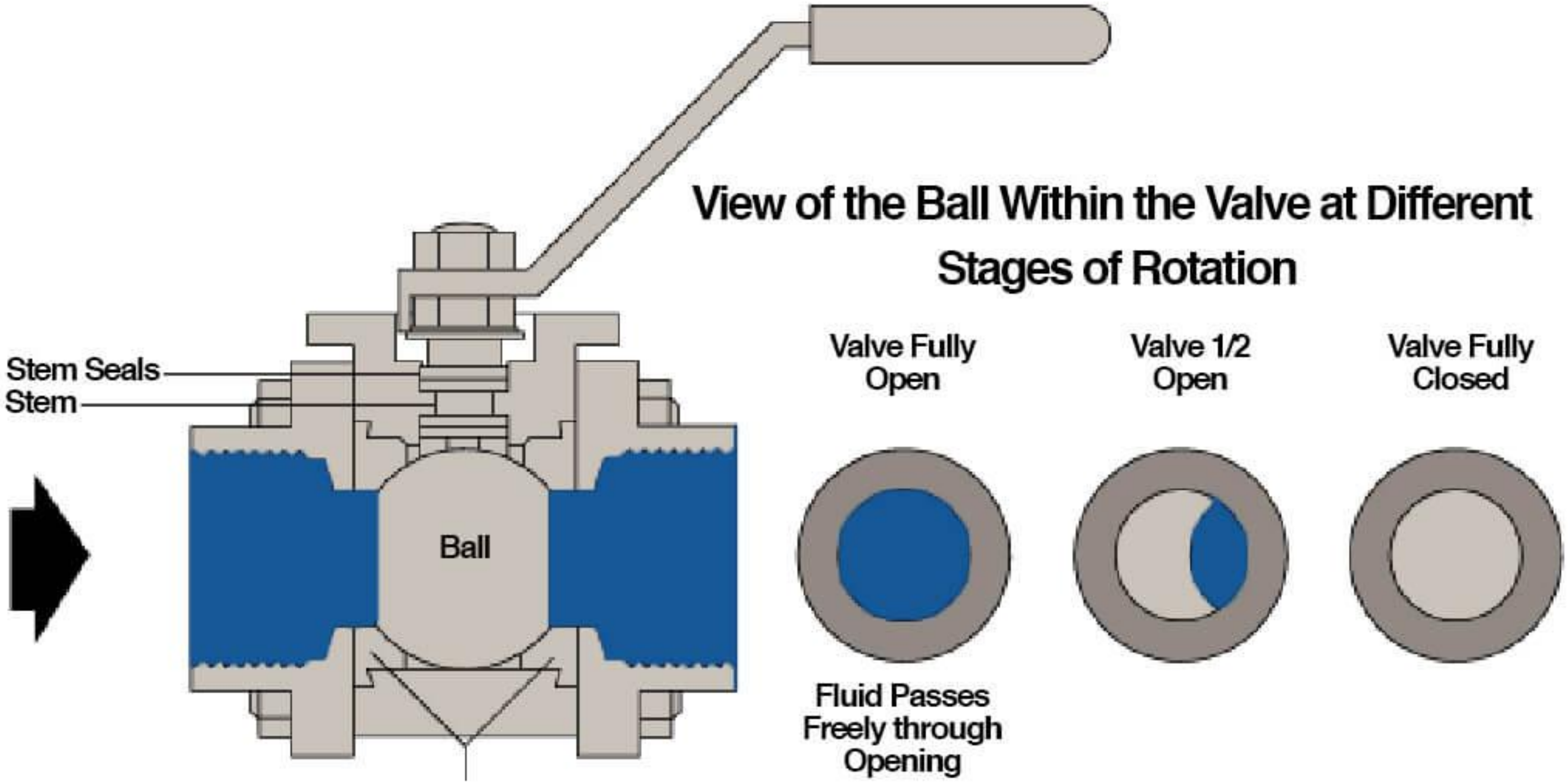
Butterfly Valves



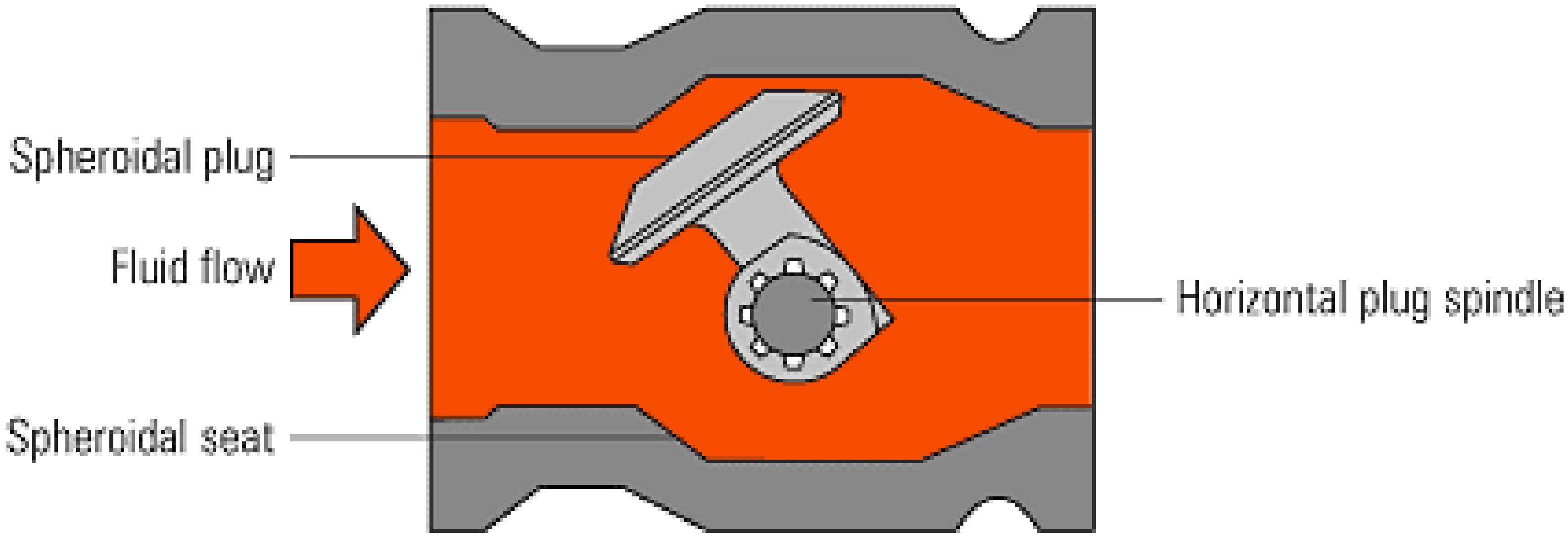
Butterfly Valves



Ball Valves


View of the Ball Within the Valve at Different Stages of Rotation
Stem Seals
Stem
Ball
Valve Fully Open
Valve 1/2 Open
Valve Fully Closed
Fluid Passes Freely through Opening

