Lesson No 2. - Liquid Control Valve Sizing

Problem Statement

A Single ported, Globe styled Control Valve is to be sized for Liquid Propane service. The valve plug style is cage-guided with equal percentage characteristics. The control valve is placed on an 8” DN (ASME B36.10M) pipe that has a wall thickness of 8.18 mm.

Based on ANSI/ISA S75.01.01 Standards, the requirement is to check if a 2”, 3” or a 4” control valve caters to the service & how much should the control valve %opening be, during service.

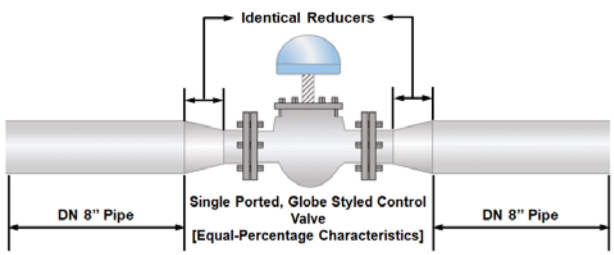

Figure 1. Control Valve Schematic

The process flow conditions are as follows,

Table 1. Input Data [1]

Parameter	Value	Units
Flow Rate [Q]	800	GPM
Inlet Pressure [P_1]	300	psig
Outlet Pressure [P_2]	275	psig
Pressure Drop [ΔP_{Valve}]	25	psi
Inlet Temperature [T_1]	70	^{0}F
ρ_1/ρ_0	0.5	-
Vapour Pressure [P_v]	124.3	psia
Critical Pressure [P_c]	616.3	psia

The control valve details to be checked for are,

Table 2. Control Valve Details [1]

Control Valve	C_v@100% Opening	F_L
2” Size	59.7	0.85
3” Size	136	0.82
4” Size	224	0.82

Based on the process conditions, to size the control valve, the following Liquid control valve sizing set of equations can be used,

Step 1: Calculate Piping Geometry (F_p) & Liquid Pressure Recovery Factor (F_{LP})

$$F_P = \left[1 + \frac{\sum K}{N_2}\left(\frac{C_V}{d^2}\right)^2\right]^{-1/2} \quad (1)$$

Where,

F_p = Piping geometric Factor [-]

N_1 = Constant [Value = 1.0]

N_2 = Constant [Value = 890]

C_v = Valve Coefficient [GPM/√psi]

d = Control Valve Size [inch]

The value of F_p is dependent on the fittings such as reducers, elbows or tees that are directly attached to the inlet & outlet connections of the control valve. If there are no fittings, F_p is taken to be 1.0. The term ΣK is the algebraic sum of the velocity head loss coefficients of all the fittings that are attached to the control valve & is estimated as,

$$\sum K = K_1 + K_2 + K_{B1} - K_{B2} \quad (2)$$

Where,

K_1 = Upstream fitting Resistance Coefficient [-]

K_2 = Downstream fitting Resistance Coefficient [-]

K_{B1} = Inlet Bernoulli Coefficient [-]

K_{B2} = Outlet Bernoulli Coefficient [-]

Where,

$$K_{B1} = 1 - \left(\frac{d}{D_1}\right)^4 \quad (3)$$

$$K_{B2} = 1 - \left(\frac{d}{D_2}\right)^4 \quad (4)$$

Where,

D_1 = Pipe Inlet Diameter [in]

D_2 = Pipe Outlet Diameter [in]

If the upstream and downstream piping are of equal size, then, K_{B1} = K_{B2}, and therefore, are dropped from the ΣK equation.

