Piping Line Pressure Balance

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Introduction

- In a piping line which sends liquid from a column or tank to another column or tank, a control valve is provided to adjust the flow rate.
- The control valve changes the valve opening position to adjust the flow rate, but in the piping line, the pressure drop of other devices such as orifice flowmeters and heat exchangers will also change according to the flow rate. Therefore, it is the pressure balance between the control valve and other devices that will determine the flow rate.
- In this paper, we will examine the relationship between the pressure drops, the flow rate and a control valve opening position considering a typical piping line model.

Pressure Balance

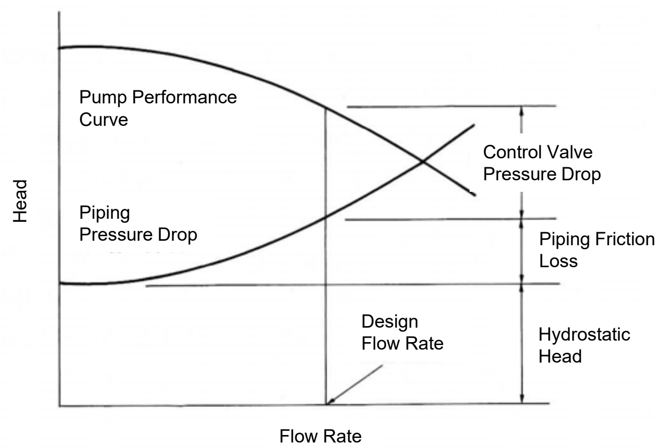
The discharge pressure of a pump is used as the static pressure of the height difference and the pressure drop of piping and heat exchangers during liquid delivery. Normally, a control valve is provided to adjust the flow rate, and an orifice flowmeter or the like is further provided to monitor the flow rate, and these elements also generate pressure drops. This design is not easy because the flow rate is determined by these pressure drops.

The pressure drop is large when the opening position of the control valve is small, so it can play the role of adjusting the flow rate. However, when the valve opening position becomes considerably large, the sum of pressure drops of other piping elements will outweigh the pressure drop of the control valve. In other words, in such a case, the contribution of other piping elements becomes important for determining the flow rate.

Pressure Balance

The pump head, pressure drop of piping and other elements, and pressure drop of the control valve are related to the flow rate as shown in the figure. That is, when the control valve is opened to increase the flow rate, the pump head is reduced, and the pressure drop of piping and the like increases. At the design flow rate, the head will be divided between the pressure drop of the control valve, the resistance of piping, and the hydrostatic head.

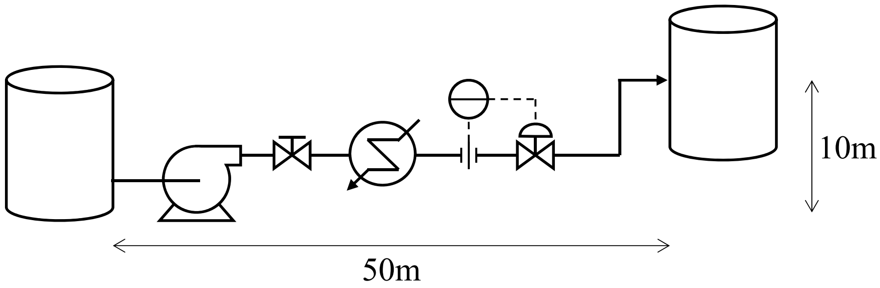
In this study, we will try to calculate a typical piping line.



"Nyumon Kagaku Puranto Sekkei" *in Japanese* : Introductory Chemical Plant Design, P.156 (Baifukan, 1998)

Estimated Piping Line

- Consider piping lines between tanks with large holdups where pressure does not change significantly with flow rate. The fluid is cooling water, and as shown in the figure, a pump, a gate valve, a heat exchanger, an orifice flowmeter, and a control valve are included in the line.
- Considering the case where the design flow rate is 28 m^3 per hour for 3 inches piping of 50 m in length, it is assumed that the tank of the liquid transfer destination is 10 m higher. Cooling water flows on the tube side of a 6-pass multi-tubular cylindrical heat exchanger. The piping has eight 90 degrees elbows and one gate valve (fully open).

