Solutions for R&D to Design

Control Valve Characteristics

July 1, 2017

PreFEED Corporation

Katsumi Yokoyama

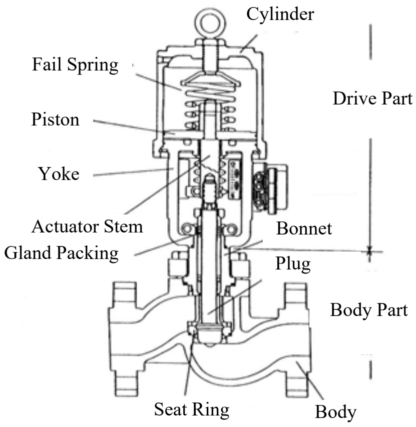
All rights reserved, preFEED Corporation

Introduction

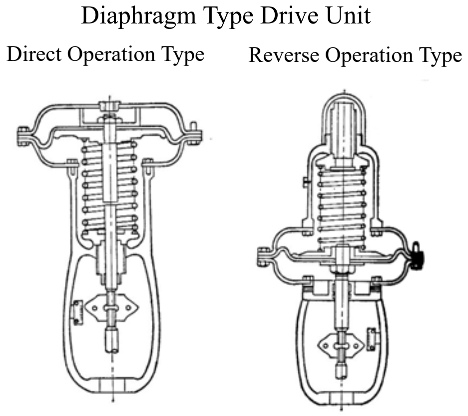
- A control valve adjusts a flow rate by obtaining a control signal and changing the valve opening position. The valve sizing is determined by considering the following three factors: the Cv value, the flow characteristic, and the rangeability.
- Typical flow characteristics are the linear characteristic and the equal percentage characteristic. These characteristics differ greatly with respect to the valve opening position.
- In this document, we will discuss control valves and their design, and examine the linear and equal percentage characteristics.

Control Valve Structure

- The control valve has a structure as shown in the figures below, and is divided into a drive part and a body part.
- The diaphragm type as shown in the right figure is generally used for the drive part. The left figure is a cylinder type. Air pressure is applied to the diaphragm and piston to open and close the valve in balance with the spring.



"Purosesu Seigyo" *in Japanese*: "Process Control", P.37



"Keiso Seigyo Shisutemu" *in Japanese*: "Instrumentation Control System", P.336

Control Valve Types

The body portion is the core section of the valve, and various valves are used depending on the temperature, the pressure, the viscosity, and the properties, such as slurry conditions, of the fluids that are handled.

- Globe valve: A valve with a hemispherical plug that squeezes the fluid passage as shown on the previous page. It is most commonly used as a control valve from low pressure to high pressure and at high viscosity.
- Angle valve: The channel makes it easy to flow at a right angle, and it is used for slurries and high viscosity fluids.
- Diaphragm valve: Also called a Saunders valve, a diaphragm is provided at the center of the valve and the flow path is opened and closed by the diaphragm. It is used for corrosive fluids and slurries.
- Gate valve: A valve that opens and closes a partition plate provided in the flow path. It is used for relatively low cost large diameter valves.
- Butterfly valve: A valve that adjusts by rotating a disc about an axis perpendicular to the flow path. It is used for large diameter valves.
- Ball valve: A valve that has a through hole as a flow path in the valve body and is adjusted by rotating it. It is used for slurries and high viscosity fluids.

Control Valve Operation

- A control valve can have either a direct operation where the drive shaft goes down as the air pressure increases, or conversely, a reverse operation where the drive shaft goes up as the air pressure increases. For both types it can be thought that the valve will be automatically brought to the safe side in the open (fail-open) or closed (fail-close) direction when an air pressure drop problem occurs, and either is selected according to the process conditions (fail-safe concept).
- There are forward plugs that close when pushed down on the valve body, and conversely, there are reverse plugs that will open in the same situation.

Three Elements of Sizing (1)

There are three elements to consider when designing (sizing) control valves: the Cv value, the flow characteristic, and the rangeability.

- Cv Value (Capacity Coefficient or Flow Coefficient)

  This is an index that represents the maximum flow rate that can pass though the valve (a factor that represents the volume of the valve).

  It is defined as "the flow rate in USgal/min when fresh water at 60F (15.6C) flows at the maximum position at a differential pressure of 1 psi". For example, if $Cv = 20$, it represents 20 gal/min (4.542 m^3/h) of water that can flow at a pressure drop of 1 psi (6.897 kPa) when the valve is fully open.