"In the current undertaking, assume that downstream pipe size is similar to upstream pipe size of 8", i.e., $D_1 = D_2$. Hence $K_{B1} = K_{B2}$"

The most commonly used fitting in control valve installations is the short-length concentric reducer. The equations for these fittings are as follows,

$$K_1 = 0.5 \times \left[1 - \left(\frac{d^2}{D_1^2}\right)\right]^2 \text{, for inlet reducer} \quad (5)$$

$$K_2 = 1.0 \times \left[1 - \left(\frac{d^2}{D_2^2}\right)\right]^2 \text{, for outlet reducer} \quad (6)$$

If the concentric reducers installed on either side of the control valve are identical, then

$$\sum K = K_1 + K_2 = 1.5 \times \left[1 - \left(\frac{d^2}{D^2}\right)\right]^2 \quad (7)$$

"In the current undertaking, assume that concentric reducers installed on either side of the control valve are identical, i.e., $\Sigma K = K_1 + K_2$

The liquid Pressure Recovery Factor (F_{LP}) can be calculated as,

$$F_{LP} = \left[\frac{K_1 + K_{B1}}{N_2}\left(\frac{C_v}{d^2}\right)^2 + \frac{1}{F_L^2}\right]^{-1/2} \quad (8)$$

Step 2: Calculate Pressure Drop Required for Sizing (ΔP_{sizing})

To estimate the pressure drop required for sizing, ΔP_{sizing}, first the liquid critical pressure ratio (F_F) is calculated. Therefore,

$$F_F = 0.96 - 0.28\sqrt{\frac{P_v}{P_c}} \quad (9)$$

Where,

F_F = Liquid Critical Pressure Ratio [-]

Pv = Vapour Pressure [psia]

Pc = Critical Pressure [psia]

Using the value of F_F, ΔP_{choked} is calculated as,

$$\Delta P_{choked} = \left[\frac{F_{LP}}{F_P}\right]^2 [P_1 - F_F P_v] \quad (10)$$

If $\Delta P_{Valve} \leq \Delta P_{Choked}$, then $\Delta P = \Delta P_{Szing}$

Else, Repeat calculations for next size.

Step 3: Calculate Required Control Valve C_v

The required control valve C_v is calculated as,

$$C_v = \frac{Q}{N_1 F_p \sqrt{\frac{\Delta P_{Sizing}}{\left[\rho_1/\rho_0\right]}}} \quad (11)$$

Upon calculating the required C_v, it is required to check if the calculated C_v is within the C_v limit of the selected control valve. If not, the next size of control valve is chosen and the calculations are repeated.

To arrive at accurate predictions for C_v of the selected size, the calculations are repeated by re-inserting the calculated C_v & control valve size (*d*) value into the F_p equation, i.e., Eq. 1 to calculate the new value of F_p & further continued to estimate the final value of C_v. If the F_L value were to change between iterations, these values would need to be updated, and C_v re-calculated.

References

Control Valve Handbook, 5th Edition, Emerson

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LIQUID CONTROL VALVE SIZING

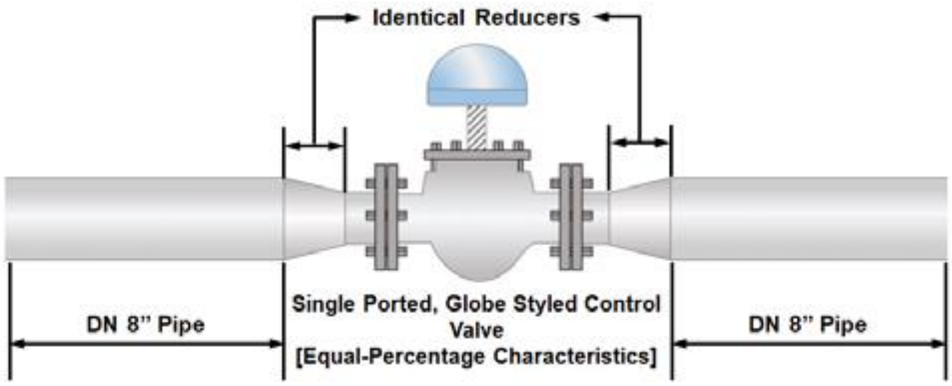

Figure 1. Control Valve Schematic

Given Parameters

Process Fluid = Liquid Propane

Volumetric Flow rate[**Q**] = 800 gpm

Valve Inlet Pressure [$\mathbf{P_1}$] = 300 psig = 314.7psia

Valve Outlet pressure [$\mathbf{P_2}$] = 275 psig = 289.7 psia

Valve Pressure drop [ΔP_{valve}] = 25 psi

Valve Inlet Temperature [$\mathbf{T_1}$] = 70 ^{0}F

Relative density of process fluid at inlet temperature [ρ_1/ρ_0] = 0.5

Vapour Pressure of process fluid at inlet temperature [$\mathbf{P_v}$] = 124.3 psia