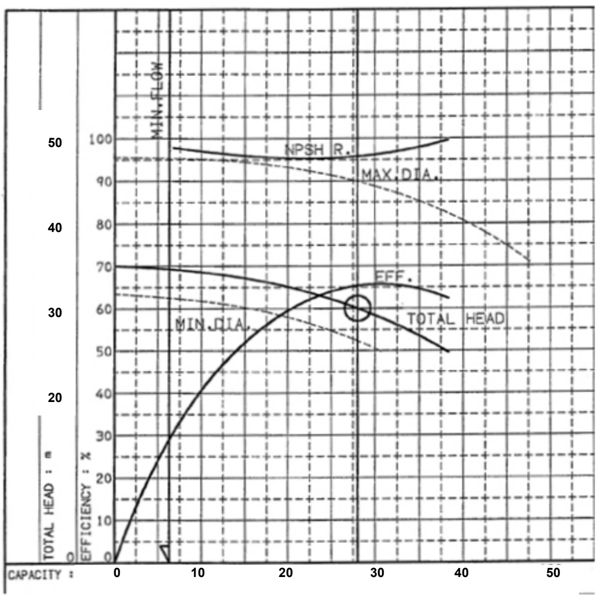


Pump Discharge Pressure

- Pump Discharge Pressure

Consider a pump with a design flow rate of 28 m^3/h and a design head of 30 m. From the performance curve of the pump, the hydraulic head H [mH_2O] is approximated by a quadratic equation as a function of the flow rate Q [m^3/h].

$$H = -0.007490Q^2 + 0.02636Q + 35.0 \qquad (1)$$



Heat Exchanger (Tube Side) Pressure Drop

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- The tube side pressure drop ΔP_H [Pa] of the multi-tubular cylindrical heat exchanger is the sum of the pressure drops in the tube sections and the pressure drops for the direction changes in the partitions. The pipe sections can be calculated by the equation for normal circular pipe flow and the pressure drops in the partitions is four times the hydraulic velocity head per pass. The flow velocity u can be obtained from the flow rate Q, and the pressure drop can be calculated.

$$\left.\begin{aligned} \Delta P_H &= \Delta P_t + \Delta P_r \\ \Delta P_t &= 4f\left(\frac{\rho u^2}{2}\right)\left(\frac{L n_{pass}}{D}\right) \\ \Delta P_r &= 4\left(\frac{\rho u^2}{2}\right) n_{pass} \end{aligned}\right\} \quad (2)$$

where n_{pass} is the number of passes.

f : Tube Friction Factor [-]
L : Heat Transfer Tube Length [m]
D : Inner Diameter of Heat Transfer Tube [m]
u : Velocity [m/s]
ρ : Liquid Density [kg/m^3]

6-pass 1-6 heat exchanger with a length of 5 m and 132 heat transfer tubes with an inner diameter of 20.8 mm.
D=0.0208[m]
L=5[m]
n_{pass}=6

"Netsukokanki Sekkei Handobukku" *in Japanese*: Heat Exchanger Design Handbook, P. 444 (Kougaku Tosho, 1974)

Heat Exchanger (Shell Side) Pressure Drop

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- Although not included in this calculation, the pressure drop on the shell side of the multi-tubular cylindrical heat exchanger can be estimated. Consider a simple case with smooth tubes and without round baffles.

$$\left.\begin{aligned} \Delta P_H &= 4f\frac{G_B^2}{2\rho}\frac{L}{D_B} \\ G_B &= W/S_B \\ S_B &= \frac{\pi}{4}\left(D_S^2 - N\cdot D_O^2\right) \\ D_B &= \frac{4S_B}{N\cdot \pi D_O} \\ Re &= \frac{D_B G_B}{\mu} \end{aligned}\right\} \quad (3)$$

f : Tube Friction Factor [-]
L : Heat Transfer Tube Length [m]
D_O : Outer Diameter of Heat Transfer Tube [m]
D_S : Inside Diameter [m]
D_B : Equivalent Diameter of Tube Bundle Channel [m]
G_B : Tube Bundle Mass Flow Rate [kg/m^2･s]
W : Flow Rate [kg/s]
S_B :Tube Bundle Channel Area [m^2]
N : Number of Heat Transfer Tubes [-]
ρ : Liquid Density [kg/m^3]

The heat exchanger is 5 m long and has a shell side inside diameter of 535 mm. The 132 heat transfer tubes each have an outer diameter of 25 mm.