Eccentric Plug Valves

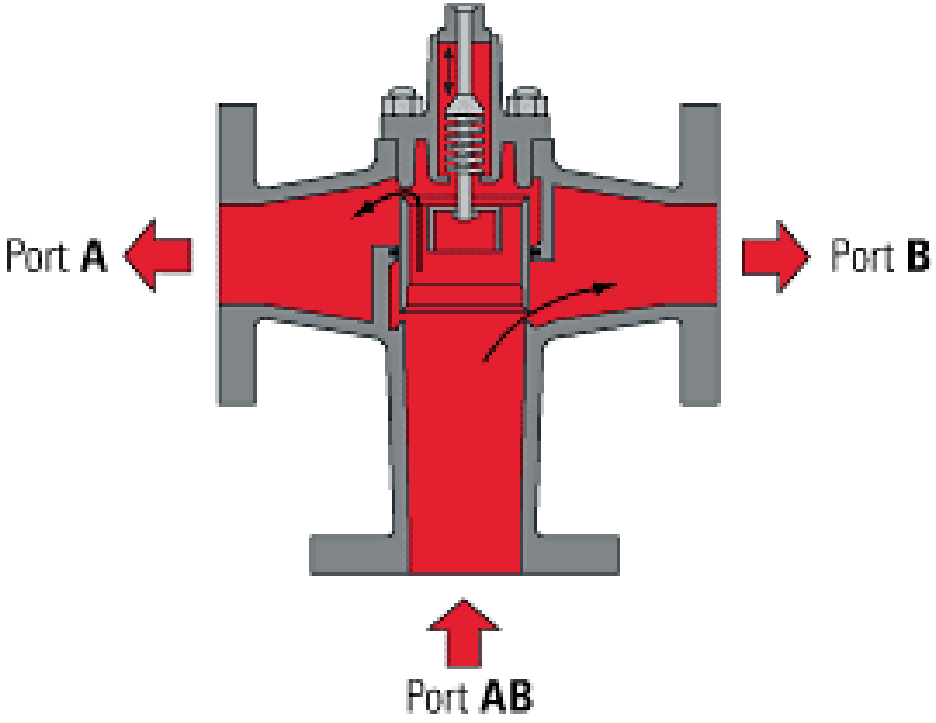


Three port valves

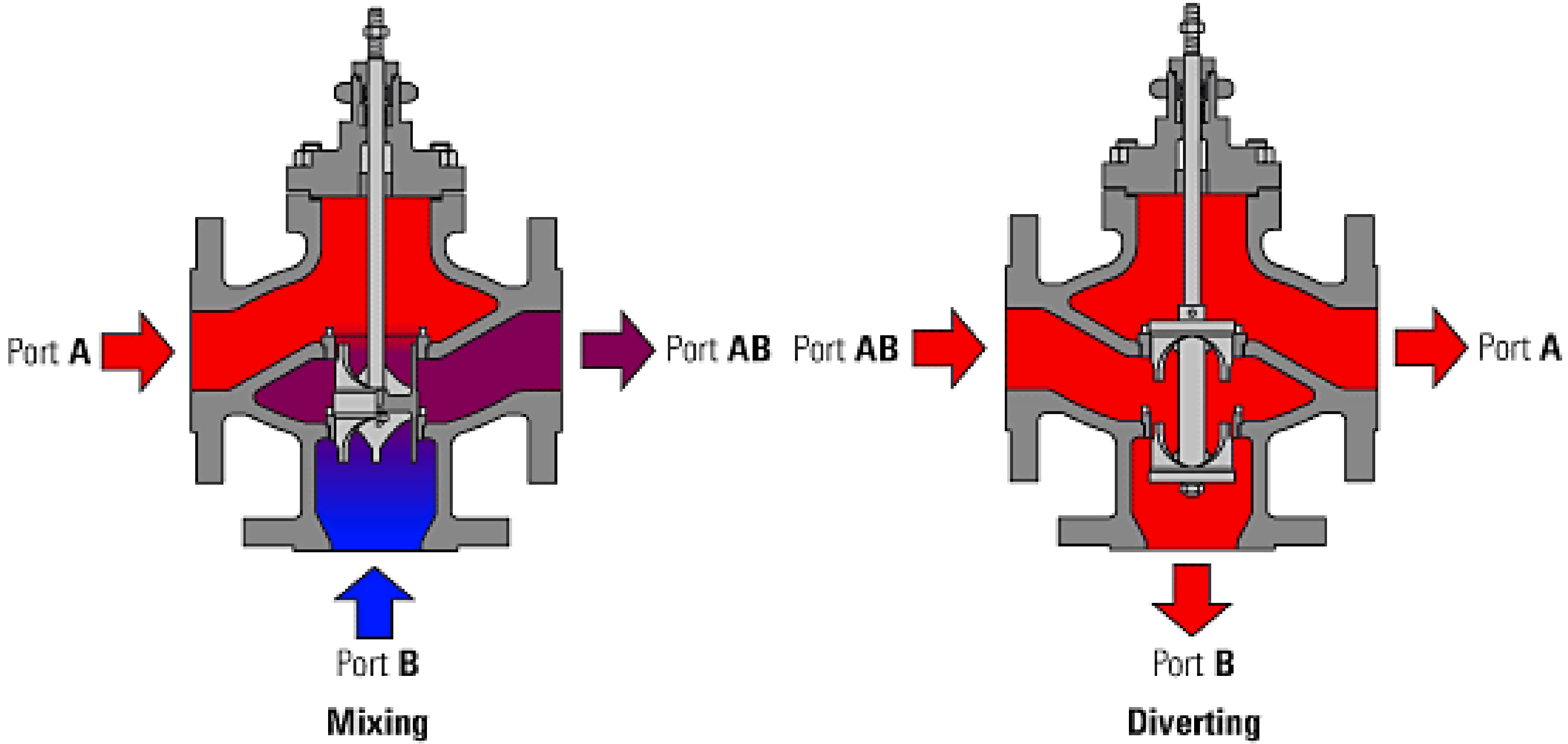
There are three basic types of three-port valve:

- Piston valve type.
- Globe plug type.
- Rotating shoe type.

