



IndiTech Valves Pvt. Ltd.

*Control Valve Sizing Manual*

Values 'n' Valves

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## 1 Introduction

A control valve is a power operated device which modifies the fluid flow rate in a process control system. It consists of a valve connected to an actuator mechanism that is capable of changing the position of a flow controlling element in the valve in response to a signal from the controlling system.

In order to perform its intended function satisfactorily, the control valve must be sized correctly for the given process conditions. This manual presents equations for predicting the flow of compressible & incompressible fluids through control valves.

## 2 Nomenclature

Symbol	Description	Unit
$d$	Nominal valve size	mm
$D$	Internal diameter of piping	mm
$f_l$	Weight fraction of liquid in two phase mixture	Dimensionless
$f_g$	Weight fraction of gas in two phase mixture	Dimensionless
$F_D$	Valve style modifier	Dimensionless
$F_F$	Liquid critical pressure ratio factor	Dimensionless
$F_k$	Specific heat ratio factor = $k/1.4$	Dimensionless
$F_L$	Liquid pressure recovery factor for a valve	Dimensionless
$F_{LP}$	Combined liquid pressure recovery factor & piping geometry factor for a valve with attached fittings	Dimensionless
$F_P$	Piping geometry factor	Dimensionless
$F_R$	Reynolds number factor	Dimensionless
$k$	Specific heat ratio	Dimensionless
$K$	Head loss coefficient of a device	Dimensionless
$K_v$	Valve flow coefficient	m <sup>3</sup> /h
$K_{vi}$	Assumed valve flow coefficient for iterative purposes	m <sup>3</sup> /h
$M$	Molecular weight	kg/kmol
$P_1$	Inlet absolute pressure	bar
$P_2$	Outlet absolute pressure	bar
$P_C$	Absolute thermodynamic critical pressure	bar
$P_V$	Absolute vapour pressure of liquid at inlet temperature	bar
$P_{VC}$	Absolute pressure at vena contracta	bar
$\Delta P$	Pressure drop ( $P_1 - P_2$ ) across the valve	bar
$\Delta P_l$	Pressure drop for liquid phase	bar
$\Delta P_g$	Pressure drop for gaseous phase	bar
$Q$	Volumetric flow rate	m <sup>3</sup> /h
$Re_v$	Valve Reynolds number	Dimensionless
$T_1$	Inlet absolute temperature	K
$W$	Mass flow rate	kg/h
$X$	Ratio of pressure drop to inlet absolute static pressure	Dimensionless
$X_T$	Pressure differential ratio factor for a valve at choked flow	Dimensionless
$X_{TP}$	Pressure differential ratio factor for a valve with attached fittings at choked flow	Dimensionless
$Y$	Expansion factor	Dimensionless
$Z$	Compressibility factor	Dimensionless
$\rho_0$	Density of water at 15.5°C = 1,000 kg/m <sup>3</sup>	kg/m <sup>3</sup>
$\rho_1$	Density of fluid at $P_1$ & $T_1$	kg/m <sup>3</sup>
$\rho_{l1}$	Density of liquid phase at inlet	kg/m <sup>3</sup>
$\rho_{g1}$	Density of gaseous phase at inlet	kg/m <sup>3</sup>
$\nu$	Kinematic viscosity	m <sup>2</sup> /s

### 3 Terminology

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**Cavitation:** Cavitation is a two stage phenomenon associated with liquids. The first stage is the formation of vapour bubbles in the liquid when the pressure in the vena contracta is reduced below the fluid's vapour pressure. The second stage is the collapse of the vapour bubbles as the fluid passes the vena contracta and the pressure recovers and increases above the vapour pressure. Cavitation can cause severe pitting and erosion damage, and can also produce high levels of noise and vibrations.

**Choked Flow:** Choked flow is a limiting condition which occurs when the fluid mass flow rate does not increase with a further decrease in the downstream pressure while the upstream pressure is fixed. Choked flow occurs due to the Venturi effect. The Venturi effect is the reduction in fluid pressure that results when a fluid flows through a restriction. For liquids, choked flow occurs when the Venturi effect decreases the liquid pressure to below that of the liquid vapour pressure at the prevailing liquid temperature. At this point, the liquid partially flashes into vapour bubbles and the subsequent collapse of these bubbles causes cavitation. The vapour bubble formation in the restriction limits the flow from increasing any further. For gases, choked flow occurs when the flow velocity at the vena contracta reaches sonic velocity. Choked flow is also called critical flow.

**Flashing:** Flashing is similar to cavitation except that the vapour bubbles do not collapse, as the downstream pressure remains less than the vapour pressure. The flow remains a mixture of vapour and liquid.

**$K_v$ :** The valve flow coefficient  $K_v$  is defined as the flow rate in cubic meters per hour ( $m^3/h$ ) of water at a temperature of  $15.5^\circ C$  with a pressure drop across the valve of 1 bar.

### 4 Process Data

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The selection of a correct valve size, as determined by formula, is always based on the assumption of full knowledge of the actual flowing conditions. The following data must be available for performing the sizing calculations:

- Fluid properties viz. pressure  $P$ , temperature  $T$ , vapour pressure  $P_v$ , thermodynamic critical pressure  $P_c$ , density  $\rho$ , kinematic viscosity  $\nu$ , specific heat ratio  $k$ , molecular weight  $M$ , compressibility factor  $Z$ .
- Operating conditions (normal, maximum, minimum etc.).
- Inlet & outlet pipe sizes.

### 5 Sizing Equations for Liquids

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#### 5.1 Turbulent Flow

The type of flow through a valve is determined by the valve Reynolds number,  $Re_v$ . The flow through the valve is turbulent if  $Re_v \geq 10,000$ .

