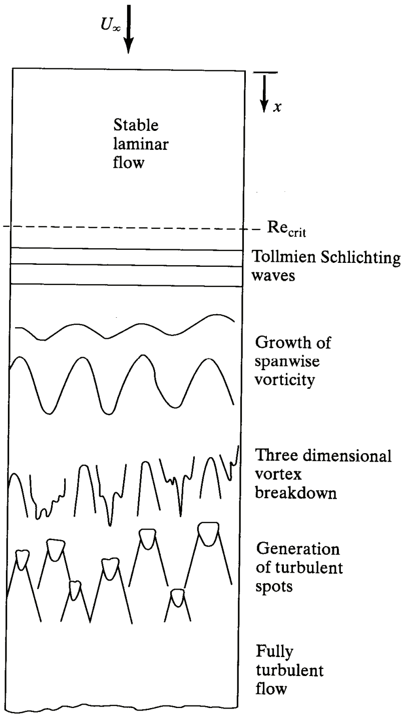
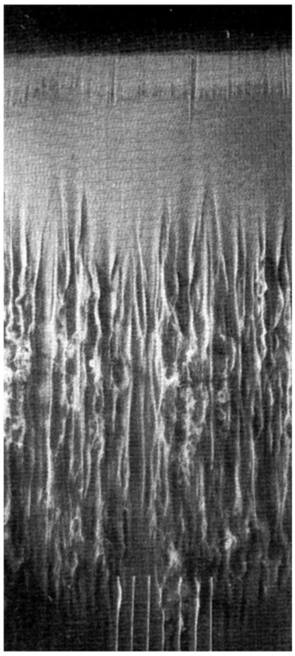
Turbulence Transition Mechanism

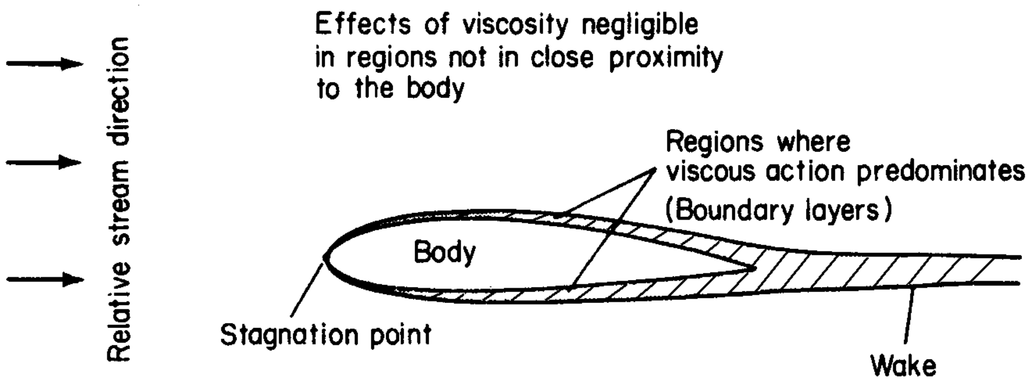
- Transition from laminar to turbulent flow idealised by the stages shown below (do not memorise), however in analysis transition often taken as instantaneous. Factors that have a strong effect on the onset and length of transition include: Reynolds Number; streamwise pressure gradient *(slowing flows transition earlier & vice versa, accelerating turbulent flows can even become laminar again);* surface roughness produces early onset & short transition length but no effect if roughness very small -“hydraulically smooth” (*used to fix transition to specific location in wind tunnel models*); freestream turbulence similar to surface roughness.





Boundary Layer Hypothesis - Streamlined Bodies

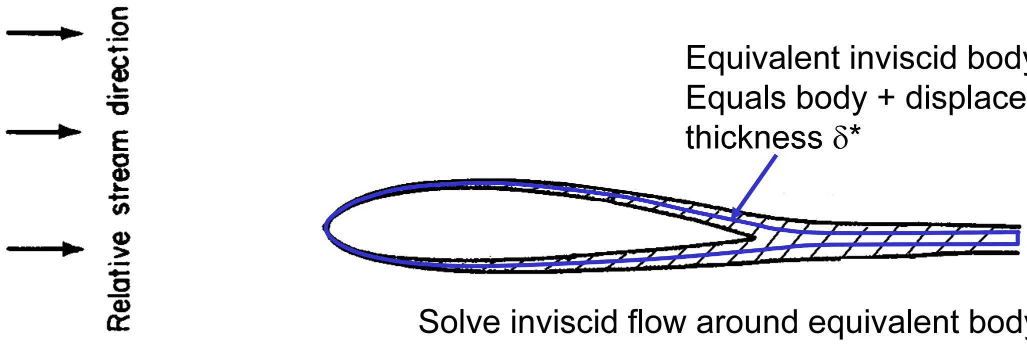
- due to Prandtl (1904)-made application of fluid dynamic theory possible!
- for many practical flows (high Reynolds number, not necessarily but usually turbulent), effects of viscosity are largely confined to a ‘***thin’*** region near the boundary - flow outside this region is essentially inviscid



- Leads to the description of the boundary layer as though it were physically separate to the rest of the flow.