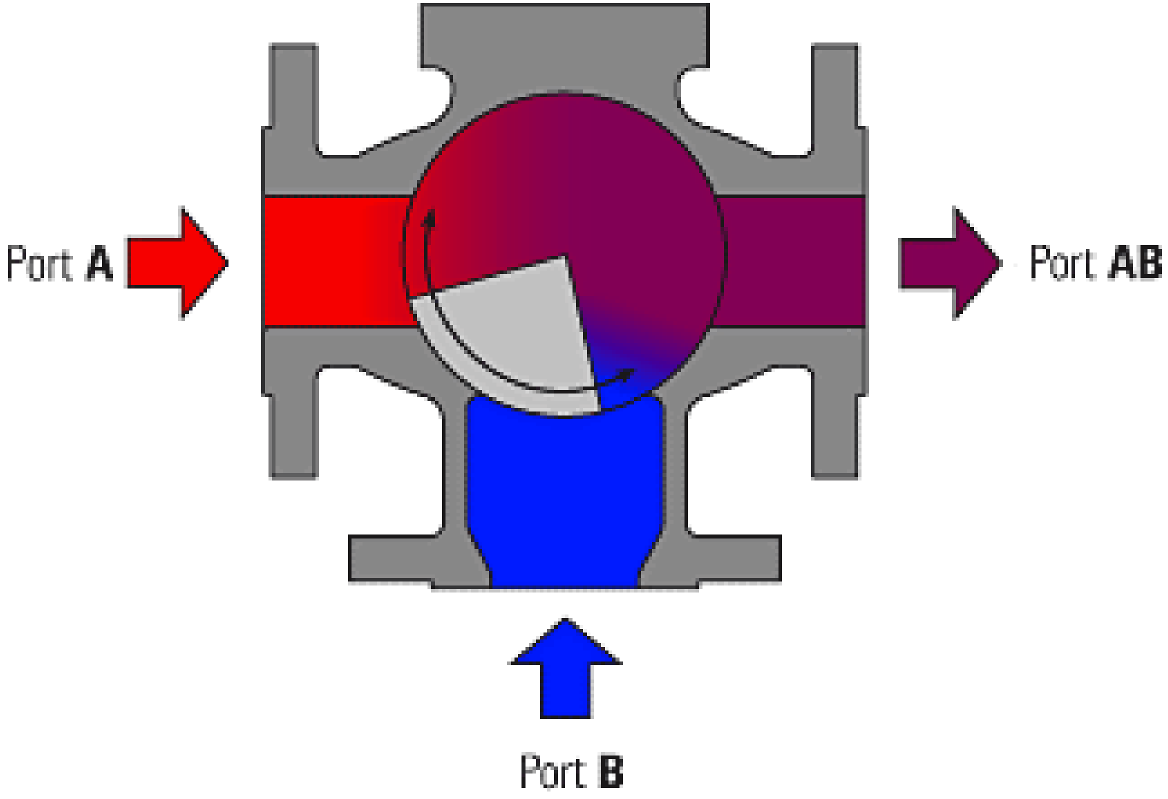
Three port valves: Piston type



Three port valves: Globe Plug Type



Three port valves: Rotating Shoe Type



Valve Sizing

- The first step in finding the size of a valve is to determine the flow coefficient (Cv) that is required for the system.
- Cv factor is defined as "the number of US, gallons per minute of 60F water that will flow through a fully open valve with a 1 psi drop across it". This factor is determined by the construction of the valve and will not change.
- Identical valves sizes may have different Cv's if the body style or valve trim is different. This value of Cv is probably the most useful piece of information necessary to size a valve.

$$C_V = \frac{q}{\sqrt{\Delta P_v / G_f}} \qquad q : GPM$$

The basic valve sizing equation $Q = Cv\sqrt{\Delta P}$ can be used to calculate pressure drop, flow rate, or the flow coefficient.

Example 1

Given: Flow Rate (Q) = 90 gpm
Flow Coefficient (C_v)=51

Find: Valve Pressure Drop (ΔP)

Solution

$$\Delta P = \left(\frac{Q}{C_v}\right)^2 = \left(\frac{90}{51}\right)^2 = 3.1 psi$$

