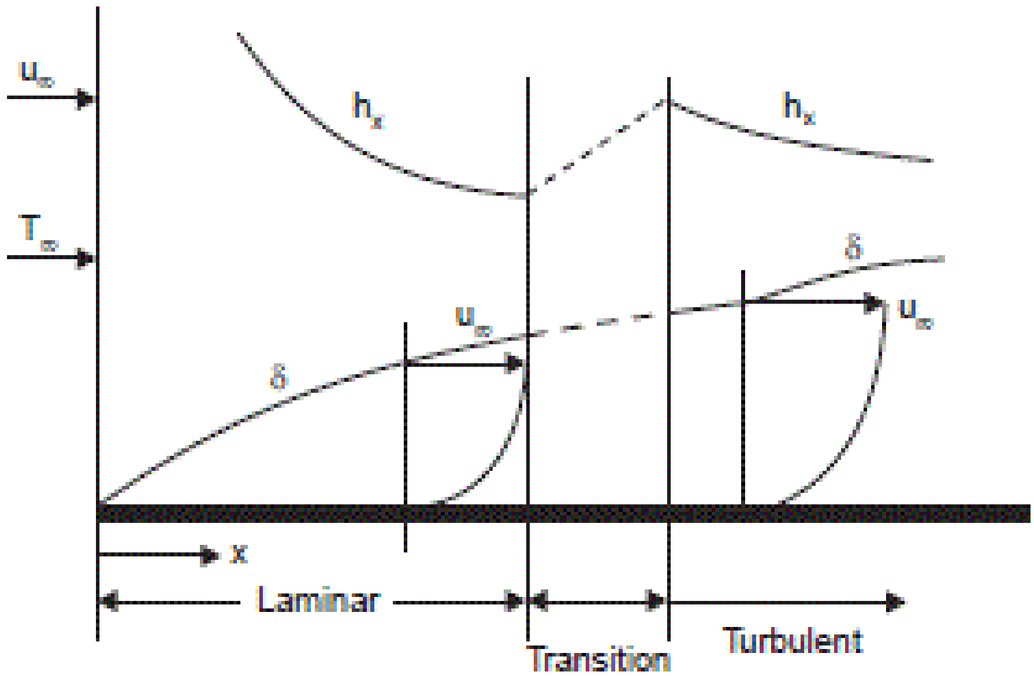
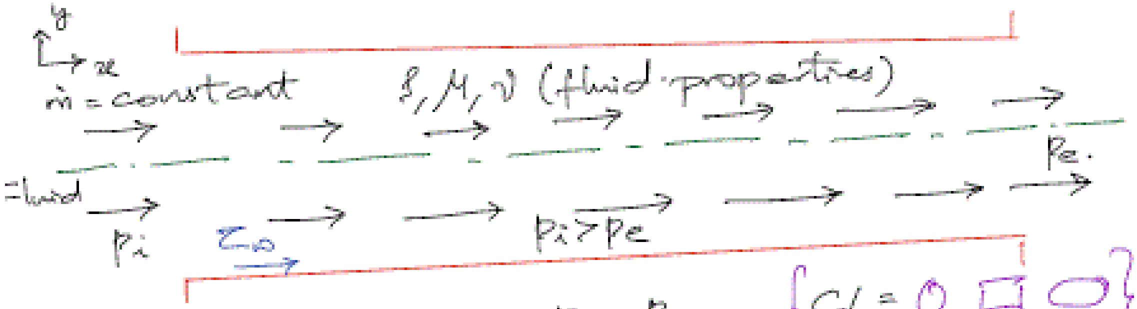
The formation of the boundary layer starts at the leading edge. In the starting region the flow is well ordered. The streamlines along which particles move is regular. The velocity at any point remains steady. This type of flow is defined as laminar flow. There is no macroscopic mixing between layers. The momentum or heat transfer is mainly at the molecular diffusion level. After some distance in the flow, macroscopic mixing is found to occur. Large particles of fluid is found to move from one layer to another. The motion of particles become irregular. The velocity at any location varies with respect to a mean value. The flow is said to be turbulent. Due to the mixing the boundary layer thickness is larger. The energy flow rate is also higher. The velocity and temperature profiles are flatter, but the gradient at the surface is steeper due to the same reason. This variation is shown in Fig



Building up of boundary layer over a flat plate—Laminar—Turbulent.

① Internal flow → Flow through a duct [○, □, ○]



{C/s = ○, □, ○}

Pressure drop $\Delta p = p_i - p_e$.