Boundary Layer Hypothesis - Streamlined Bodies

- due to Prandtl (1904)-made application of fluid dynamic theory possible!
- for many practical flows (high Reynolds number, not necessarily but usually turbulent), effects of viscosity are largely confined to a '***thin'*** region near the boundary - flow outside this region is essentially inviscid

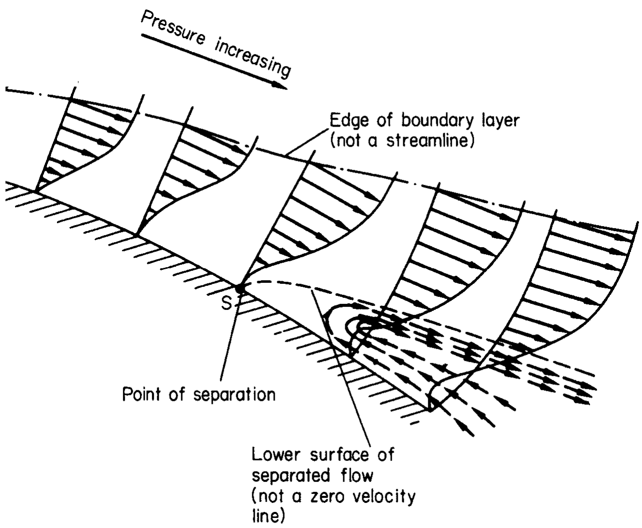


Solve inviscid flow around equivalent body
Static pressure on body and equivalent inviscid body approximately equal.

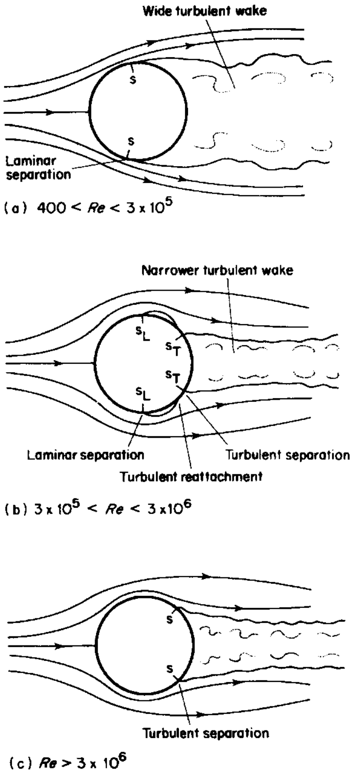
Background, not in exam

Boundary Layer Separation

- Separation defined by pressure gradient.
  accelerating flow = "favourable" pressure gradient (pressure falling)
  decelerating flow = "adverse" pressure gradient (pressure rising)
- Sharp expansions lead to high "adverse" pressure gradients and separation.
- Flow separation from 'smooth' surfaces can be difficult to predict
- Onset of flow separation has a major impact on rest of flow field. Significant regions of viscous flow (ie boundary layer forms discrete vorticies) shed into outer flow
- laminar flow separates much earlier than turbulent flow, "fuller" turbulent profile stays attached for longer.

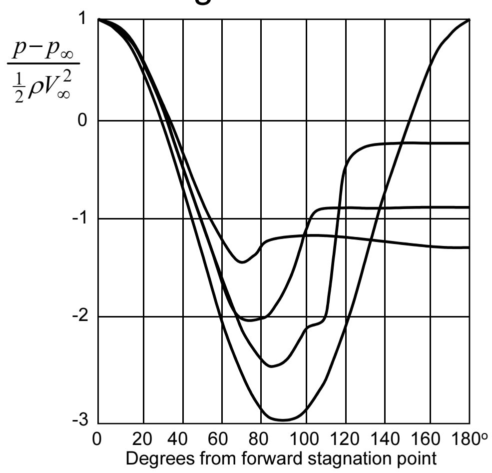


Streamlines over bluff bodies revisited



- 3 major categories high Re of flow

(a) *subcritical* ($Re_d \approx 4x10^2$ to $3x10^5$) early laminar separation
(b) *critical* ($Re_d \approx 3x10^5$ to $3x10^6$) laminar separation bubble, followed by delayed turbulent separation
(c) *supercritical* ($Re_d > 3x10^6$) turbulent separation
note region of constant pressure at the rear
– the wider the wake the higher the suction & the greater the drag