Critical Pressure of process fluid at inlet temperature [$\mathbf{P_c}$] = 616.3 psia

Pipe wall thickness = 8.18mm = 0.322”

Upstream Pipe ID = 8”; Upstream pipe inner diameter $\mathbf{D_1}$ = 8.625 - 2(0.322) = 7.981” (8.625 is the outer diameter of 8” pipe gotten from ASMEB36.1 pipe table)

Downstream pipe ID = 8”; Downstream pipe inner diameter $\mathbf{D_2}$ = 8.625 - 2(0.322) 7.981”

Requirement

Required to check if a 2”, 3”, 4” control valve will cater for the service & how much should the control valve open %opening be during service

Solution

Step 1: Assume valve size from specified sizes to be checked (i.e. 2”, 3”, 4”)

Initial assumed valve size, **d** = 2”

For 2”, $\mathbf{C_v}$@100% opening = 59.7; $\mathbf{F_L}$ = 0.85

Where, $\mathbf{F_L}$ = Liquid pressure recovery factor

Step 2: Calculate Piping Geometry ($\mathbf{F_p}$) & Liquid Pressure Recovery Factor ($\mathbf{F_{LP}}$)

$$\mathbf{F_P} = \left[1 + \frac{\sum k}{N_2}\left(\frac{C_v}{d^2}\right)^2\right]^{-1/2} \qquad (1)$$

Where,
$\mathbf{F_p}$ = Piping geometric Factor
$\mathbf{N_1}$ = Constant [Value = 1.0]
$\mathbf{N_2}$ = Constant [Value = 890]
$\mathbf{C_v}$ = Valve Coefficient [GPM/$\sqrt{\text{PSi}}$]
d = Control Valve Size [inch]

$$\sum \mathbf{k} = \mathbf{k_1} + \mathbf{k_2} + \mathbf{k_{B1}} - \mathbf{k_{B2}} \qquad (2)$$

Where,
$\mathbf{K_1}$ = Upstream fitting Resistance Coefficient
$\mathbf{K_2}$ = Downstream fitting Resistance Coefficient
$\mathbf{K_{B1}}$ = Inlet Bernoulli Coefficient
$\mathbf{K_{B2}}$ = Outlet Bernoulli Coefficient

Where,

$$\mathbf{K_{B1}} = 1 - \left(\frac{d}{D_1}\right)^4 = 1 - \left(\frac{2}{7.981}\right)^4 = 0.996 \qquad (3)$$

$$\mathbf{K_{B2}} = 1 - \left(\frac{d}{D_2}\right)^4 = 1 - \left(\frac{2}{7.981}\right)^4 = 0.996 \qquad (4)$$

Where,
D_1 = Pipe Inlet Diameter [in]
D_2 = Pipe Outlet Diameter [in]

Since $D_1 = D_2$. Then $K_{B1} = K_{B2}$

$$\therefore from\ eqn\ (2):\ \sum \mathbf{k} = \mathbf{k_1} + \mathbf{k_2} \qquad (5)$$

Calculate for K1 and K_2

Upstream fitting (concentric reducer) resistance coefficient, **K_1**

$$\mathbf{K_1} = 0.5 \times \left[1 - \left(\frac{d^2}{D_1^2}\right)\right]^2 = 0.5 \times \left[1 - \left(\frac{2^2}{7.981^2}\right)\right]^2 = 0.439$$

downstream fitting (concentric reducer) resistance coefficient, **K_2**

$$\mathbf{K_2} = 1 \times \left[1 - \left(\frac{d^2}{D_1^2}\right)\right]^2 = 1 \times \left[1 - \left(\frac{2^2}{7.981^2}\right)\right]^2 = 0.878$$

$$\therefore from\ eqn\ (5):\ \sum \mathbf{k} = 0.439 + 0.878 = 1.317$$

Substitute to get F_P

$$\Rightarrow from\ eqn\ (1): \mathbf{F_P} = \left[1 + \frac{1.317}{890}\left(\frac{59.7}{2^2}\right)^2\right]^{-1/2} = 0.867$$