"Netsukokanki Sekkei Handobukku" *in Japanese*: Heat Exchanger Design Handbook, (Kougaku Tosho, 1974)

Orifice Flowmeter Pressure Drop

- The pressure drop ΔP_O [Pa] of the orifice plate of the orifice flowmeter is expressed as follows. The pressure drop can be calculated from the flow rate Q.

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

$$\left.\begin{aligned} &\therefore \Delta P_O = \frac{\rho}{2}\left(\frac{Q}{CS}\right)^2 \\ &C = 0.597 - 0.011m + 0.432m^2 \\ &m = \left(D_O / D_P\right)^2 \\ &S = \frac{\pi}{4} D_O^2 \end{aligned}\right\} \quad (4)$$

Q : Flow Rate [m³/h]
D_p : Pipe Inner Diameter [m]
D_o : Orifice Hole Diameter [m]
ρ : Liquid Density [kg/m³]

The hole diameter of the orifice is 40 mm.
D_O=0.040[m]

"Kagaku Kogaku Binran" *in Japanese*: Chemical Engineering Handbook, 7th Ed., p. 188 (Maruzen, 2011)

Piping and Fittings Pressure Drop

- The pressure drop ΔP_p [Pa] of pipes and piping accessories such as elbows and gate valves that exist in normal piping is calculated by the following equation. Also in this case, the flow velocity u can be obtained from the flow rate Q and the pressure drop can be calculated.

$$\Delta P_P = 4f\left(\frac{\rho u^2}{2}\right)\left(\frac{L + Le}{D_P}\right) \quad (5)$$

- Here, Le is the equivalent length of piping accessories. There are eight 90 degrees elbows and one fully open gate valve. Although it can be considered that the concept of the equivalent length lacks accuracy, in this example L = 50 and Le = 15, so the pressure drop of the pipes is dominant.

f : Pipe Friction Factor [-]
L : Pipe Length [m]
Le : Equivalent Length [m]
D_p : Pipe Inner Diameter [m]
u : Flow Velocity [m/s]
ρ : Liquid Density [kg/m³]

There are eight 90 degrees elbows and one gate valve (fully open) in the piping.
D_P=0.0807[m]
L=50[m]
Le=15.0 [m] $\left((22\times 8+10)\times 0.0807\right)$

Control Valve

- Control valve pressure drop

  Equal percentage characteristic

$$\left.\begin{aligned}\Delta P_V &= \left(\frac{1.17Q}{Cv_{\max} F}\right)^2 G \\ F &= R^{\ell-1}\end{aligned}\right\} \quad (6)$$

Q : Flow Rate [m^3/h]
G : Specific Gravity [-]
ΔP_V : Pressure Drop [kg/cm2]
F : Flow Coefficient Ratio (Cv/Cv_{max})
ℓ : Stroke Ratio (Valve Opening Position, L/L_{max})
R : Rangeability (Cv_{max}/Cv_{min})

Rangeability R=50
Maximum controllable CV value
Cv_{max}=200 (150～300)

- The pressure drop is determined by the flow rate Q and the position ℓ of the control valve, but when thinking in terms of the pressure balance, it is the flow rate that is determined from the valve opening position.
- For the pressure drop and flow characteristics of the control valve, refer to "Control Valve Characteristics" (Tips to Scale-up & Design #1707).

Pressure Balance

- The discharge pressure H of the pump is equal to the sum of the hydrostatic head h [mH_2O] of the tank and the pressure drops (equations (2) to (6)) that have been detailed until now. The flow rate Q which satisfies this condition is determined.

$$H \times \frac{101300}{10.33} = h \times \frac{101300}{10.33} + \Delta P_H + \Delta P_O + \Delta P_P + \Delta P_V \quad (7)$$

- The calculation procedure determines the valve opening position ℓ of the control valve and by assuming an initial value of the flow rate Q and calculating each term from equations (1) to (6), a convergence calculation is performed to find the correct flow rate Q so that equation (7) holds. In other words, when the valve opening position is determined, the relationship between the flow rate and the pressure drop can be obtained.
- Case studies were calculated using the Excel solver function.

Friction Factor in a Circular Pipe

The friction factor f in a circular pipe used in the calculation of piping and heat exchangers is presented in documents such as handbooks as follows.