Example 2

Given: Valve Pressure Drop (ΔP) = 10 ft
Flow Coefficient (Cv) = 51

Find: Flow Rate

Solution

10 ft of head * 0.433 *psi/ft* = 4.33 psi; 1 ft of head = 0.433 psi

$Q = Cv\sqrt{\Delta P} = 51\sqrt{4.33} = 106$ gpm

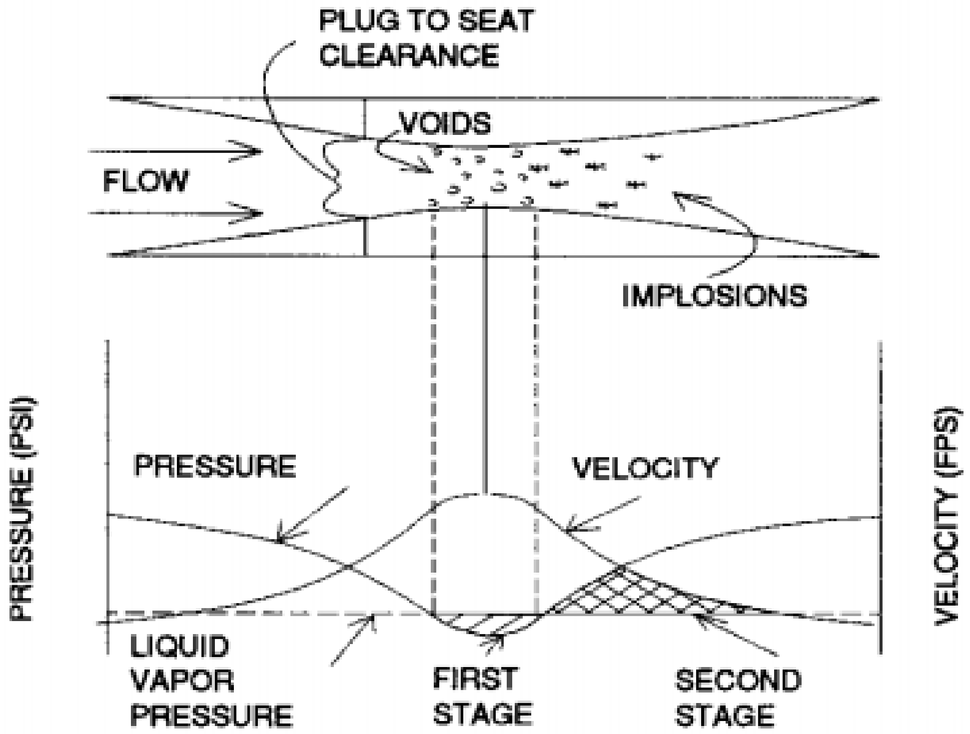
Example 3

Given: Flow Rate (Q) = 90 gpm

Valve Pressure Drop = 12 ft

Find: Valve Flow Coefficient (Cv)

Flashing and Cavitation



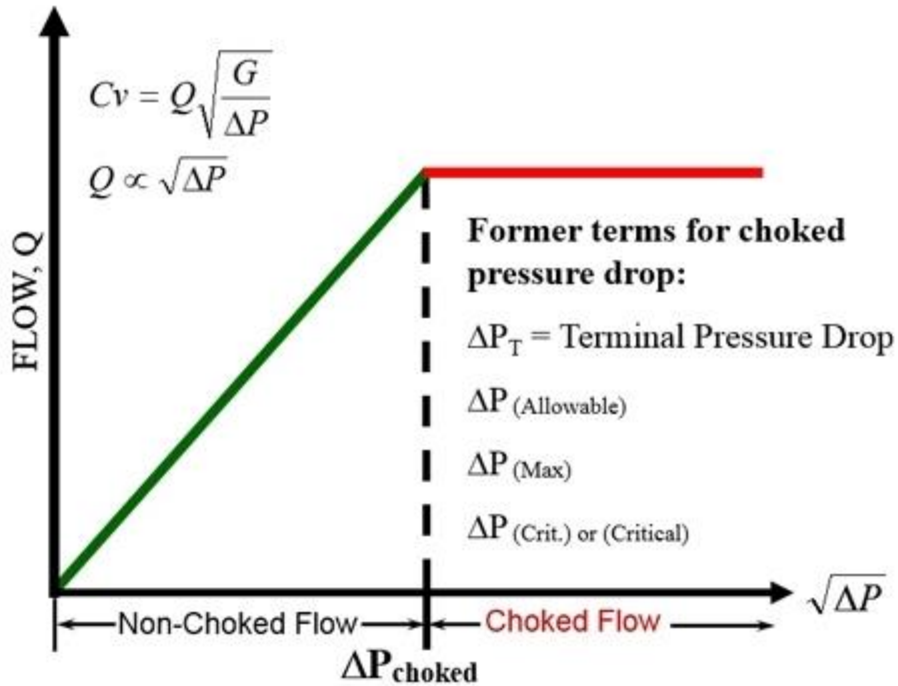
Variations of Pressure and Velocity for Points Along a Flow Stream Through a Restriction.