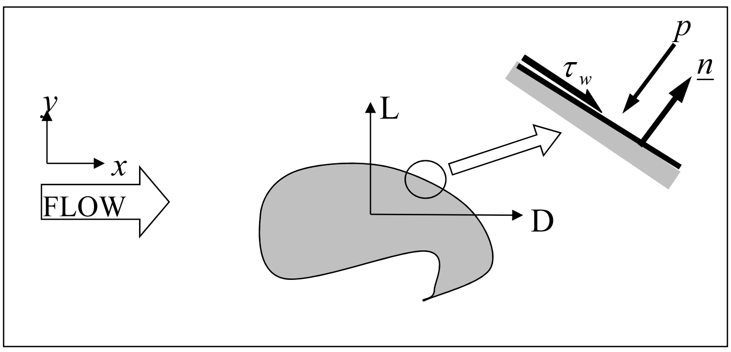


Lift and Drag Definitions

- We can integrate the forces on a body into components normal to the flow (Lift or Vertical Thrust) and parallel to the flow (Drag).
- These forces have two parts, formed from the integration of pressure, p, and shear stress, $\tau_w = (\tau_x, \tau_y)$, around the body
- For a 2D shape in a flow aligned with the x-axis, the force per unit span is given by

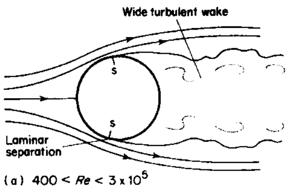
$$D = \int_{body} \tau_x dx - \int_{body} p n_x dy$$

$$L = \int_{body} \tau_y dy - \int_{body} p n_y dx$$

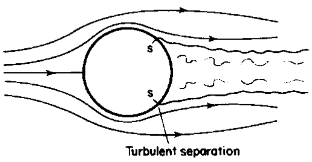


- The drag & lift coefficient is defined as the force normalised by an appropriate area and dynamic pressure. $C_D = \frac{D}{\frac{1}{2}\rho V_\infty^2 A_D}$ $C_L = \frac{L}{\frac{1}{2}\rho V_\infty^2 A_L}$
- For a particular shape it is assumed that the coefficients are universal, so "force = coefficient x dynamic pressure x Area" in all conditions.

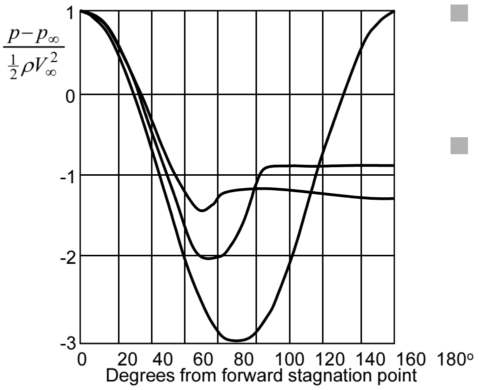
Drag around bluff bodies (cylinder example)



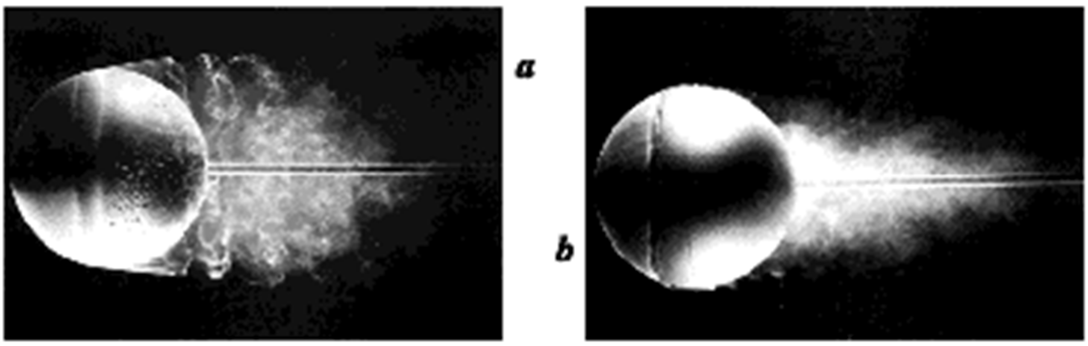
(a) $400 < Re < 3 \times 10^5$



(c) $Re > 3 \times 10^6$



- Consider previous subcritical and supercritical flows around cylinders as examples of a bluff body flows.
- The drag is dominated by the pressure integral (Form Drag).
- The pressure aft of the separation is approximately constant. Furthermore the earlier the separation the lower the pressure.
- Leads to the general principle that the form drag is proportional to the width of the separated wake
- For streamlined bodies shear stress is more important (especially for turbulent flows)

