

Fig. 2 .... Boundary-Layer Separation in a Zone of Deceleration[2]

sults. With flow in circular pipes, it appears that the transition from laminar to turbulent flow starts at a Reynolds number of about 2000 with the transition being complete at about 3000. A more detailed discussion of the critical Reynolds number can be found in Reference 2.

The velocity profile in a closed conduit is a function of the Reynolds number as shown in Fig. 1.

In laminar flow, the velocity profile is parabolic, and therefore the average velocity is one half the centerline velocity. In turbulent flow, the velocity profile is a function of Reynolds number and the ratio of average to centerline velocity varies.[3]

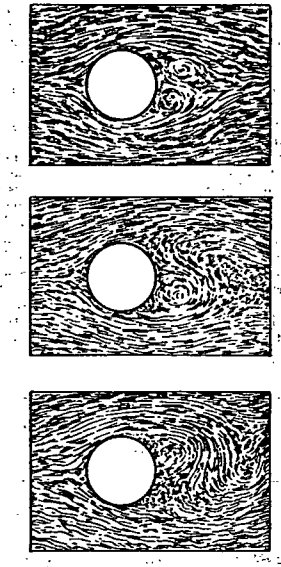

Fig. 3 .... Wake Behind a Stationary Cylinder, Showing Successive Stages of Eddy Formation After the Commencement of Flow[2]

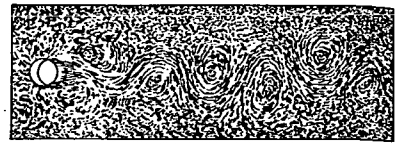

Fig. 4 .... Vortex Trail in the Wake of a Moving Cylinder[2]

A fluid flowing past a boundary which curves in such a way as to produce a deceleration of the fluid results in an expansion of the boundary layer with distance in the direction of flow. Since the velocity at the boundary is already zero, further deceleration is physically impossible; the flow as a whole can continue beyond this zone only if a discontinuity at the boundary is produced. As shown in Fig. 2, such discontinuity involves *separation* of the flow from the boundary. Reverse flow then occurs in the region between the boundary and the fluid stream downstream of the point of separation. For the case of flow around a circular cylinder the reverse flow results in the formation of *eddies* as shown in Fig. 3, part *A*. As Reynolds number is increased the eddies break off alternately on either side in a periodic fashion (Fig. 3, parts *B* and *C*) and this is the so-called *von Kármán vortex trail* shown in Fig. 4.

With the flow of liquids, if at some point in the system the existing fluid pressure is reduced to the vapor pressure at the particular temperature, the liquid will vaporize forming a cavity or void. This phenomenon is called *cavitation*. If the fluid pressure fluctuates above and below the vapor pressure, there will be an alternate formation and collapse of the vapor bubbles. This causes surface pitting on materials exposed to the fluid and usually results in a noticeable noise.

Frictional Pressure Drop for Incompressible Flow in Uniform Ducts

For incompressible flow in uniform ducts, the continuity Equation 2 shows that the velocity is constant, since:

$$\frac{dV}{dz_L} = 0 \tag{20}$$

Then, Equation 1 reduces to (for horizontal ducts):

$$\frac{dp}{dz_L} + \frac{f_D}{D}\frac{\rho V^2}{2} = 0 \tag{21}$$

Since V and D and, hence, f_D are constant, Equation 21 can be integrated to give:

$$p_1 - p_2 = \Delta p = \frac{f_D L}{D}\frac{\rho V^2}{2} \tag{22}$$

where Δp is the static pressure drop in duct length L.

As mentioned previously, the friction factor f_D is in general a function of Reynolds number N_{Re}, and relative roughness e/D. For $N_{Re} < 2000$, the flow is laminar and

$$f_D = \frac{64}{N_{Re}} \tag{23}$$

Note that for laminar flow, the friction factor f_D and hence Δp is independent of surface roughness.

For Reynolds numbers greater than about 3000, the flow can be considered turbulent and the friction factor can be evaluated from Fig. 5. Upon referring to Fig. 5, it is seen that

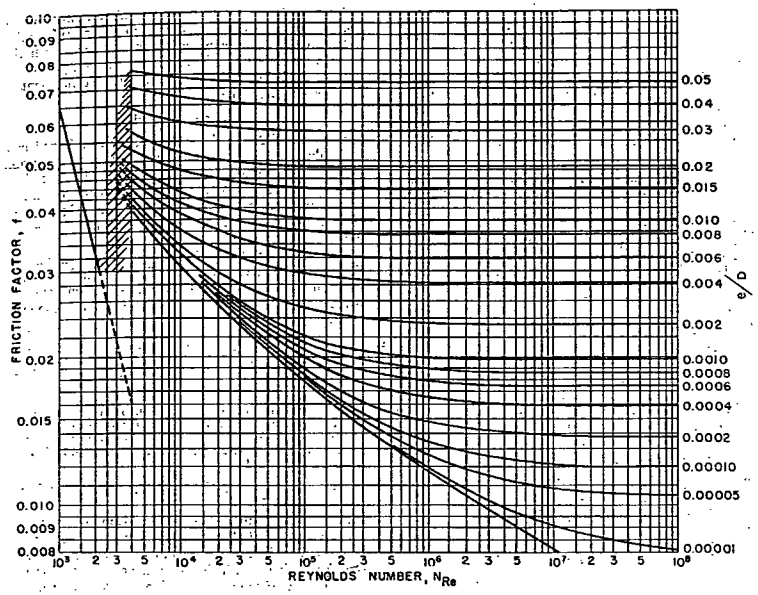

Fig. 5 .... Relation Between Friction Factor and Reynolds Number

a curve of f_D versus N_{Re} exists for each relative roughness. The lowest curve represents a limiting envelope for vanishing roughness. It is the so-called smooth pipe resistance law. For Reynolds numbers up to 10^5, the smooth pipe friction factor is given by the Blasius relation

$$f_D = 0.316(N_{Re})^{-1/4} \tag{24}$$

Table 4 lists the absolute roughness e for various commercial surfaces (new).

As mentioned previously, the parameter D of Equation 22 is the duct equivalent diameter defined by

$$D = \frac{4A}{P_w} \tag{25}$$

Although the above value of D can be used in computing Reynolds number, a slightly better procedure for rectangular ducts is to replace D by the shortest dimension plus one fourth of D. That is

$$N_{Re} = \frac{V(b + 0.25D)}{\nu} \tag{26}$$

where b is the shortest dimension of the rectangular cross section.

Two-Phase Flow

In addition to examining single phase flow phenomena, it is also of interest to consider the situation where both liquid and vapor phases exist simultaneously. This situation is encountered in evaporators, condensers, capillary tubes and other components used in refrigeration and air-conditioning equipment. Although both heat transfer and hydraulic data are, in general, of interest for these two phase flows, the discussion here will be limited to hydraulics and particularly to pressure drop computations for tubes in which the flow pattern is such that the tube walls are wetted primarily with liquid. It will

Table 4 .... Absolute Roughness Values

Type of Surface	Absolute Roughness, e, ft
Glass, drawn metallic tubing	Smooth
Wrought iron, steel	0.00015
Asphalted cast iron	0.0004
Galvanized iron	0.0005
Cast steel	0.00085
Concrete	0.001 to 0.01
Riveted steel	0.003 to 0.03