Flashing and Cavitation

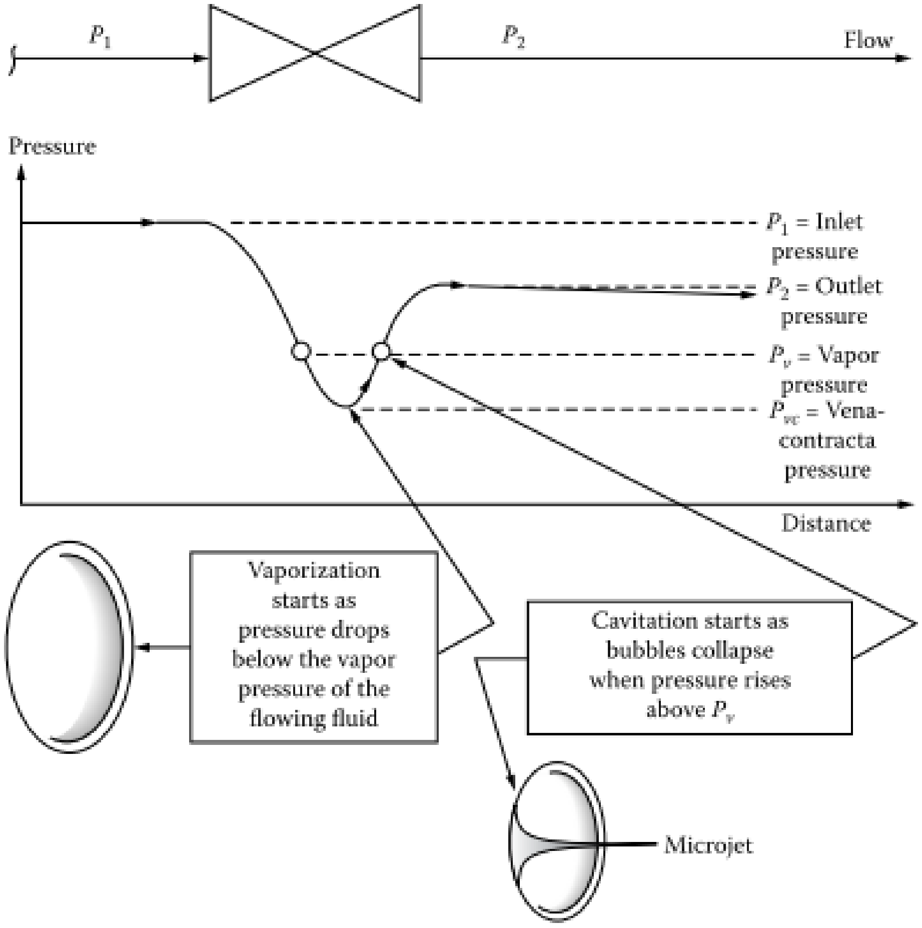
- This condition is referred as “chocked flow’. If large amount of dissolved gases come out of solutions as the pressure drop in the flow, these released gases will also restrict the flow.
- Vaporization can cause cavitation or flashing. Cavitation occurs when static pressure anywhere in the valve drops to or below the vapour pressure of the process liquid.
- Vaporization begins around microscopic gaseous nuclei. The cavitation process includes the vapour cavity formation and sudden condensation (collapse) of the vapour bubble driven by pressure changes.