  For liquids, the following equation is used:

$$Cv = 1.17Q\sqrt{\frac{G}{\Delta P_V}} \qquad (1)$$

Q : Flow Rate [m^3/h]
G : Specific Gravity [-]
ΔP_V: Pressure Drop [kg/cm^2]

"Nyumon Kagaku Puranto Sekkei" *in Japanese*: "Introduction to Chemical Plant Design", P.178, Baifukan (1998)

Three Elements of Sizing (2)

- <u>Flow Characteristic</u>

The flow characteristic is the relationship between the valve opening position and the Cv value when the valve opening position is changed from 0% to 100%.。

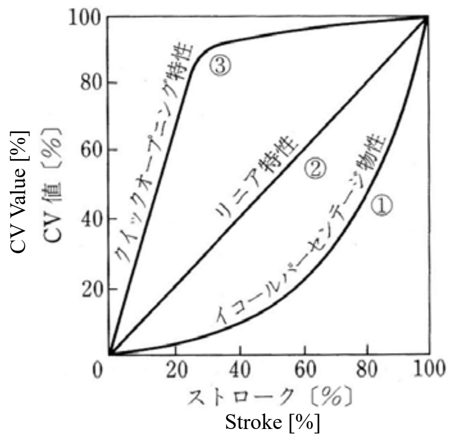
① Equal-Percentage Characteristic (or Equal-Percent Characteristic)
The ratio of the change in flow rate to the change in valve opening position is proportional to the flow rate before the change, and is expressed by the following equation. Here, L is the valve opening position, and K is a constant.

$$\frac{dCv}{dL} = KCv \longrightarrow Cv = e^{K(L-1)} \qquad (2)$$

② Linear Characteristic
With the linear characteristic, the valve opening position and the flow rate are proportional to each other.

$$Cv = KL \qquad (3)$$

③ Quick Open Characteristic
Also known as the on-off characteristic, this is a characteristic that is efficient when switching the flow rate between a maximum and a minimum, such as on-off control。



"Purosesu Seigyo" *in Japanese*: "Process Control", P.42

Solu

Three Elements of Sizing (3)

- <u>Rangeability</u>

The rangeability is the ratio of the maximum flow rate to the minimum flow rate that can be controlled by the valve.

$$\text{Rangeability } R = \frac{\text{Maximum Controllable Flow Rate}}{\text{Minimum Controllable Flow Rate}} = \frac{Cv_{max}}{Cv_{min}}$$

The true minimum flow rate is often zero when completely closed, but the flow rate becomes unstable and uncontrollable near the closed position. For that purpose, a distinction is made between the minimum controllable flow rate and the minimum flow rate at complete closing.

Using the rangeability R, the flow characteristics are expressed as follows.

Linear Characteristic
$$\ell = \frac{F - 1/R}{1 - 1/R} \rightarrow F = \frac{\ell(R-1)+1}{R} \qquad (4)$$

Equal Percentage Characteristic
$$\ell = \frac{\log F}{\log R} + 1 \rightarrow F = R^{\ell-1} \qquad (5)$$

Where F is the flow coefficient ratio (Cv/Cv_{max}) and ℓ is the stroke ratio (valve opening position, L/L_{max}).

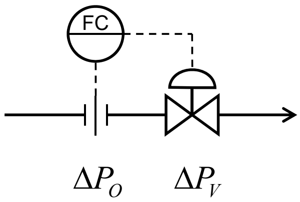
"Nyumon Kagaku Puranto Sekkei" *in Japanese*: "Introduction to Chemical Plant Design", P.179-180

Solutions for R&D to Design

Relationship between Valve Opening Position and Flow Rate

- Let us calculate the flow rate when changing the valve opening position for control valves that have linear and equal percentage flow characteristics.
- Here, we will consider the flow adjustment by combining an orifice flowmeter and a control valve as shown in the figure. The control valve changes its pressure drop as the valve opening position changes. Thus, the flow rate is adjusted, but in this study, a so-called piping resistance that changes the pressure drop depending on the adjusted flow rate is required, and an orifice flowmeter was introduced for that purpose.
- Also, since the purpose of this study is to investigate flow characteristics, it is assumed that the pressure drop of this combination of units is constant.

$$\Delta P_V + \Delta P_O = \Delta P_T \text{ (Constant)} \qquad (6)$$



Control Valve Pressure Drop

- If Eq. (1) is solved for the pressure drop, and if the flow coefficient ratio $F(=Cv/Cv_{max})$ is used, the pressure drop can be derived as follows.

$$\Delta P_V = \left(\frac{1.17Q}{Cv}\right)^2 G, \quad F = \frac{Cv}{Cv_{\max}}$$

$$\Delta P_V = \left(\frac{1.17Q}{Cv_{\max} F}\right)^2 G \qquad (7)$$

- Given the rangeability R, F can be obtained from the valve opening position (L/L_{max}) using Eqs. (4) and (5) for flow characteristics.
- Given Cv_{max}, which represents the volume of the control valve, the pressure drop can be obtained from the flow rate Q.