Liquid Pressure Recovery Factor (F_{LP}) can be calculated as,

$$\mathbf{F_{LP}} = \left[\frac{1}{F_L^2} + \frac{K_1 + K_{B1}}{N_2}\left(\frac{C_V}{\mathrm{d}^2}\right)^2\right]^{-1/2} = \left[\frac{1}{0.85^2} + \frac{0.439 + 0.996}{890}\left(\frac{59.7}{2^2}\right)^2\right]^{-1/2} = 0.757 \qquad (6)$$

Step 3: Calculate Pressure Drop Required for Sizing (ΔP_{sizing})

To estimate the pressure drop required for sizing, (ΔP_{sizing}), first the liquid critical pressure ratio (**F_F**) is calculated. Therefore,

$$\boldsymbol{F_F} = 0.96 - 0.28\sqrt{\frac{P_V}{P_C}} \qquad (7)$$

$$= 0.96 - 0.28\sqrt{\frac{124.3}{616.3}} = 0.834$$

Using the value of **F_F**, ΔP_{choked} is calculated as,

$$\Delta P_{Choked} = \left[\frac{F_{LP}}{F_P}\right]^2 [P_1 - F_F P_V] \qquad (8)$$

$$If\ \Delta P_{valve} \leq \Delta P_{choked}, then\ \Delta P = \Delta P_{sizing}$$

Else, Repeat calculations for next size.

$\Rightarrow from\ eqn\ (8): \Delta P_{Choked} = \left[\frac{0.757}{0.867}\right]^2 [314.7 - 0.834 \times 124.3] = 160.88\ psi$

- Since the actual pressure drop is lower than the choked pressure drop (i.e. $\Delta P_{valve} \leq \Delta P_{choked}, then\ \Delta P = \Delta P_{sizing} = 25\ psi$)

Step 4: Calculate Required Control Valve C_v

The required control valve Cv is calculated as,

$$\boldsymbol{C_v} = \frac{Q}{N_1 F_P \sqrt{\frac{\Delta P_{Sizing}}{[\rho_1/\rho_0]}}} \qquad (9)$$

$$= \frac{800}{1 \times 0.867\sqrt{\frac{25}{[0.5]}}} = 130.493$$

- The required **C_V** of 130.493 exceeds the capacity of the assumed valve, which has a **C_V** of 59.7

$\therefore\Rightarrow We\ choose\ the\ next\ control\ valve\ sze\ and\ repeat\ the\ calculations$

Step 5: Assume next valve size and repeat from step 2

Next assumed valve size, d = 3”

For 3”, **C_v**@100% opening = 136;   **F_L** = 0.82

Calculating for Piping Geometry (F_p) & Liquid Pressure Recovery Factor (F_{LP})

$$\mathbf{F_P} = \left[1 + \frac{\sum k}{N_2}\left(\frac{C_v}{d^2}\right)^2\right]^{-1/2}$$

$\sum \mathbf{k} = \mathbf{k_1} + \mathbf{k_2}$ ……………… (Upstream and downstream line are equal in size)

Upstream fitting (concentric reducer) resistance coefficient, **K_1**

$\mathbf{K_1} = 0.5 \times \left[1 - \left(\frac{d^2}{D_1^2}\right)\right]^2 = 0.5 \times \left[1 - \left(\frac{3^2}{7.981^2}\right)\right]^2 = 0.369$

downstream fitting (concentric reducer) resistance coefficient, **K_2**

$\mathbf{K_2} = 1 \times \left[1 - \left(\frac{d^2}{D_1^2}\right)\right]^2 = 1 \times \left[1 - \left(\frac{3^2}{7.981^2}\right)\right]^2 = 0.737$

$\therefore\Rightarrow \sum \mathbf{k} = 0.369 + 0.737 = 1.106$

Also, $\mathbf{F_P} = \left[1 + \frac{1.106}{890}\left(\frac{136}{3^2}\right)^2\right]^{-1/2} = 0.883$