- Laminar flow (Re<2000) $f = 16/Re$ (8)
- Transition region (2000<Re<4000)
- Turbulent flow (Re>4000)

Smooth pipe (glass, copper) $\frac{1}{\sqrt{f}} = 4\log\left(Re\sqrt{f}\right) - 0.4$ (9)

Rough pipe (steel, cast iron) $\frac{1}{\sqrt{f}} = 3.2\log\left(Re\sqrt{f}\right) + 1.2$ (10)

Other than for laminar flow, since equations for calculating f directly from the Re number are preferable, the following were used. The transition region was obtained by linear interpolation of laminar flow and turbulent flow. Also, turbulent flow (4000<Re<4 × 10^5) was refitted to obtain an approximation.

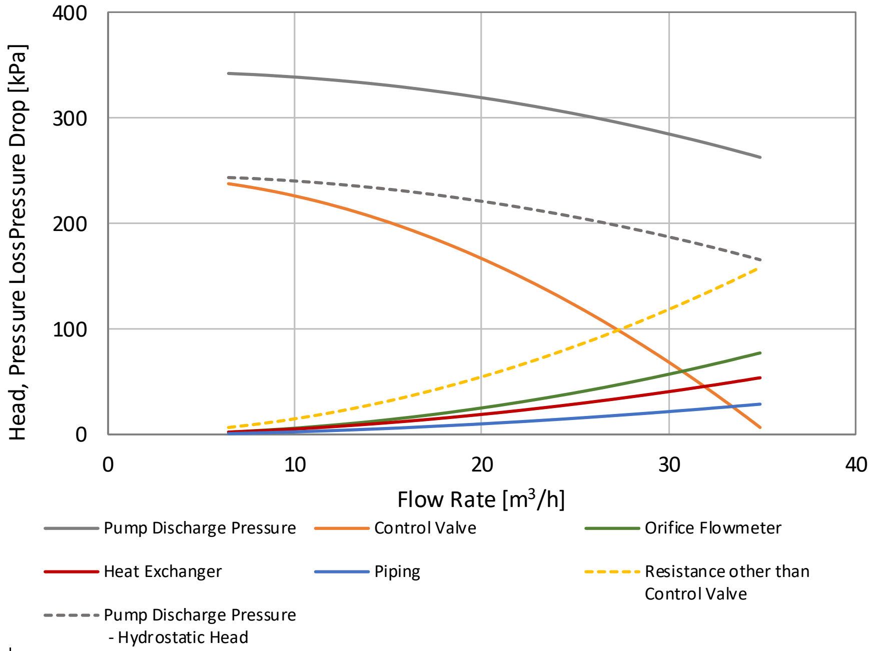
Transition region $f = 1.399\times10^{-6} Re + 0.005202$ (11)

Turbulent flow (rough pipe)

$$\sqrt{f} = 4.264\times10^{-3}\left(\log(Re)\right)^2 - 5.847\times10^{-2}\log(Re) + 0.2592 \quad (12)$$

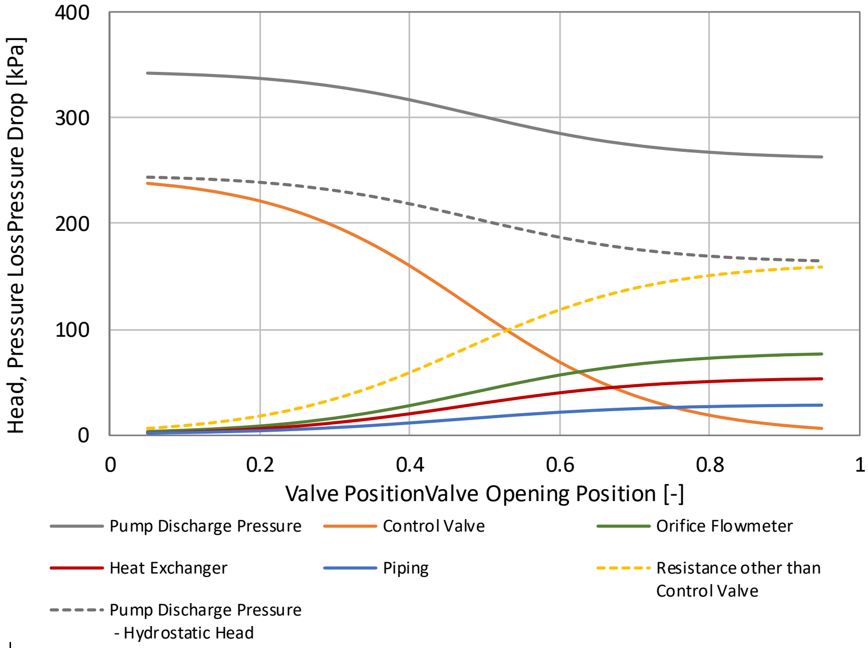
Case Study (1)

The pump discharge pressure and the pressure drop of each piece of equipment were plotted against flow rate for equal percentage characteristics (CVmax = 200).



