TURBULENT FLOW IN PIPES

The turbulent flow is characterised by the presence of eddies (eddy - a circular movement of, say, water causing a small whirlpool). The eddies are of various sizes and they coexist. The fluctuations/oscillations are present in all the three directions. The fluctuations cause the mixing of different fluid portions by lateral movement. The turbulent flow is of a great importance because it brings about mixing of the fluid elements which results in higher rates of heat and mass transfer.

Fanning friction factor as a function of the Reynolds number for turbulent flow through a smooth pipe is given by

$$\frac{1}{\sqrt{f}} = 4 \log (N_{Re} \sqrt{f}) - 0.40 \quad \text{... (7.117)}$$

Equation (7.117) is known as the Nikuradse equation. This equation requires a trial and error procedure for estimating the friction factor.

The other empirical relation that can be used for estimating the friction factor from the Reynolds number for turbulent flow is

$$f = \frac{0.078}{(N_{Re})^{0.25}} \quad \text{... (7.118)}$$

EFFECT OF ROUGHNESS

Our foregoing discussion was restricted to smooth conduits. In turbulent flow, a rough pipe results in a larger friction factor than that with a smooth pipe, for a given Reynolds number. If a rough pipe is made smooth, the friction factor is reduced and ultimately a stage will come when further smoothening of the pipe does not reduce the friction factor for a given Reynolds number. The pipe is then said to be *hydraulically smooth.*

A roughness parameter (k) is a length representing the magnitude of surface roughness. Relative roughness is the *ratio of the roughness parameter to the diameter of pipe*, i.e., k/D. The friction factor dependency on the surface roughness is given through the relative roughness. For low values of Reynolds number (N_{Re} < 2100), the friction factor is independent of the surface roughness. For large values of Reynolds number (N_{Re} > 2500), the friction factor is also a function of the surface roughness. At very large values of Reynolds number, the friction factor is independent of N_{Re} but is a function of the surface roughness.

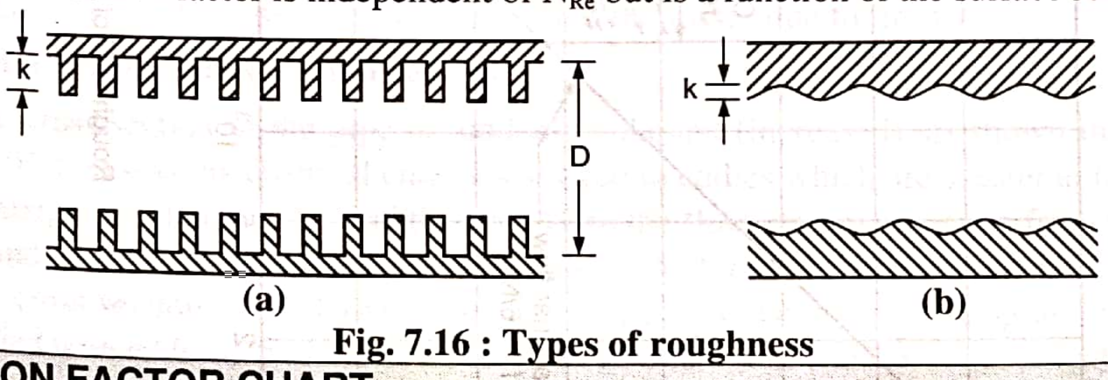

Fig. 7.16 : Types of roughness

FRICTION FACTOR CHART

It is a logarithmic plot of friction factor v/s Reynolds number over a wide range of the Reynolds number for flow of fluids in smooth as well as rough pipes. The data for the plot are taken over a wide range of each variable such as velocity, density and pipe diameter, etc. using liquids and gases. This chart is also termed as the friction factor – Reynolds number correlation chart. Such a plot is shown in Fig. 7.17. This chart is a graphical representation of the relationship : f = (N_{Re}, k/D), i.e., the relationship between the friction factor and the Reynolds number with k/D as a parameter on log-log paper.