##### 5.1.1 Normal Flow (Non-Choked)

Applicable if

$$\Delta P < \left( \frac{F_{LP}}{F_P} \right)^2 (P_1 - F_F P_V) \quad \text{Eq. 1}$$

In this case, the following equation is used:

$$K_v = \frac{Q}{F_P} \sqrt{\frac{\rho_1 / \rho_0}{\Delta P}} \quad \text{Eq. 2}$$

### 5.1.2 Choked Flow

Applicable if

$$\Delta P \geq \left( \frac{F_{LP}}{F_P} \right)^2 (P_1 - F_F P_V) \quad \text{Eq. 3}$$

In this case, the following equation is used:

$$K_v = \frac{Q}{F_{LP}} \sqrt{\frac{\rho_1 / \rho_0}{P_1 - F_F P_V}} \quad \text{Eq. 4}$$

### 5.2 Non-Turbulent Flow

Non-turbulent flow conditions are established through a control valve because of a low pressure differential, a high viscosity, a very small flow coefficient, or a combination thereof. The flow through the valve is non-turbulent if  $Re_v < 10,000$ . In this case, the following equation is used:

$$K_v = \frac{Q}{F_R} \sqrt{\frac{\rho_1 / \rho_0}{\Delta P}} \quad \text{Eq. 5}$$

**Note:**

- 1) In all the above equations,  $K_v$  is in  $m^3/h$ ,  $Q$  is in  $m^3/h$ ,  $\rho$  is in  $kg/m^3$  and  $P$  is in bar.
- 2) If the valve size is equal to the line size, then  $F_P = 1$  and  $F_{LP}$  becomes  $F_L$ .
- 3) Refer Annexure 1 for determining various control valve sizing parameters.

## 6 Sizing Equations for Compressible Fluids

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### 6.1 Turbulent Flow

#### 6.1.1 Normal Flow (Non-Choked)

Applicable if

$$X < F_k X_{TP} \quad \text{Eq. 6}$$

In this case, one of the following equations is used:

$$K_v = \frac{Q}{2460 F_P P_1 Y} \sqrt{\frac{M T_1 Z}{X}} \quad \text{Eq. 7}$$

$$K_v = \frac{W}{110 F_P P_1 Y} \sqrt{\frac{T_1 Z}{X M}} \quad \text{Eq. 8}$$

#### 6.1.2 Choked Flow

Applicable if

$$X \geq F_k X_{TP} \quad \text{Eq. 9}$$

In this case, one of the following equations is used:

$$K_v = \frac{Q}{1640.8 F_P P_1} \sqrt{\frac{M T_1 Z}{F_k X_{TP}}} \quad \text{Eq. 10}$$

$$K_v = \frac{W}{73.4 F_P P_1} \sqrt{\frac{T_1 Z}{F_k X_{TP} M}} \quad \text{Eq. 11}$$

## 6.2 Non-Turbulent Flow

The valve flow coefficient is calculated by one of the following equations:

$$K_v = \frac{Q}{1730F_R} \sqrt{\frac{MT_1}{\Delta P(P_1 + P_2)}} \quad \text{Eq. 12}$$

$$K_v = \frac{W}{77.5F_R} \sqrt{\frac{T_1}{\Delta P(P_1 + P_2)M}} \quad \text{Eq. 13}$$

**Note:**

- 1) In all the above equations,  $K_v$  is in  $\text{m}^3/\text{h}$ ,  $Q$  is in  $\text{m}^3/\text{h}$ ,  $W$  is in  $\text{kg}/\text{h}$ ,  $M$  is in  $\text{kg}/\text{kmol}$ ,  $T$  is in  $\text{K}$  and  $P$  is in  $\text{bar}$ .
- 2) If the valve size is equal to the line size, then  $F_P = 1$  and  $X_{TP}$  becomes  $X_T$ .
- 3) Refer Annexure 1 for determining various control valve sizing parameters.

## 7 Sizing Equations for Two-Phase Flows

Two phase flows can be observed for a single fluid occurring by itself as two different phases (steam & water), or for a mixture of two different fluids having different phases (air & water). The valve flow coefficient for two phase flows is given by:

$$K_v = \frac{W}{31.6F_P} \sqrt{\frac{f_f}{\Delta P_f \rho_{f1}} + \frac{f_g}{\Delta P_g \rho_{g1} Y^2}} \quad \text{Eq. 14}$$

Liquid phase pressure drop

$$\Delta P_f = \left(\frac{F_{LP}}{F_P}\right)^2 (P_1 - F_F P_V) \quad \text{Eq. 15}$$

Gaseous phase pressure drop

$$\Delta P_g = F_k X_{TP} P_1 \quad \text{Eq. 16}$$

**Note:**

- 1) In all the above equations,  $K_v$  is in  $\text{m}^3/\text{h}$ ,  $W$  is in  $\text{kg}/\text{h}$ ,  $M$  is in  $\text{kg}/\text{kmol}$  and  $P$  is in  $\text{bar}$ .
- 2) If the valve size is equal to the line size, then  $F_P = 1$  and  $X_{TP}$  becomes  $X_T$ .
- 3) Refer Annexure 1 for determining various control valve sizing parameters.

## Annexure A - Control Valve Sizing Parameters

### A.1 Valve Style Modifier $F_D$

The valve style modifier  $F_D$  is the ratio of the hydraulic diameter of a single flow passage to the diameter of a circular orifice, the area of which is equivalent to the sum of areas of all identical flow passages at a given travel. Refer Table 1 for typical values of  $F_D$ .

### A.2 Liquid Critical Pressure Ratio Factor $F_F$

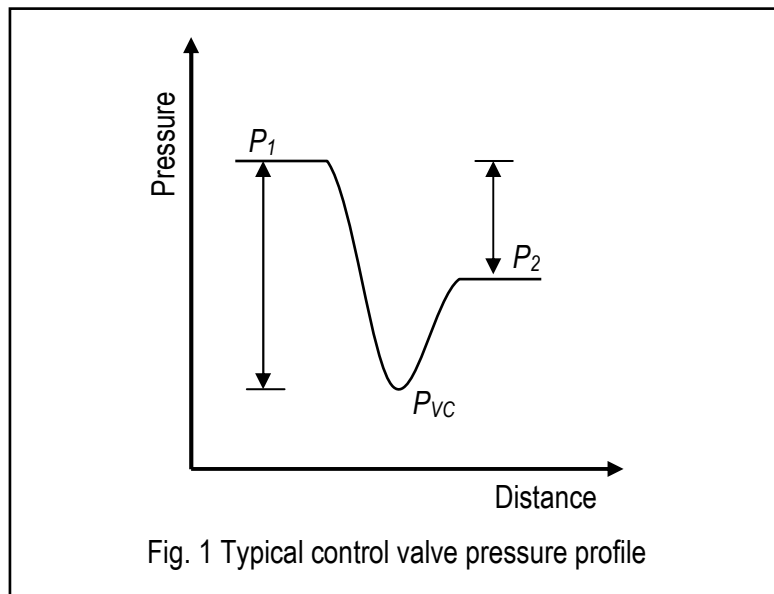
The liquid critical pressure ratio factor  $F_F$  is the ratio of the apparent vena contracta pressure at choked flow conditions to the vapour pressure of the liquid at the inlet temperature. It is determined by:

$$F_F = 0.96 - 0.28 \sqrt{\frac{P_v}{P_c}} \quad \text{Eq. 17}$$

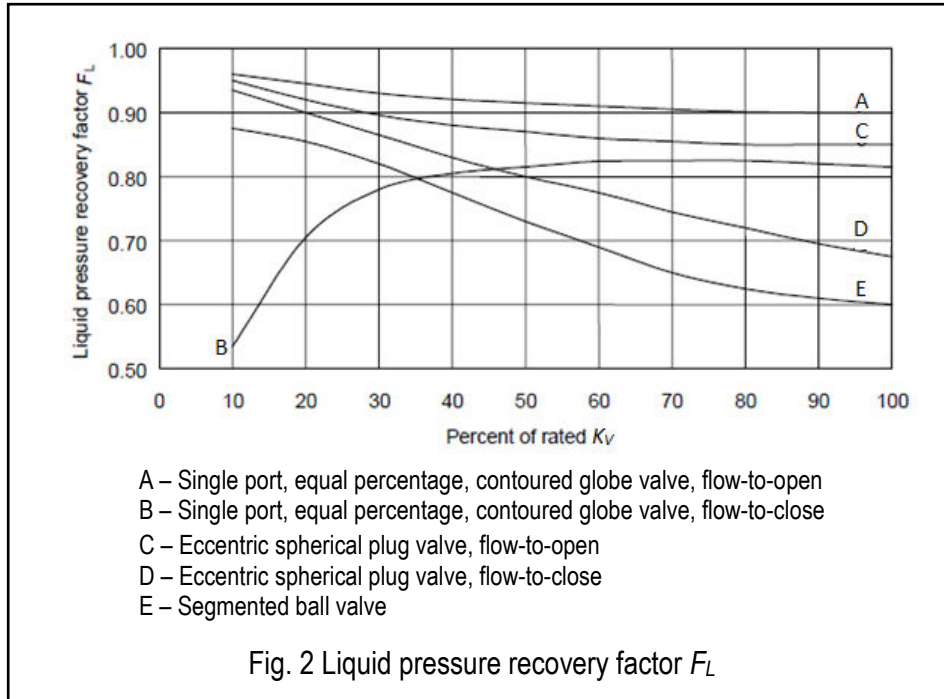
### A.3 Liquid Pressure Recovery Factor $F_L$

The liquid pressure recovery factor  $F_L$  is the square root of the ratio of the valve pressure drop to the pressure drop from the inlet pressure to the pressure at the vena contracta.

$$F_L = \sqrt{\frac{P_1 - P_2}{P_1 - P_{VC}}} \quad \text{Eq. 18}$$



The  $F_L$  factor indicates what fraction of  $(P_1 - P_{VC})$  is recovered on the downstream side. If  $F_L$  is 1, the vena contracta pressure will be equal to the valve's outlet pressure & there will be no pressure recovery. As the  $F_L$  value becomes smaller, the vena contracta pressure becomes increasingly lower than the valve's outlet pressure and the valve is more likely to cavitate. Typical values of  $F_L$  versus percent of rated flow coefficient are shown in Fig. 2.



#### A.4 Combined Liquid Pressure Recovery Factor & Piping Geometry Factor with Attached Fittings $F_{LP}$

The  $F_{LP}$  factor is determined by the following equation:

$$F_{LP} = \frac{F_L}{\sqrt{1 + \frac{(\sum K_1) F_L^2 (K_{v1})^2}{0.0016 d^2}}}$$

Eq. 19

$\sum K_1$  is the velocity head loss coefficient of the fitting attached upstream of the valve. It is given by:

$$\sum K_1 = K_1 + K_{B1}$$

Eq. 20

Refer Eq. 23 and Eq. 25 for determining values of  $K_1$  and  $K_{B1}$ .

#### A.5 Piping Geometry Factor $F_P$

When valves are mounted between pipe reducers/expanders, there is a reduction in the actual valve capacity. The reducers & expanders cause an additional pressure drop in the system by acting as contractions and enlargements in series with the valve. The piping geometry factor  $F_P$  is used to account for this effect. The  $F_P$  factor is calculated by the following equation:

$$F_P = \frac{1}{\sqrt{1 + \frac{\sum K (K_{v1})^2}{0.0016 d^2}}}$$

Eq. 21

Note: 1) In all the above equations,  $K_v$  is in  $m^3/h$  and  $d$  is in mm.





In this equation, the factor  $\sum K$  is the algebraic sum of all the effective velocity head loss coefficients of all fittings attached to the control valve. It is given by:

$$\sum K = K_1 + K_2 + K_{B1} - K_{B2} \tag{Eq. 22}$$

The velocity head loss coefficients are given by:

Inlet (Reducer)  $K_1 = 0.5 \left[ 1 - \left( \frac{d}{D_1} \right)^2 \right]^2 \tag{Eq. 23}$

Outlet (Expander)  $K_2 = 0.5 \left[ 1 - \left( \frac{d}{D_2} \right)^2 \right]^2 \tag{Eq. 24}$

Bernoulli coefficients  $K_{B1} = 1 - \left( \frac{d}{D_1} \right)^4 \tag{Eq. 25}$

$$K_{B2} = 1 - \left( \frac{d}{D_2} \right)^4 \tag{Eq. 26}$$

The calculation of  $F_P$  is an iterative procedure. Initially, proceed by calculating the flow coefficient  $K_V$  by assuming  $F_P = 1$ . Next, establish  $K_{vi}$  by the following equation:

$$K_{vi} = 1.3K_V \tag{Eq. 27}$$

Using this value of  $K_{vi}$ , calculate  $F_P$ . Then determine if

$$\frac{K_V}{F_P} \leq K_{vi} \tag{Eq. 28}$$

If the condition in Eq. 28 is satisfied, then use  $K_{vi}$  established from Eq. 27. If the condition is not satisfied, repeat the above procedure by again increasing  $K_{vi}$  by 30% until the condition in Eq. 28 is met. If the pipe diameter  $D$  is the same size at both ends of the valve, then  $F_P$  may instead be determined from Fig. 3.