$\Delta p = f(\vec{V}, L, \text{fluid properties})$.

Friction factor → A relation for pressure drop.

$$f = \frac{-\left(\frac{dp}{dz}\right) A}{P\left(\frac{1}{2}\rho \bar{V}^2\right)} = \frac{\tau_w}{\frac{1}{2}\rho \bar{V}^2}.$$ [Dimensionless].

$-\frac{dp}{dz}$ → Pressure drop in the flow direction.

A = C/s area

P = Perimeter.

For laminar, fully developed flow

$f = F(Re)$.

For turbulent, fully developed flow.

$f = F(Re, e/D)$

e/D is the roughness parameter for the inner wall of the duct.

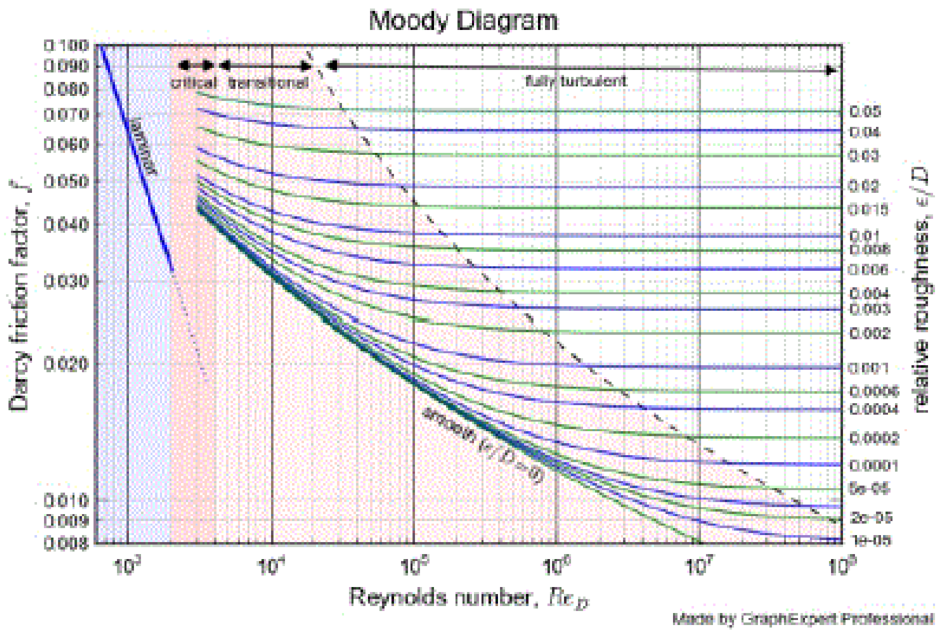
Fully developed flow in circular pipe

Laminar flow

$$\Delta p = \frac{32 \mu \vec{V} L}{D}, \qquad f = \frac{16}{Re_D}.$$

Turbulent flow → Experimental data.

Moody diagram



For non-circular ducts, Equivalent diameter.

$$D_e = \frac{4 \times \text{Cross-sectional area of flow}}{\text{Wetted perimeter}}.$$

The changeover does not occur at a sharp location. However for calculations some location has to be taken as the change over point. In the velocity boundary layer, this transition is determined by a dimensionless group, Reynolds number-defined for flow over a plate by the equation

$$Re_x = \rho\, u_\infty\, x/\mu \quad \text{or} \quad u_\infty\, x/\nu \qquad ...(7.7(a))$$

For flow in a tube or across a tube or sphere it is given by the equation.

$$Re = \rho\, u_\infty\, D/\mu \quad \text{or} \quad u_\infty\, D/\nu \qquad ...(7.7(b))$$

The grouping represents the ratio of inertia and viscous forces. Upto a point the inertia forces keep the flow in order and laminar flow exists. When the viscous forces begin to predominate, movement of particles begin to be more random and turbulence prevails.

The transition Reynolds number for flow over a flat plate depends on many factors and may be anywhere from 10^5 to 3×10^6. Generally the value is taken as 5×10^5 unless otherwise specified. For flow through tubes the transition value is 2300, unless otherwise specified.

In the quantitative estimation of heat flow, the correlation equations for the two regions are distinctly different and hence it becomes necessary first to establish whether the flow is laminar or turbulent.

Turbulent flow is more complex and exact analytical solutions are difficult to obtain. Analogical model is used to obtain solutions.