- The basic process of cavitation is related to the conservation of energy and Bernoulli’s theorem, which describes the pressure profile of a liquid flowing through a restriction or orifice.

Flashing and Cavitation

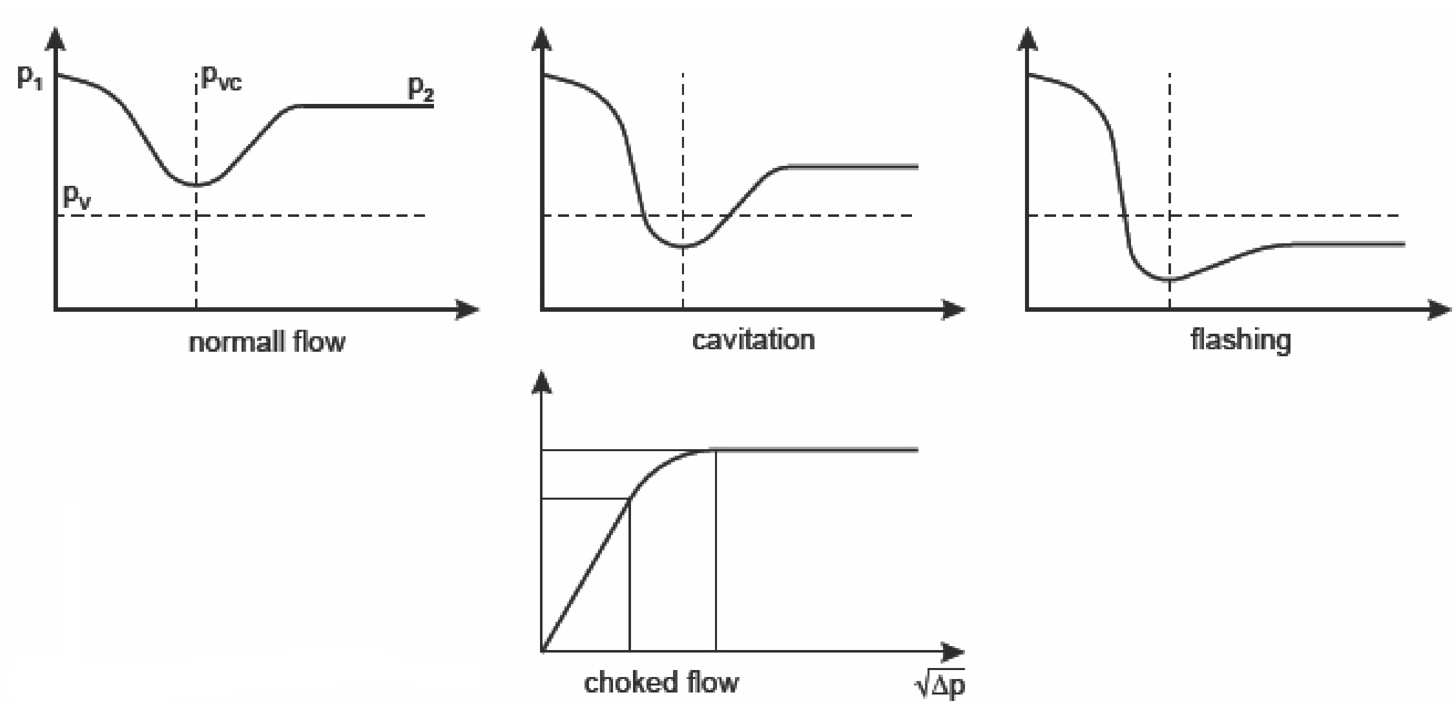
- When vaporization occurs, the proportionality between flow rate and the square root of pressure drop ceases.
- The flow rate reaches a maximum (chocked) value, which is constant and though the down stream pressure is further reduced. The curve will be