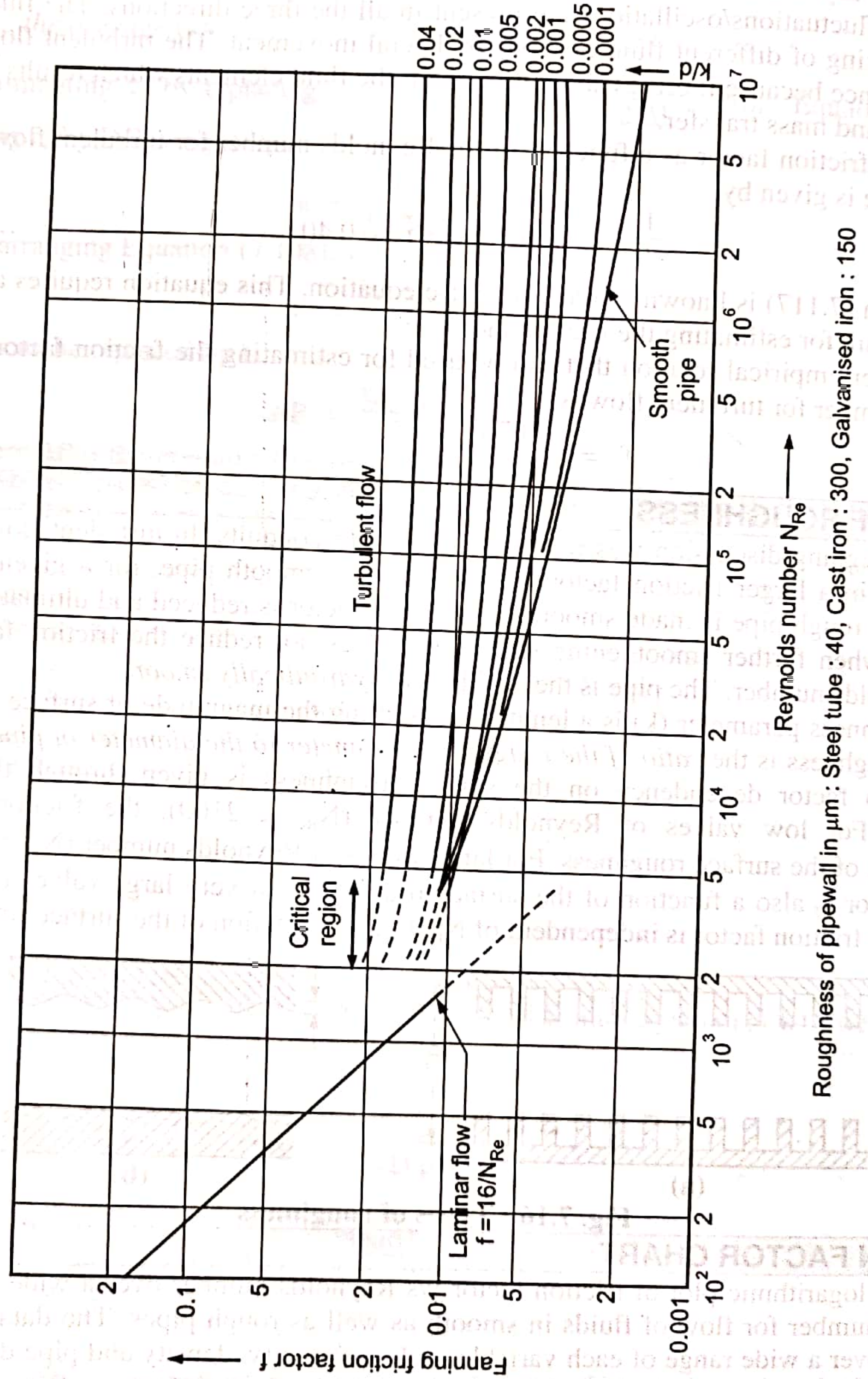

Fig. 7.17 : Friction factors for fluids flowing through pipes / Friction factor chart

The friction factor is a function of both the Reynolds number and relative roughness. For laminar flow region, the friction factor is not affected by the relative roughness of a pipe, therefore, only one line is shown for Reynolds number upto about 2100.