Flowmeter Pressure Drop

- The pressure drop ΔP_O [Pa] of the orifice plate of the orifice flowmeter is expressed as follows.

$$Q = CS\sqrt{\frac{2\Delta P_O}{\rho}}$$

$$\therefore \Delta P_O = \frac{\rho}{2}\left(\frac{Q}{CS}\right)^2$$

$$C = 0.597 - 0.011m + 0.432m^2$$

$$m = \left(D_O / D_P\right)^2$$

$$S = \frac{\pi}{4}D_O^2 \qquad (8)$$

Q : Flow Rate [m^3/h]
D_p : Inner Diameter of Piping [m]
D_o : Orifice Hole Diameter [m]
ρ : Liquid Density [kg/m^3]

- Here, the pressure drop can be calculated from the flow rate Q.

"Kagaku Kogaku Binran" *in Japanese*: Chemical Engineering Handbook, revised 7th ed., p. 188

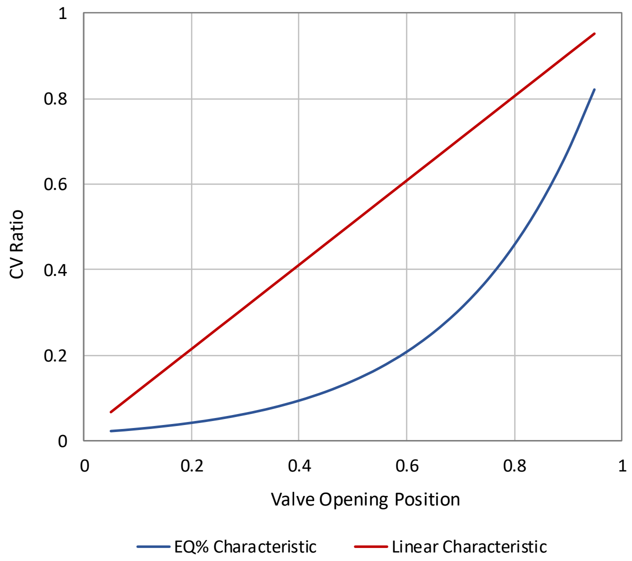
Calculation by Excel

- The relationships between the valve opening positions and the flow rates were calculated using Excel.
- The calculation procedure is as follows.
  1. Give Cv_{max}, R and the density (specific gravity) of the fluid.
  2. Specify the valve opening position.
  3. Calculate the flow coefficient ratio F from the valve opening position using Eqs. (4) or (5).
  4. Assume a flow rate Q and calculate each pressure drop with Eqs. (7) and (8).
  5. Correct the flow rate Q so as to satisfy Eq. (6) and repeat step 4 iteratively (the Excel solver was used for this convergence calculation).
- The following values were used. The fluid was assumed to be water.

$Cvmax$=100〜500、R=50
ρ=1000 [kg/m3]、G=1.0 [-]
D_P=0.0807 [m] 、D_O=0.040 [m]
ΔP_T=200 [kPa]

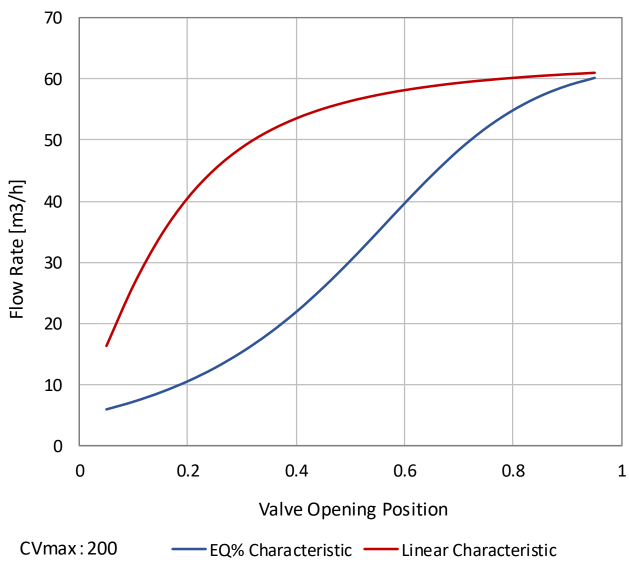
Comparison of Characteristics

- The following figure was calculated and plotted by Eqs. (4) and (5). It represents the change in the flow coefficient ratio (Cv/Cv_{max}) to the valve opening position. It corresponds to the figure on page 7.