Flashing and Cavitation



Flashing and Cavitation



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Flashing and Cavitation

- Cavitation occurs when $p_2 > p_v$, while flashing takes place when $p_2 < p_v$.

- When a liquid flashes into vapour, there is a large increase in volume.

- Method to avoid , the piping downstream of a valve needs to be much larger than the inlet piping in order to keep the velocity of the two-phase stream low enough to prevent erosion.

- The ideal valve to use for such applications is an angle valve with an oversized outlet connection.

Flashing and Cavitation

- In order to accelerate the fluid through the restriction, some of the pressure head is converted into velocity head.
- This transfer of static energy is needed to maintain the same mass flow through the reduced passage. The fluid accelerates to its maximum velocity, which corresponds to the point of minimum pressure (vena contracta).
- The fluid velocity gradually slows down as it expands back to the full pipe area. The static pressure also recovers somewhat, but part of it is lost due to turbulence and friction.
- If the static pressure at any point drops below the liquid vapour pressure (Pv) corresponding to the process temperature, then vapour bubbles will form.

Flashing and Cavitation

- If enough energy is imparted to the growing vapour bubble to overcome surface tension effects, the bubble will reach a critical diameter and expand rapidly.
- As the static pressure recovers to a point greater than the vapour pressure, the vapour will condense, causing the bubbles to collapse violently back into their liquid phase.
- The growth and collapse of the bubbles produce high-energy shock waves in the fluid. The collapse stage of the process (the bubble implosion) produces the more severe shock waves.
- Shock waves and liquid microjets radiate for short distances from imploding cavities and erode nearby surfaces.

Flashing and Erosion

Flashing and Erosion:

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Flashing and Erosion:

- Cavitation can cause erosion, noise, and vibration in piping systems and therefore must be avoided.
- Extensive cavitation also causes choked flow conditions in the valve.

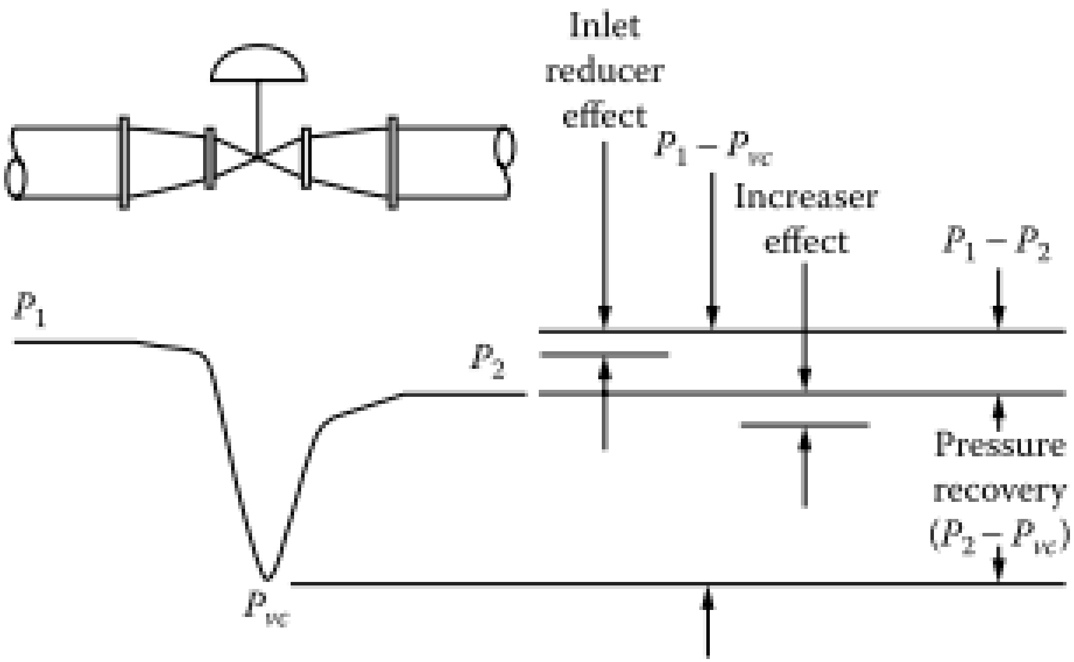
Predicting and Mitigating Cavitation:

- Sizing a valve in liquid service for choked flow allows one to determine its maximum flow capacity, but this is of limited value, because most liquid-service valves should not be operated under choked conditions.
- Special trim designs with multiple stages or multiple flow paths are typically used to prevent severe cavitation and are better able to operate at or near choked conditions without damage.