For the laminar flow region, the relation $f = 16/N_{Re}$ expresses the dependency of f on N_{Re}. A log-log plot of the above relation results in a straight line with a slope equal to minus one.

For turbulent flow, the relationship between 'f' and N_{Re} is given by the Nukuradse equation. Since 'f' is also a function of the relative roughness for turbulent flow, curves with different values of the dimensionless ratio k/D are presented in the chart for $N_{Re} > 2100$ assuming that turbulent flow exist at all Reynolds number greater than 2100. It is clear from Fig. 7.17 that the friction factor is low for a smooth pipe as compared to a rough pipe and increases as the relative roughness increases for a given Reynolds number. For Reynolds number above 4000, the flow is turbulent and values of f should be read from lines at the right of Fig. 7.17, where the lowest line represents the friction factor for smooth pipes.

FRICTION LOSSES

When a fluid is flowing through a straight pipe, only skin friction exists and so far we have considered only this kind of friction. Whenever there are disturbances in a fluid flow path due to a change in the direction of flow or a change in the size of the pipe or due to the presence of fittings and valves, friction is generated in addition to the skin friction, i.e., additional friction losses occur. When the cross-section of the pipe changes gradually to a new cross-section or when there is a gradual change in the direction of flow, disturbance to the normal flow pattern can be small and the amount of mechanical energy loss as friction is negligible. If the change is sudden, an appreciable amount of mechanical energy is lost as friction (heat). Similarly, the presence of fittings and valves disturbs the normal flow pattern and this can cause friction losses. All these losses should be included in the friction term, h_f, of the Bernoulli equation (Equation 7.66).

Now, we will deal with the friction losses occurring as a result of a sudden enlargement or contraction of the cross-section of the pipe and the losses due to fittings.

Friction Loss from Sudden Enlargement

If the cross-section of the pipe is suddenly enlarged (increased), as shown in Fig. 7.18, there is a friction loss (mechanical energy loss) due to eddies which are greater at the point of sudden enlargement than in the straight pipe. Here the fluid stream separates from the wall of the pipe and issues in the enlarged section as a jet, which then expands and consequently fills the entire cross-section of the larger pipe. The space between the expanding jet and the pipe wall is filled with eddies (fluid vortices) and a large amount of friction is generated there.

The friction head loss from a sudden enlargement (expansion) of the cross-section of the pipe for turbulent flow is proportional to the velocity head of the fluid in the smaller pipe and is given by

$$h_{fe} = K_e \cdot \frac{u_1^2}{2g} \quad \ldots (7.119)$$

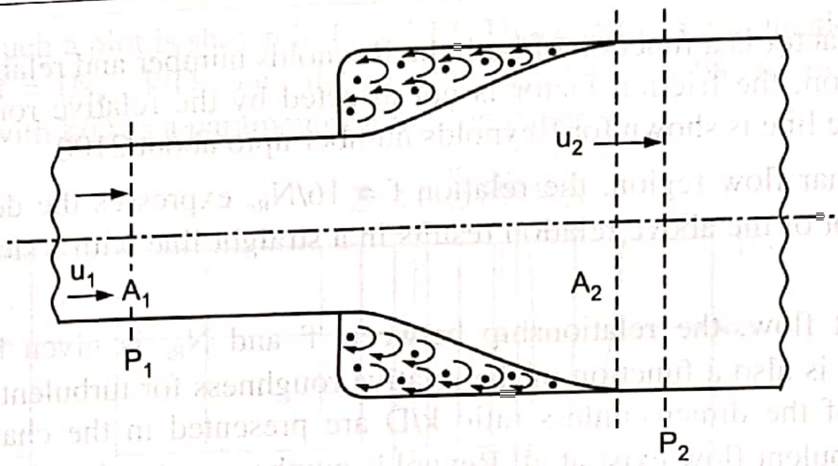

Fig. 7.18 : Flow through sudden enlargement / expansion in a pipeline

In Equation (7.119), the friction loss is expressed in m of flowing fluid.