Calculating Required Control Valve C_v

$$C_v = \frac{Q}{N_1 F_P \sqrt{\frac{\Delta P_{Sizing}}{[\rho_1/\rho_0]}}}$$

$$= \frac{800}{1 \times 0.883\sqrt{\frac{25}{[0.5]}}} = 128.128$$

- The required **C_V** of 128.128 will meet the capacity of the assumed valve, which has a **C_V** of 136

For a more accurate prediction of the C_v, the required C_v will be redetermined several times using a new F_P value based on the C_V obtained from the previous.

$$\Rightarrow \mathbf{F_P} = \left[1 + \frac{\sum k}{N_2}\left(\frac{C_V}{d^2}\right)^2\right]^{-1/2} = \left[1 + \frac{1.106}{890}\left(\frac{128.128}{3^2}\right)^2\right]^{-1/2} = 0.894$$

So,

$$C_v = \frac{Q}{N_1 F_P \sqrt{\frac{\Delta P_{Sizing}}{[\rho_1/\rho_0]}}}$$

$$= \frac{800}{1 \times 0.894\sqrt{\frac{25}{[0.5]}}} = 126.552$$

Further redetermination of C_v through several iterations resulted in:

Iterations	F_p	C_v
1	0.89592	126.2803
2	0.896346	126.2203
3	0.89643	126.2085
4	0.896446	126.2062
5	0.89645	126.2057
6	0.89645	126.2057
7	0.89645	126.2056
8	0.89645	126.2056
9	0.89645	126.2056

From several iterations the C_v converges to 126.2056, which implies that the valve be open about 97.5% during service

Checking also for a 4" valve
For 4", **C_v@100% opening** = 224; **F_L** = 0.82

Calculating for Piping Geometry (F_p) & Liquid Pressure Recovery Factor (F_{LP})

$$\mathbf{F_P} = \left[1 + \frac{\sum k}{N_2}\left(\frac{C_v}{d^2}\right)^2\right]^{-1/2}$$

$\sum \mathbf{k} = \mathbf{k_1} + \mathbf{k_2}$ ………………. (Upstream and downstream line are equal in size)

Upstream fitting (concentric reducer) resistance coefficient, $\mathbf{K_1}$

$\mathbf{K_1} = 0.5 \times \left[1 - \left(\frac{d^2}{D_1^2}\right)\right]^2 = 0.5 \times \left[1 - \left(\frac{4^2}{7.981^2}\right)\right]^2 = 0.28$

downstream fitting (concentric reducer) resistance coefficient, $\mathbf{K_2}$

$\mathbf{K_2} = 1 \times \left[1 - \left(\frac{d^2}{D_1^2}\right)\right]^2 = 1 \times \left[1 - \left(\frac{4^2}{7.981^2}\right)\right]^2 = 0.561$

∴⇒ $\sum \mathbf{k} = 0.28 + 0.561 = 0.841$

Also, $\mathbf{F_P} = \left[1 + \frac{0.841}{890}\left(\frac{224}{4^2}\right)^2\right]^{-1/2} = 0.92$

Calculating Required Control Valve C_v

$$\boldsymbol{C_v} = \frac{Q}{N_1 F_P \sqrt{\frac{\Delta P_{Sizing}}{\left[\rho_1/\rho_0\right]}}}$$

$$= \frac{800}{1 \times 0.92\sqrt{\frac{25}{[0.5]}}} = 122.975$$

- Als the required **C_V** of 122.975 will meet the capacity of the assumed valve, which has a **C_V** of 224

Also, for a more accurate prediction of the C_v, the required C_v will be redetermined several times using a new F_P value based on the C_V obtained from the previous.

$\Rightarrow$ $\mathbf{F_P} = \left[1 + \frac{\sum k}{N_2}\left(\frac{C_v}{d^2}\right)^2\right]^{-1/2}$ = $\left[1 + \frac{0.841}{890}\left(\frac{122.975}{4^2}\right)^2\right]^{-1/2}$ = 0.973

So,

$$\boldsymbol{C_v} = \frac{Q}{N_1 F_P \sqrt{\frac{\Delta P_{Sizing}}{[\rho_1/\rho_0]}}}$$

$$= \frac{800}{1 \times 0.973\sqrt{\frac{25}{[0.5]}}} = 116.28$$

Further redetermination of C_v through several iterations resulted in:

Iterations	F_p	C_v
1	0.975954	115.9246
2	0.976084	115.9092
3	0.97609	115.9084
4	0.976091	115.9084
5	0.976091	115.9084
6	0.976091	115.9084
7	0.976091	115.9084
8	0.976091	115.9084
9	0.976091	115.9084

From several iterations, the C_v converges to 115.9084, which implies that the valve be open about 80% during service

Checking also for a 6" valve

For 4", $\mathbf{C_v}$@100% opening = 394; $\mathbf{F_L}$ = 0.85

Calculating for Piping Geometry (F_p) & Liquid Pressure Recovery Factor (F_{LP})

$$\mathbf{F_P} = \left[1 + \frac{\sum k}{N_2}\left(\frac{C_v}{d^2}\right)^2\right]^{-1/2}$$

$\boldsymbol{\sum k = k_1 + k_2}$ ……………… (Upstream and downstream line are equal in size)

Upstream fitting (concentric reducer) resistance coefficient, $\mathbf{K_1}$

$\mathbf{K_1}$ = $0.5 \times \left[1-\left(\frac{d^2}{D_1^2}\right)\right]^2$ = $0.5 \times \left[1-\left(\frac{6^2}{7.981^2}\right)\right]^2$ = 0.0945

downstream fitting (concentric reducer) resistance coefficient, $\mathbf{K_2}$

$\mathbf{K_2}$ = $1 \times \left[1-\left(\frac{d^2}{D_1^2}\right)\right]^2$ = $1 \times \left[1-\left(\frac{6^2}{7.981^2}\right)\right]^2$ = 0.189

$\therefore\Rightarrow$ $\sum \mathbf{k}$ **=** 0.0945 + 0.189 = 0.2835

Also, $\mathbf{F_P} = \left[1+\frac{0.2835}{890}\left(\frac{394}{6^2}\right)^2\right]^{-1/2}$ = 0.98

Calculating Required Control Valve C_v

$$\boldsymbol{C_v} = \frac{Q}{N_1 F_P \sqrt{\frac{\Delta P_{Sizing}}{\left[\rho_1/\rho_0\right]}}}$$

$$= \frac{800}{1 \times 0.98\sqrt{\frac{25}{[0.5]}}} = 115.446$$

- Also, the required $\mathbf{C_V}$ of 115.446 will meet the capacity of the assumed valve, which has a $\mathbf{C_V}$ of 394

Again, for a more accurate prediction of the C_v, the required C_v will be redetermined several times using a new F_P value based on the C_V obtained from the previous.

$\Rightarrow$ $\mathbf{F_P} = \left[1+\frac{\sum \mathrm{k}}{\mathrm{N_2}}\left(\frac{\mathrm{C_V}}{\mathrm{d^2}}\right)^2\right]^{-1/2}$ = $\left[1+\frac{0.2835}{890}\left(\frac{115.446}{6^2}\right)^2\right]^{-1/2}$ = 0.998

So,

$$\boldsymbol{C_v} = \frac{Q}{N_1 F_P \sqrt{\frac{\Delta P_{Sizing}}{\left[\rho_1/\rho_0\right]}}}$$

$$= \frac{800}{1 \times 0.998\sqrt{\frac{25}{[0.5]}}} = 113.36$$

Further redetermination of C_v through several iterations resulted in:

Iterations	F_p	C_v
1	0.998426	113.3155
2	0.998426	113.3155
3	0.998426	113.3155
4	0.998426	113.3155
5	0.998426	113.3155
6	0.998426	113.3155
7	0.998426	113.3155
8	0.998426	113.3155
9	0.998426	113.3155

From several iterations, the C_v converges to 113.3155, which implies that the valve be open about 66% during service.

Overall Conclusion

- A **3”** control valve will cater for the service, but should open about **97.5%** during service
- A **4”** control valve will cater for the service but should open about **80%** during service.
- A **6”** control valve will cater for the service and should open about **66%**

A **6”** control valve will be best suitable for the service since ideally a control valve opening range should be somewhere between **25%** to **75%** for the sized flow rate. This is to enable the valve to be capable of controlling when there is an upset (higher than sized flow occurring)