Note: 1) In all the above equations,  $K_V$  is in  $m^3/h$  and  $d$  is in mm.

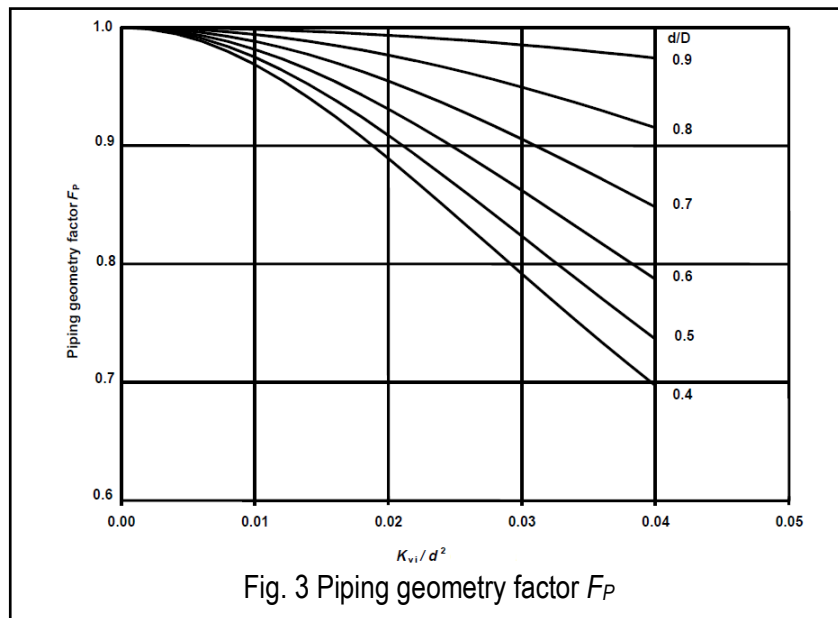


Fig. 3 Piping geometry factor  $F_P$





### A.6 Reynolds Number Factor $F_R$

The Reynolds number factor  $F_R$  is required when non-turbulent flow conditions are established through a control valve.  $F_R$  can be determined from Fig. 4a or Fig. 4b using  $Re_v$  calculated from the following equation:

$$Re_v = \frac{7.07 \times 10^{-2} F_D Q}{v \sqrt{K_{vi} F_L}} \left( \frac{F_L^2 K_{vi}^2}{0.0016 D^4} + 1 \right)^{1/4} \quad \text{Eq. 29}$$

The calculation of  $F_R$  is an iterative procedure. Initially, proceed by calculating the flow coefficient  $K_v$  for turbulent flow. Next, establish  $K_{vi}$  by the following equation:

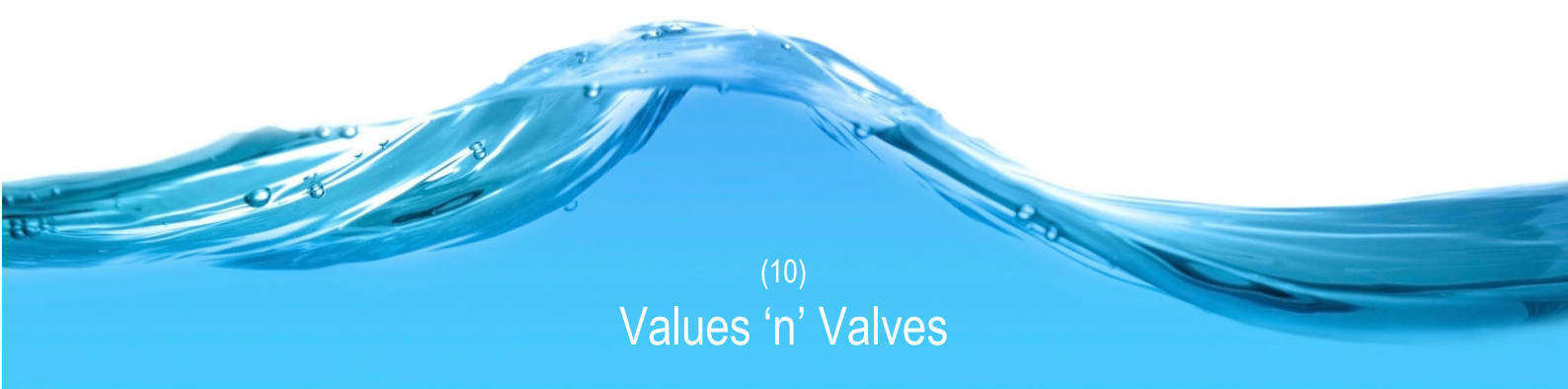
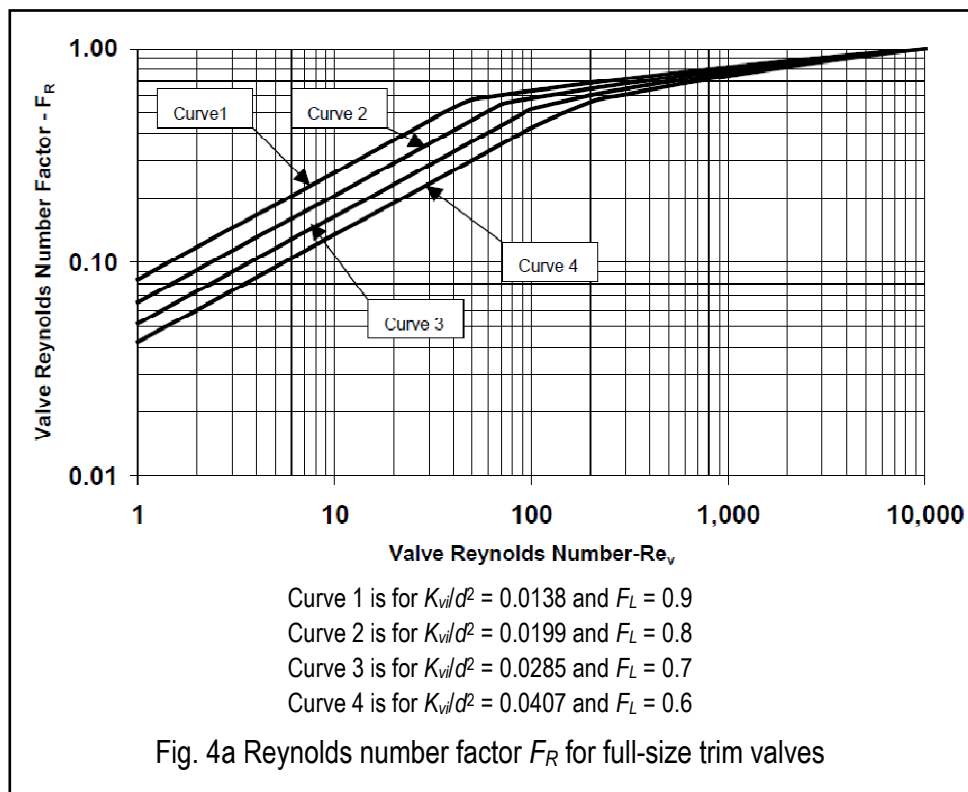
$$K_{vi} = 1.3 K_v \quad \text{Eq. 30}$$