In the energy units (J/kg), $h_{fe} = K_e \frac{u_1^2}{2}$ . ... (7.120)

where K_e is a proportionality constant and known as the expansion-loss coefficient and u_1 is the average velocity of fluid in the smaller pipe/upstream pipe.

The expansion-loss coefficient is calculated by the following relation :

$$K_e = \left(1 - \frac{A_1}{A_2}\right)^2$$

where A_1 is the cross-sectional area of the smaller pipe and A_2 is the cross-sectional area of the larger pipe.

Friction Loss from Sudden Contraction

When the cross-section of the pipe is suddenly reduced, as shown in Fig. 7.19, the fluid stream gets separated from the wall of the pipe and a fluid jet is formed. This jet first contracts, at a short distance from the sudden contraction, in the smaller pipe and then expands to fill the entire cross-section of the smaller pipe. *The cross-section of minimum effective flow area at which the fluid jet changes from a contraction to an expansion is known as the* ***vena contracta***. Upto the vena contracta, the fluid is accelerated and losses are very small. But beyond it, the velocity decreases as the flow area increases and conditions are equivalent to those for a sudden expansion. The space between the wall and the jet is filled with eddies (as shown in Fig. 7.19).

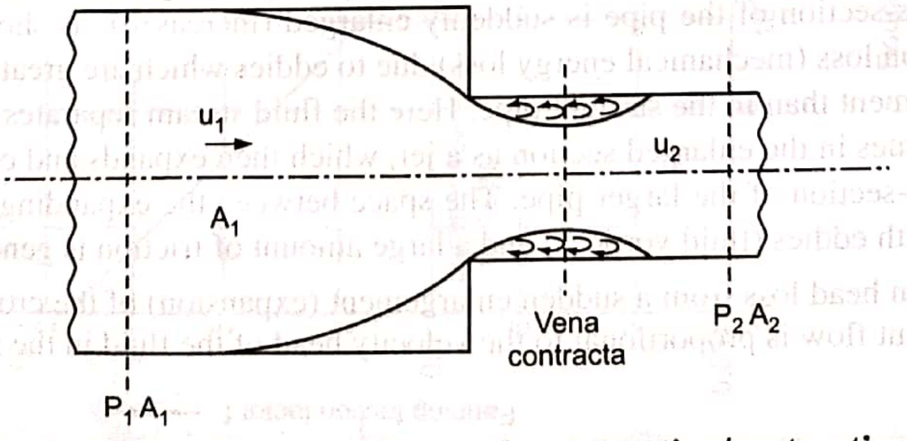

Fig. 7.19 : Flow through sudden contraction of cross-section/contraction in a pipeline

The friction loss or frictional head loss from a sudden contraction of the cross-section of the pipe is proportional to the velocity head of the fluid in the smaller diameter pipe. It is given by the relation

$$h_{fc} = K_c \frac{u_2^2}{2g}, \text{ in m of flowing fluid} \quad \ldots (7.121)$$

where K_c is a proportionality constant and is known as the contraction-loss coefficient, u_2 is the average velocity in the smaller or downstream pipe.

For turbulent flow, K_c is given by the following relation :

$$K_c = 0.4 \left[1 - \frac{A_2}{A_1}\right] \quad \ldots (7.122)$$

where A_1 is the cross-sectional area of the larger pipe/upstream pipe and A_2 is the cross-sectional area of the smaller pipe/downstream pipe.