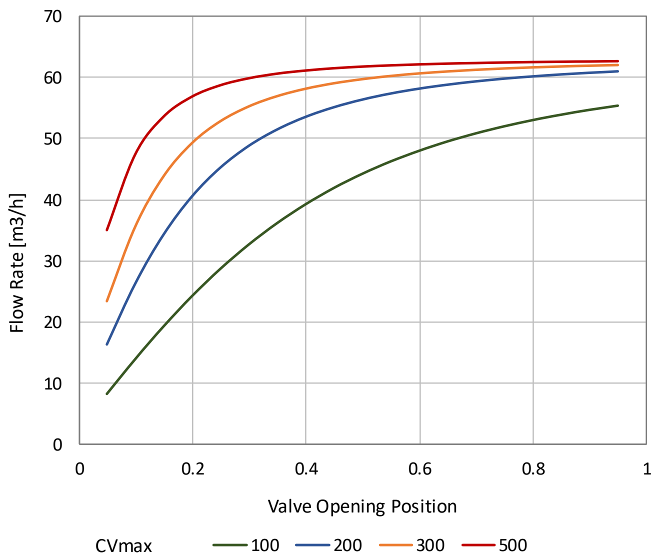
Comparison of Characteristics

- The figure shows the relationship between the valve opening position and the flow rate. With the linear characteristic, the flow rate rapidly increases as the valve is opened. On the other hand, with the equal percentage characteristic the flow rate increases almost linearly, which is advantageous for controllability.



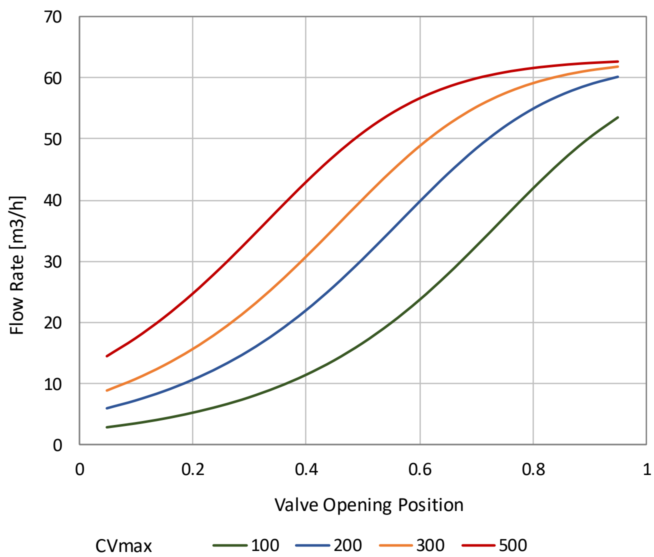
Linear Characteristic

The influence of the flow coefficient Cv_{max} was investigated. With the linear characteristic, as the value of Cv_{max} becomes larger, it is understood that the flow rate rapidly increases with the increase of the valve opening position and that flow rate adjustments can hardly be performed when Cv_{max} is 300 or more.



Equal Percentage Characteristic

- As the valve opening position becomes large, the curve will flatten out, and the controllability will deteriorate. It can be understood that it is better to avoid operation at large valve opening positions when a valve with a large Cv_{max} is selected.



Conclusion

- The relationship between the valve opening position and the flow rate was investigated for different control valve characteristics.
- The linear characteristic will saturate as the flow rate rapidly increases with the valve opening position. On the other hand, the equal percentage characteristic is advantageous for controllability because the flow rate increases relatively linearly with the valve opening position.
- However, even with the equal percentage characteristic, it was found that, for larger valve opening positions, the flow rate levels off and the controllability worsens.

<References>

- Satoshi Sagara: “Nyumon Kagaku Puranto Sekkei” *in Japanese*: "Introduction to Chemical Plant Design", Baifukan (1998)
- Dale E. Seborg *et al*.: “Process Dynamics & Control”, Wiley (1989)
- Takatsu Haruo Ed: “Purosesu Seigyo” *in Japanese*: “Process Control”, Corona Publishing (2003)
- Yasushi Ishii: “Keiso Seigyo Shisutemu” *in Japanese*: “Instrumentation Control System”, Denki Shoin (1973)