Flashing and Erosion:

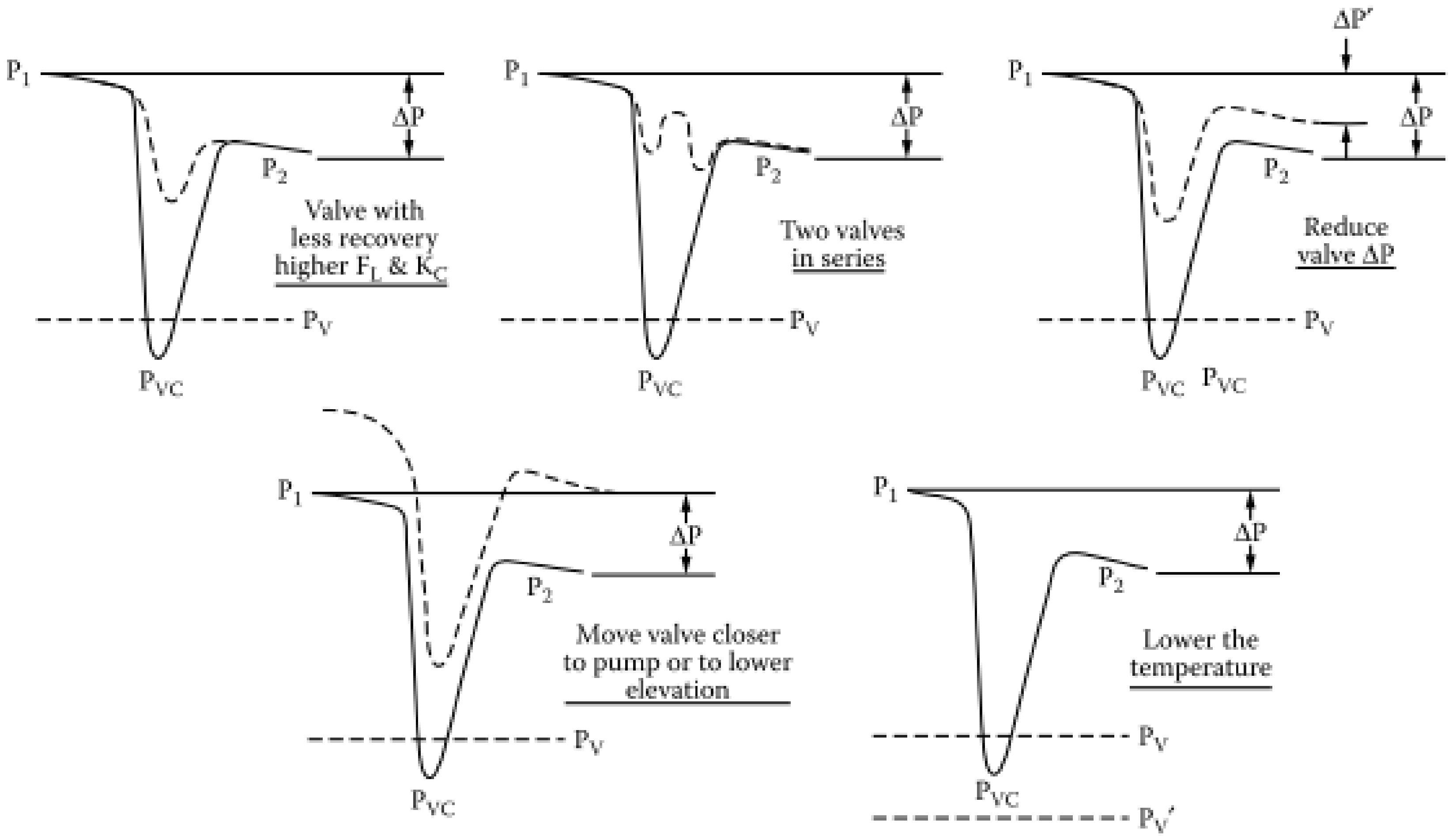
Pressure Recovery Factor (F_L):

- F_L is the pressure recovery factor, which indicates the size of the pressure recovery relative to the valve pressure drop (Figure).



$$F_L = [(P_1 - P_2)/(P_1 - P_{vc})]^{1/2}$$

Flashing and Erosion



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