The frictional loss in J/kg is given by

$$h_{fc} = K_c' u_2^2 / 2 \quad \ldots (7.123)$$

Friction Losses in Fittings and Valves

Various types of fittings and valves are used in industrial piping systems to change the direction of flow, for connecting pipes of different diameters, etc. and valves are used to control the flow or to stop the flow of a fluid. Fittings and valves disturb the normal flow-line and cause friction and may lead to greater frictional loss than that caused by the straight pipe. The frictional loss due to fittings and valves may be given either in terms of the velocity head or in terms of the equivalent length.

The frictional head loss in terms of the velocity head is given by the following equation :

$$h_{ff} = K_f \frac{u_1^2}{2g} \quad \ldots (7.124)$$

The frictional loss in J/kg is given by

$$h_{ff} = K_f' \frac{u_1^2}{2} \quad \ldots (7.125)$$

where K_f is the loss factor for the fitting and u_1 is the average velocity of the fluid in the piping leading to the fitting.

Equivalent Length

Another way to express the frictional loss in fittings and valves is through the equivalent length of fittings. The **equivalent length** of a fitting is *that length of straight pipe of the same nominal size as that of the fitting, which would cause the same friction loss as that caused by the fitting.*

The equivalent length of a fitting/valve is usually expressed as a certain number of pipe diameters. Thus, if a bend has an equivalent length of X diameters and if the nominal pipe diameter is 5 cm, then the bend will cause the frictional loss equivalent to that caused by the straight pipe of length 5 X cm.

The equivalent length of a fitting is to be added to the length of a straight pipe to get the total equivalent length of a flow system composed of the straight pipe and the fitting.

Equivalent lengths of some pipe fittings are :

Fitting	Equivalent length, pipe diameters
45° Elbow	15
90° Elbow	32 (upto D = 40 mm)
Tee	60 to 90
Coupler and union joint	Negligible
Gate valve (fully open)	10
Globe valve (fully open)	300

Form-friction losses in the Bernoulli equation

Consider a flow system for the flow of an incompressible fluid as shown in Fig. 7.20, which is composed of two enlarged headers, the connecting pipes and a globe valve.

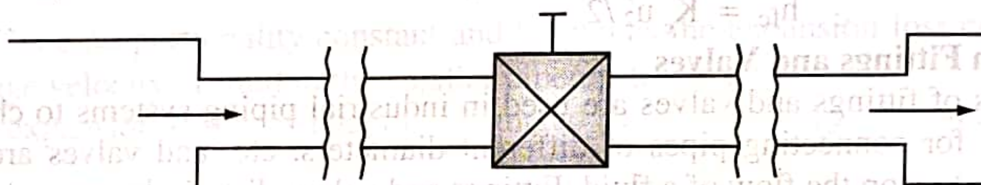

Fig. 7.20 : Typical flow system for incompressible fluid

For obtaining the total frictional loss, the losses in the expansion and contraction headers and the valve must be combined with the skin friction loss of the straight pipe.

$$\text{Skin friction loss in J/kg} = \frac{4\,fL\,u^2}{2\,D} \quad \text{... (7.126)}$$

where D is the diameter of the straight pipe, u is the average velocity of the fluid through the pipe and L is the length of the straight pipe.

$$h_f = \text{total friction loss in J/kg} = \left[\frac{4fL}{D} + K_c' + K_e' + K_f'\right]\frac{u^2}{2} \quad \text{... (7.127)}$$

Assume that the piping system under consideration involves a straight pipe of length L, two globe valves and one elbow. Further assume that the equivalent length of the globe valve is given as X pipe diameters (e.g., 190 D, so X = 190) and that of the elbow is given as Y pipe diameters.

In this situation, the total friction loss is obtained as follows :

Equivalent length of elbow = YD

Equivalent length of globe valve = XD

Total equivalent length of the piping system = L' = L + YD + 2 XD

$$h_f = \text{total friction loss in J/kg} = \frac{4\,fL'\,u^2}{2\,D} \quad \text{... (7.128)}$$

Total head loss due to friction in m of flowing fluid for the system of Fig. 7.20 is given by

$$h_f = \left[\frac{4\,fL}{D} + K_c + K_e + K_f\right]\frac{u^2}{2g} \quad \text{... (7.129)}$$

where u is the average velocity of the fluid through the pipe of diameter D and f is the Fanning friction factor.