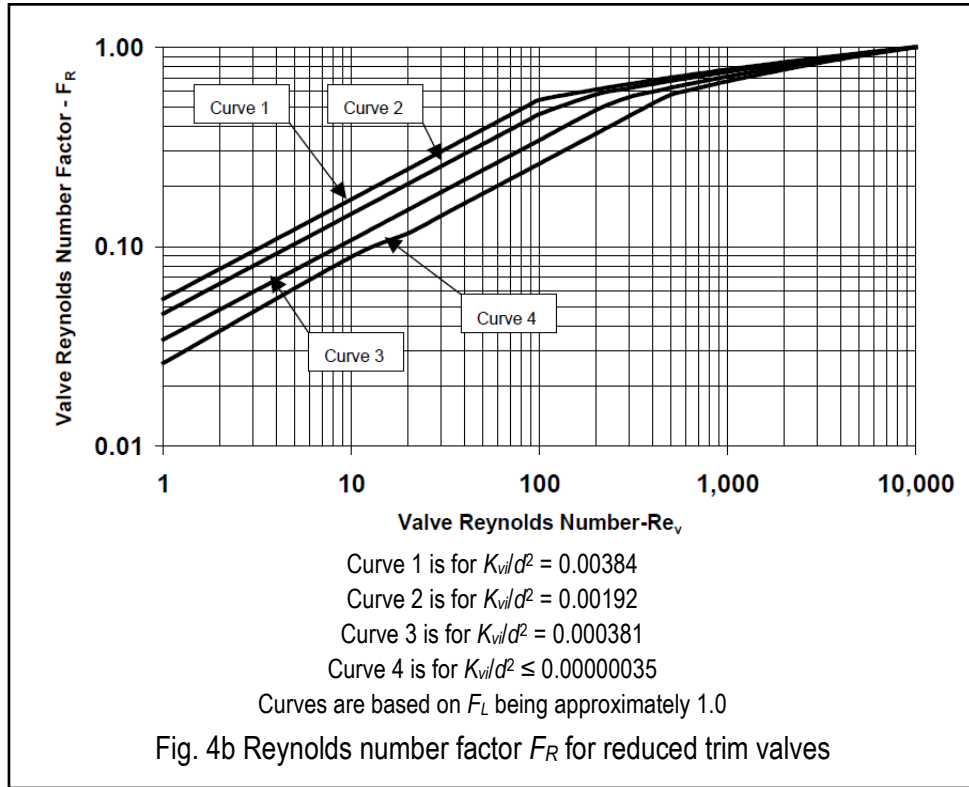
Apply  $K_{vi}$  & determine  $F_R$ .  $F_R$  is determined from Fig. 4a for full-size trim valves.  $F_R$  is determined from Fig. 4b for reduced trim valves where  $K_{vi}/d^2$  at rated travel is less than 0.0138.

Using the value of  $F_R$  from Fig. 4a or Fig. 4b, determine if

$$\frac{K_v}{F_R} \leq K_{vi} \quad \text{Eq. 31}$$

If the condition of Eq. 31 is satisfied, then use the  $K_{vi}$  established from Eq. 30. If the condition is not satisfied, repeat the above procedure by again increasing  $K_{vi}$  by 30% until the condition in Eq. 31 is met.





### A.7 Pressure Differential Ratio Factor $X_T$

If the inlet pressure  $P_1$  is held constant and the outlet pressure  $P_2$  is progressively lowered, the mass flow rate through a valve will increase to a maximum limit, a condition referred to as choked flow. Further reductions in  $P_2$  will produce no further increase in flow rate. This limit is reached when the pressure differential ratio  $X$  reaches a value of  $F_k X_T$ . Representative values of  $X_T$  for several types of control valves with full-size trims and at full rated openings are given in Table 1.

### A.8 Pressure Differential Ratio Factor with Attached Fittings $X_{TP}$

If a control valve is installed with attached fittings, the value of  $X_T$  will be affected. The  $X_{TP}$  factor is determined by the following equation:

$$X_{TP} = \frac{\frac{X_T}{F_P^2}}{1 + \frac{X_T \sum K_1 \left(\frac{K_{vi}}{d^2}\right)^2}{0.0018}}$$
Eq. 32

$\sum K_1$  is the velocity head loss coefficient of the fitting attached upstream of the valve (Refer Eq. 20).





### A.9 Expansion Factor Y

The expansion factor  $Y$  accounts for the change in density as the fluid passes from the valve inlet to the vena contracta. It also accounts for the change in the vena contracta area as the pressure differential is varied. The  $Y$  factor may be calculated using the following equation:

$$Y = 1 - \frac{X}{3F_k X_T} \tag{Eq. 33}$$

The value of  $X$  for calculation purposes shall not exceed  $F_k X_T$ . If  $X > F_k X_T$ , then the flow becomes choked and  $Y$  becomes 0.667.