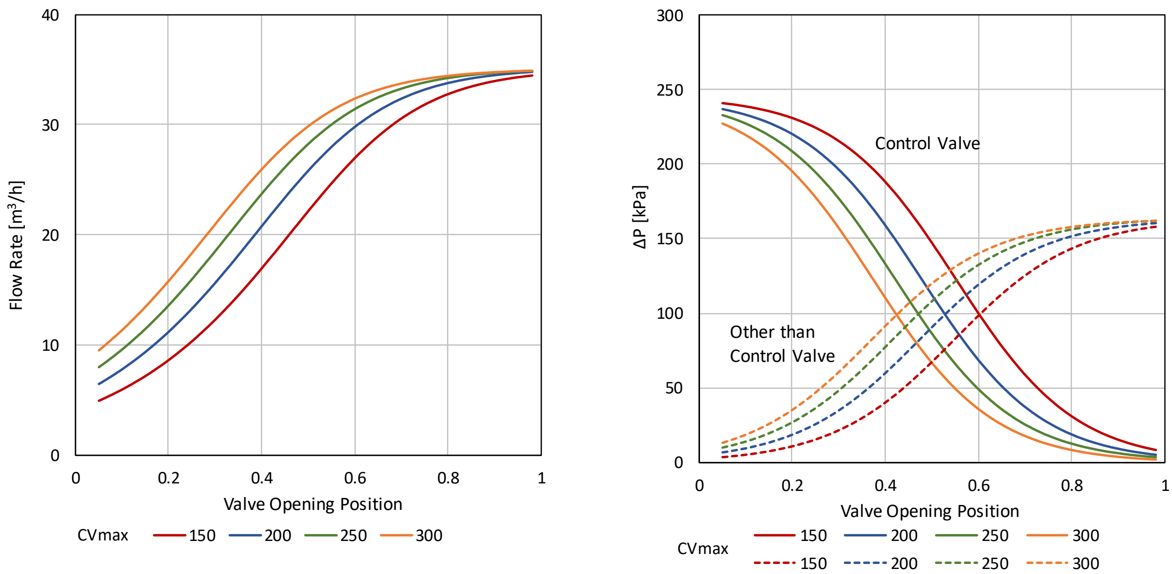
Case Study (2)

Then, under the same conditions, the pump discharge pressure and the pressure drop of each piece of equipment were plotted against the valve opening position.



Case Study (3)

Next, the flow rate and the valve opening position were plotted. In addition, the influence of CVmax on pressure drop was investigated. In order to perform flow control with good controllability, it is necessary to select a valve that has an appropriate size.



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Case Study Results

From the results of the case study, it can be seen that, other than that of the control valve, the order of the pressure drops from the largest to the smallest is that of the orifice flowmeter, the heat exchanger, and the piping.

As can be deduced from the original equations, the pressure drop of a piece of equipment increases in proportion to the square of the flow rate.

As the control valve is opened (that is, as its pressure drop is reduced) and the flow rate is increased, the pump head decreases and the pressure drops of the flowmeter, the heat exchanger, the piping, and the like increase.

In this case, the valve opening position was about 0.55 at a design flow rate of 28 m^3/h. The discharge pressure is 293 kPa, which is approximately equally divided between the pressure drop of the control valve of 90 kPa, the pressure drops other than that of the control valve of 105 kPa, and the hydrostatic head of 98 kPa.

Also, above the design flow rate, the total pressure drop of other devices reverses with the pressure drop of the control valve. It has been found that the flow rate almost stops increasing and that the controllability deteriorates when the valve opening position is high.

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Conclusion

- Using a typical piping line model, a case study has been conducted regarding the relationship between pressure and flow rate when changing the opening position of a control valve.
- It was found that the pressure drops of the control valve and other piping elements became similar when the valve opening position was large, and that the flow rate adjustment became sluggish as the valve opening position was further increased.
- Usually, control valves are roughly sized, but there are many things that cannot be understood unless they are installed in the field. It is possible to perform prior investigations by using a model like this one.

<References>

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