Friction Loss at the Exit from a Pipe

The outlet end of a pipe carrying fluid may be either left free so that the fluid is discharged freely in the atmosphere or it may be connected to a large reservoir where the pipe outlet is submerged and fluid is discharged into a large body of static fluid.

In such a case, the loss of head at the exit of the pipe is equal to $u^2/2g$, where u is the average velocity of flow in the pipe.

When the end of a pipe is connected to a large reservoir, tank, etc. where the pipe end is not submerged, then the flow pattern is similar to that for a sudden enlargement. Hence, the loss of head in this case can be determined by the equation given for the head loss for a sudden enlargement.

Friction Loss at the Entrance of Pipe from a Large Vessel

When a fluid enters a pipe from a large vessel (or a tank or a reservoir), some loss of energy occurs at the entrance of the pipe which sometimes known as the inlet loss of energy. The flow pattern at the entrance to the pipe is similar to that in the case of a sudden contraction. So the equations given for the friction loss or head loss due to friction for a sudden contraction are applicable for this situation.

Frictional Losses in Coils

In some situations a fluid flows through a circular tube arranged/set out in the form of a coil (e.g., a helical cooling coil incorporated in a batch reactor in which an exothermic reaction is occurring). The coil accommodates a long tube in a small space. The frictional pressure drop in a coil (ΔP_{coil}) is greater than that in a straight tube of the same length (ΔP_{st}). The relationship between ΔP_{coil} and ΔP_{st} is

$$\Delta P_{coil} = \Delta P_{st}\left[1 + \frac{3.54\,D}{D_H}\right] \quad \text{... (7.130)}$$

where ΔP_{st} = pressure drop in the same length of the straight tube

D = diameter of the tube

D_H = diameter of a turn of the coil or a helix of the coil (helix diameter)

Pressure Drop in Turbulent Flow of Fluids through Non-circular Conduits/Ducts

For turbulent flow in ducts of constant non-circular cross-sections, the frictional losses can be estimated by using the equations that are applicable for circular pipes if the diameter in the Reynolds number and in the definition of the friction factor is replaced by an *equivalent diameter*, which is defined as

$$\text{Equivalent diameter} = 4\,(\text{Hydraulic radius}) \quad \text{... (7.131)}$$

$$D_e = 4\,r_H \quad \text{... (7.132)}$$

$$= 4\,\frac{\text{Wetted cross-sectional area of flow}}{\text{Wetted perimeter (for fluid flow)}} \quad \text{... (7.133)}$$

The equivalent diameter is defined as four times the hydraulic radius or defined as four times the cross-sectional area of the duct divided by the wetted perimeter.

(i) For an annular space between two concentric pipes, the equivalent diameter is given by

$$D_e = 4\left(\frac{\pi/4\, D_2^2 - \pi/4\, D_1^2}{\pi D_1 + \pi D_2}\right)$$

$$\therefore \quad D_e = (D_2 - D_1) \quad \text{... (7.134)}$$

where D_1 be the outside diameter of the inside pipe (inside diameter of the annulus), and D_2 be the inside diameter of the outside pipe (outside diameter of the annulus).

(ii) For a square duct of the side x,

$$D_e = 4\left[\frac{x^2}{4x}\right] = x \quad \text{... (7.135)}$$

(iii) For a rectangular duct of the size x by y :

$$D_e = \frac{4\,[x.y]}{2\,[x+y]} = \frac{2xy}{x+y} \quad \text{... (7.136)}$$

(iv) For a circular pipe :

$$D_e = 4\,\frac{\pi/4 \cdot D^2}{\pi D}$$

$$D_e = D$$

Therefore, the equivalent diameter is the same as the pipe diameter for any circular pipe.