### A.10 Compressibility Factor Z

The compressibility factor  $Z$  is a thermodynamic property for modifying the ideal gas law to account for the real gas behaviour. In general, deviations from ideal behaviour become more significant the closer a gas is to a phase change, the lower the temperature or the larger the pressure. The compressibility factor for specific gases can be read from generalized compressibility charts that plot  $Z$  as a function of reduced pressure at constant reduced temperature. Reduced pressure  $P_r$  is defined as the ratio of the actual inlet absolute pressure to the absolute thermodynamic critical pressure for the fluid. The reduced temperature  $T_r$  is defined similarly.

$$P_r = \frac{P_1}{P_c} \tag{Eq. 34}$$

$$T_r = \frac{T_1}{T_c} \tag{Eq. 35}$$

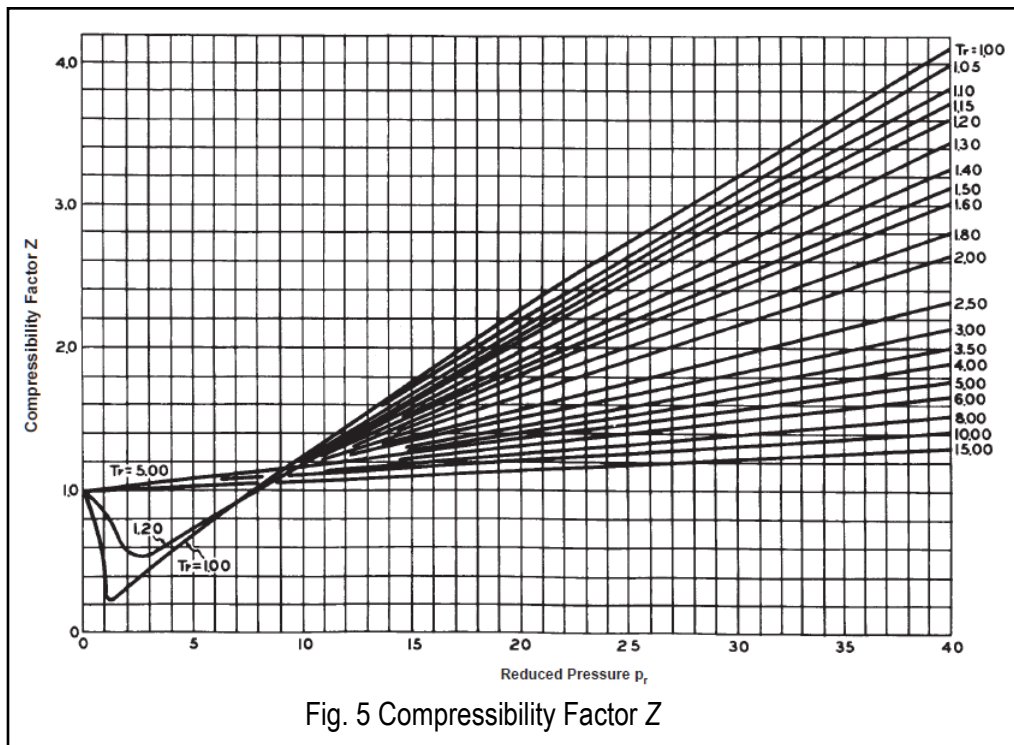


Fig. 5 Compressibility Factor Z



Table 1 – Typical values of valve style modifier  $F_D$ , liquid pressure recovery factor  $F_L$ , and pressure differential ratio factor  $X_T$  at full rated travel

Valve Type	Trim Type	Flow Direction <sup>2)</sup>	$F_L$	$X_T$	$F_D$
Globe, single port	3 V-port plug	Open or close	0.90	0.70	0.48
	4 V-port plug	Open or close	0.90	0.70	0.41
	6 V-port plug	Open or close	0.90	0.70	0.30
	Contoured plug (linear & equal %)	Open	0.90	0.72	0.46
		Close	0.80	0.55	1.00
	60 equal diameter hole drilled cage	Outward <sup>3)</sup> or Inward <sup>3)</sup>	0.90	0.68	0.13
	120 equal diameter hole drilled cage	Outward <sup>3)</sup> or Inward <sup>3)</sup>	0.90	0.68	0.09
	Characterized caged, 4-port	Outward <sup>3)</sup>	0.90	0.75	0.41
Inward <sup>3)</sup>		0.85	0.70	0.41	
Globe, double port	Ported plug	Inlet between seats	0.90	0.75	0.28
	Contoured plug	Either direction	0.85	0.70	0.32
Globe, angle	Contoured plug (linear & equal %)	Open	0.90	0.72	0.46
		Close	0.80	0.65	1.00
	Characterized caged, 4-port	Outward <sup>3)</sup>	0.90	0.65	0.41
		Inward <sup>3)</sup>	0.85	0.60	0.41
	Venturi	Close	0.50	0.20	1.00
Globe, small flow trim	V-notch	Open	0.98	0.84	0.70
	Flat seat (short travel)	Close	0.85	0.70	0.30

1) These values are typical only; contact IndiTech for actual values.  
 2) Flow tends to open or close the valve, i.e. push the closure device away from or towards the seat.  
 3) Outward means flow from centre of cage to outside, and inward means flow from outside of cage to centre.

## Annexure B – Solved Examples

### B.1 Liquids – Non-Choked Turbulent Flow without Attached Fittings

#### Process Data

Fluid	Water
Flow rate	$Q = 20 \text{ m}^3/\text{h}$
Inlet absolute pressure	$P_1 = 25 \text{ bar}$
Outlet absolute pressure	$P_2 = 22 \text{ bar}$
Inlet temperature	$T_1 = 393 \text{ K}$
Density	$\rho_1 = 941.2 \text{ kg/m}^3$
Vapour pressure	$P_V = 1.99 \text{ bar (abs)}$
Thermodynamic critical pressure	$P_C = 221.2 \text{ bar}$
Kinematic viscosity	$\nu = 2.47 \times 10^{-7} \text{ m}^2/\text{s}$
Pipe size	$D_1 = D_2 = 50 \text{ mm}$

#### Valve Data

Valve style	Globe
Trim	Parabolic
Flow direction	Flow to open
Valve size	$d = 50 \text{ mm}$
Liquid pressure recovery factor	$F_L = 0.90$ (from Table 1)
Valve style modifier	$F_D = 0.46$ (from Table 1)

#### Calculations

$$F_F = 0.96 - 0.28 \sqrt{\frac{P_V}{P_C}} = 0.933$$

where  $P_V = 1.99 \text{ bar}$  and  $P_C = 221.2 \text{ bar}$ .

Next, determine the type of flow:

$$F_L^2(P_1 - F_F P_V) = 18.75 \text{ bar}$$

which is more than the differential pressure ( $\Delta P = 3 \text{ bar}$ ); therefore the flow is non-choked. The flow coefficient  $K_v$  is calculated by:

$$K_v = Q \sqrt{\frac{\rho_1 / \rho_0}{\Delta P}} = 11.2 \text{ m}^3/\text{h}$$

where  $Q = 20 \text{ m}^3/\text{h}$ ,  $\rho_1 / \rho_0 = 0.941$  and  $\Delta P = 3 \text{ bar}$ .

Next, calculate  $Re_v$ :

$$Re_v = \frac{7.07 \times 10^{-2} F_D Q}{\nu \sqrt{K_{vi} F_L}} \left( \frac{F_L^2 K_{vi}^2}{0.0016 D^4} + 1 \right)^{1/4} = 8.294 \times 10^5$$

where  $F_D = 0.46$ ,  $Q = 20 \text{ m}^3/\text{h}$ ,  $\nu = 2.47 \times 10^{-7} \text{ m}^2/\text{s}$ ,  $K_{vi} = K_v = 11.2 \text{ m}^3/\text{h}$ ,  $F_L = 0.90$  and  $D = 50 \text{ mm}$ .

Since the valve Reynolds number is greater than 10,000, the flow is turbulent, and the flow coefficient  $K_v$  as calculated above is correct.

## B.2 Liquids – Choked Flow without Attached Fittings

### Process Data

Fluid	Water
Flow rate	$Q = 50 \text{ m}^3/\text{h}$
Inlet absolute pressure	$P_1 = 42 \text{ bar}$
Outlet absolute pressure	$P_2 = 1 \text{ bar}$
Inlet temperature	$T_1 = 308 \text{ K}$
Density	$\rho_1 = 995.8 \text{ kg/m}^3$
Vapour pressure	$P_V = 0.06 \text{ bar (abs)}$
Thermodynamic critical pressure	$P_C = 221.2 \text{ bar}$
Kinematic viscosity	$\nu = 7.23 \times 10^{-7} \text{ m}^2/\text{s}$
Pipe size	$D_1 = D_2 = 150 \text{ mm}$

### Valve Data

Valve style	Globe
Trim	120 equal diameter hole drilled cage
Flow direction	Inward
Valve size	$d = 150 \text{ mm}$
Liquid pressure recovery factor	$F_L = 0.90$ (from Table 1)
Valve style modifier	$F_D = 0.09$ (from Table 1)

### Calculations

$$F_F = 0.96 - 0.28 \sqrt{\frac{P_V}{P_C}} = 0.955$$

where  $P_V = 0.06 \text{ bar}$  and  $P_C = 221.2 \text{ bar}$ .

Next, determine the type of flow:

$$F_L^2 (P_1 - F_F P_V) = 33.97 \text{ bar}$$

which is less than the differential pressure ( $\Delta P = 41 \text{ bar}$ ); therefore the flow is choked. The flow coefficient  $K_V$  is calculated by:

$$K_V = \frac{Q}{F_L} \sqrt{\frac{\rho_1 / \rho_0}{P_1 - F_F P_V}} = 8.56 \text{ m}^3/\text{h}$$

where  $Q = 50 \text{ m}^3/\text{h}$ ,  $F_L = 0.90$ ,  $\rho_1 / \rho_0 = 0.996$ ,  $P_1 = 42 \text{ bar}$ ,  $F_F = 0.955$  and  $P_V = 0.06 \text{ bar}$ .

Next, calculate  $Re_v$ :

$$Re_v = \frac{7.07 \times 10^{-2} F_D Q}{\nu \sqrt{K_{vi} F_L}} \left( \frac{F_L^2 K_{vi}^2}{0.0016 D^4} + 1 \right)^{1/4} = 1.585 \times 10^5$$

where  $F_D = 0.09$ ,  $Q = 50 \text{ m}^3/\text{h}$ ,  $\nu = 7.23 \times 10^{-7} \text{ m}^2/\text{s}$ ,  $K_{vi} = K_V = 8.56 \text{ m}^3/\text{h}$ ,  $F_L = 0.90$  and  $D = 150 \text{ mm}$ .

Since the valve Reynolds number is greater than 10,000, the flow is turbulent, and the flow coefficient  $K_V$  as calculated above is correct.

## B.3 Compressible Fluids – Non-Choked Turbulent Flow with Attached Fittings

### Process Data

Fluid	Nitrogen
Molecular Weight	28.01 kg/kmol
Flow rate	$Q = 15,000$ standard $m^3/h$ at 1.013 bar & $0^\circ C$
Inlet absolute pressure	$P_1 = 17$ bar
Outlet absolute pressure	$P_2 = 16.5$ bar
Inlet temperature	$T_1 = 313$ K
Kinematic viscosity	$\nu = 1.22 \times 10^{-6}$ $m^2/s$
Specific heat ratio	$k = 1.424$
Compressibility factor	$Z = 0.998$
Pipe size	$D_1 = D_2 = 250$ mm
Reducers	Short length, concentric

### Valve Data

Valve style	Globe
Trim	Parabolic
Flow direction	Flow to open
Valve size	$d = 200$ mm
Pressure differential ratio factor	$X_T = 0.72$ (from Table 1)
Liquid pressure recovery factor	$F_L = 0.90$ (from Table 1)
Valve style modifier	$F_D = 0.46$ (from Table 1)

### Calculations

$$F_k = \frac{k}{1.4} = 1.017$$

where  $k = 1.424$ .

$$X = \frac{\Delta P}{P_1} = 0.029$$

which is less than  $F_k X_T = 0.732$ ; therefore the flow is non-choked and the flow coefficient is calculated from Eq. 7. Next,  $Y$  is calculated by:

$$Y = 1 - \frac{X}{3F_k X_T} = 0.987$$

where  $X = 0.029$ ,  $F_k = 1.017$  and  $X_T = 0.72$ .

The flow coefficient  $K_V$  is calculated as:

$$K_V = \frac{Q}{2460 F_P P_1 Y} \sqrt{\frac{M T_1 Z}{X}} = 199.38 \text{ m}^3/h$$

where  $Q = 15,000$   $m^3/h$ , assume  $F_P = 1$ ,  $P_1 = 17$  bar,  $Y = 0.987$ ,  $M = 28.01$  kg/kmol,  $T_1 = 313$  K,  $Z = 0.998$  and  $X = 0.029$ .

Next, calculate  $Re_v$ :

$$Re_v = \frac{7.07 \times 10^{-2} F_D Q}{\nu \sqrt{K_V F_L}} \left( \frac{F_L^2 K_V^2}{0.0016 D^4} + 1 \right)^{1/4} = 2.988 \times 10^7$$

where  $F_D = 0.46$ ,  $Q = 15,000 \text{ m}^3/\text{h}$ ,  $\nu = 1.22 \times 10^{-6} \text{ m}^2/\text{s}$ ,  $K_{vi} = K_v = 199.38 \text{ m}^3/\text{h}$ ,  $F_L = 0.90$  and  $D = 250 \text{ mm}$ .

Since the valve Reynolds number is greater than 10,000, the flow is turbulent.

Now, calculate the effect of the inlet and outlet reducers on  $K_v$ .

Since both reducers are concentric, short length and the pipe diameter  $D$  is the same size at both ends,  $F_P$  can be determined from Fig. 3.

The value of  $K_{vi}$  is given by:

$$K_{vi} = 1.3K_v = 259.2 \text{ m}^3/\text{h}$$

Using Fig. 3, the value of  $F_P$  is 0.99, where  $d/D = 0.8$  and  $K_{vi}/d^2 = 0.006$ .

Next, determine  $K_v/F_P$  as:

$$\frac{K_v}{F_P} = 201.4 \text{ m}^3/\text{h}$$

which is less than  $K_{vi} = 259.2 \text{ m}^3/\text{h}$ , so  $F_P = 0.99$  will be used for the final calculation.

Now, calculate  $X_{TP}$  as:

$$X_{TP} = \frac{\frac{X_T}{F_P^2}}{1 + \frac{X_T \sum K_1}{0.0018} \left(\frac{K_{vi}}{d^2}\right)^2} = 0.727$$

where  $X_T = 0.72$ ,  $F_P = 0.99$ ,  $\sum K_1 = K_1 + K_{B1} = 0.655$ ,  $K_{vi} = 259.2 \text{ m}^3/\text{h}$  and  $d = 200 \text{ mm}$ .

With this,  $F_k X_{TP} = 0.739$ , which is greater than  $X = 0.029$ .

Finally,  $K_v$  calculated by Eq. 7 will be:

$$K_v = \frac{Q}{2460 F_P P_1 Y} \sqrt{\frac{M T_1 Z}{X}} = 201.58 \text{ m}^3/\text{h}$$

where  $Q = 15,000 \text{ m}^3/\text{h}$ , assume  $F_P = 0.99$ ,  $P_1 = 17 \text{ bar}$ ,  $Y = 0.987$ ,  $M = 28.01 \text{ kg/kmol}$ ,  $T_1 = 313 \text{ K}$ ,  $Z = 0.998$  and  $X = 0.029$ .

## B.4 Compressible Fluids – Choked Flow without Attached Fittings

### Process Data

Fluid	Steam
Molecular Weight	18.02 kg/kmol
Flow rate	$W = 20,000$ kg/h
Inlet absolute pressure	$P_1 = 110$ bar
Outlet absolute pressure	$P_2 = 8$ bar
Inlet temperature	$T_1 = 813$ K
Kinematic viscosity	$\nu = 9.7 \times 10^{-7}$ m <sup>2</sup> /s
Specific heat ratio	$k = 1.383$
Compressibility factor	$Z = 0.928$
Pipe size	$D_1 = D_2 = 75$ mm

### Valve Data

Valve style	Globe
Trim	120 equal diameter hole drilled cage
Flow direction	Inward
Valve size	$d = 75$ mm
Pressure differential ratio factor	$X_T = 0.68$ (from Table 1)
Liquid pressure recovery factor	$F_L = 0.90$ (from Table 1)
Valve style modifier	$F_D = 0.09$ (from Table 1)

### Calculations

$$F_k = \frac{k}{1.4} = 0.988$$

where  $k = 1.383$ .

$$X = \frac{\Delta P}{P_1} = 0.927$$

which is more than  $F_k X_T = 0.672$ ; therefore the flow is choked and the flow coefficient is calculated from Eq. 11.

$$K_v = \frac{W}{73.4 F_P P_1} \sqrt{\frac{T_1 Z}{F_k X_T P M}} = 19.56 \text{ m}^3/\text{h}$$

where  $W = 20,000$  kg/h,  $F_P = 1$ ,  $P_1 = 110$  bar,  $T_1 = 813$  K,  $Z = 0.928$ ,  $F_k = 0.988$ ,  $X_T = 0.68$  and  $M = 28.01$  kg/kmol.

Next, calculate  $Re_v$ :

$$Re_v = \frac{7.07 \times 10^{-2} F_D Q}{\nu \sqrt{K_{vi} F_L}} \left( \frac{F_L^2 K_{vi}^2}{0.0016 D^4} + 1 \right)^{1/4} = 9.9 \times 10^5$$

where  $F_D = 0.09$ ,  $Q = 632.7$  m<sup>3</sup>/h,  $\nu = 9.7 \times 10^{-7}$  m<sup>2</sup>/s,  $K_{vi} = K_v = 19.56$  m<sup>3</sup>/h,  $F_L = 0.90$  and  $D = 75$  mm.

Since the valve Reynolds number is greater than 10,000, the flow is turbulent, and the flow coefficient  $K_v$  as calculated above is correct.



## References

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