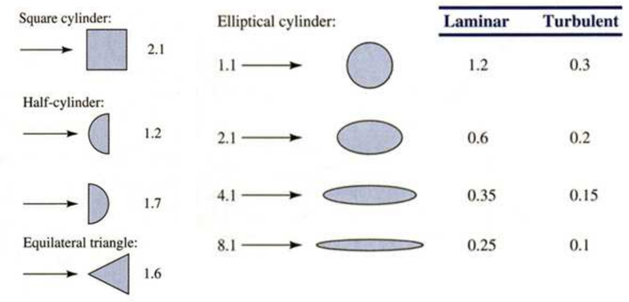


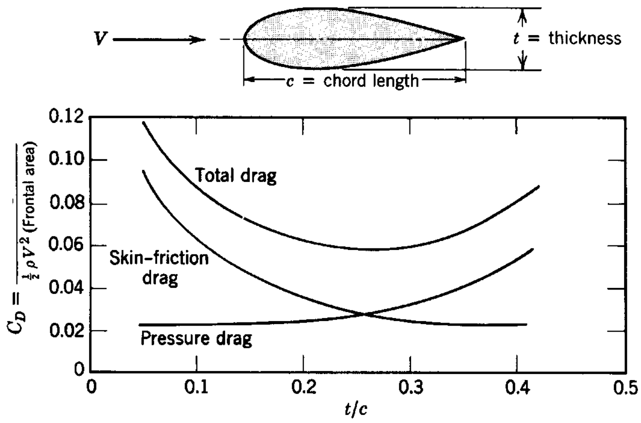
- Comparison of laminar separation around a sphere, a, with a flow that is “tripped” so that the attached boundary layer becomes fully turbulent, b.
- The laminar flow separates before it reaches maximum thickness. The tripped turbulent flow stays attached well beyond the maximum thickness.
- Separated laminar boundary layers are unstable and usually become turbulent soon after separation. Once separated the laminar boundary layer can thicken and reattach to form a “laminar separation bubble”.

Background, not in exam

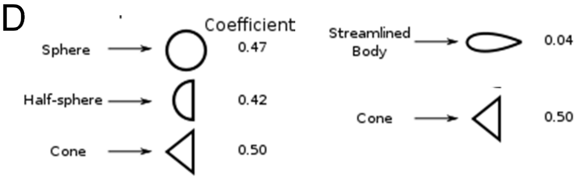
Typical Drag Coefficient Values

- 2D values





- 3D



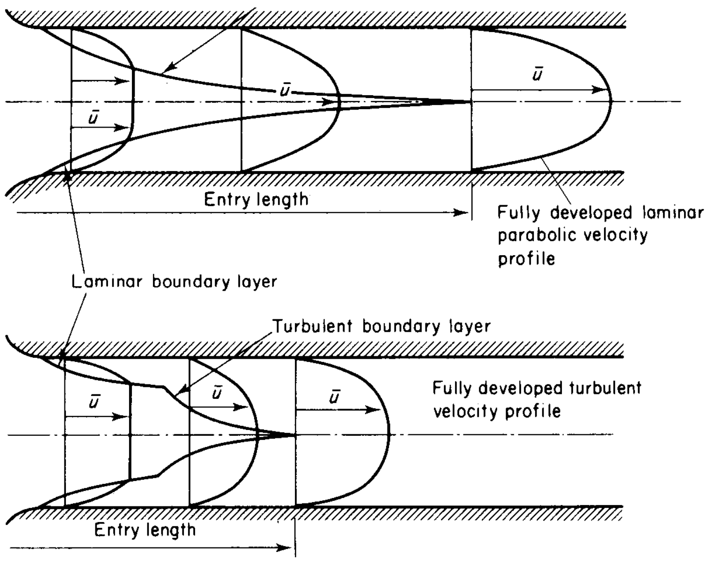
- Turbulent flow over streamlined bodies: skin friction ↑ form drag ↓
- reducing thickness/chord ratio reduces form drag
  - alleviates adverse pressure gradient on aft surfaces
- drag reduction most sensitive to changes in aft region
  - this is where separation occurs

Viscous pipe flow

- for fully-developed flow, pressure drop due to friction is expressed in terms of friction factor f

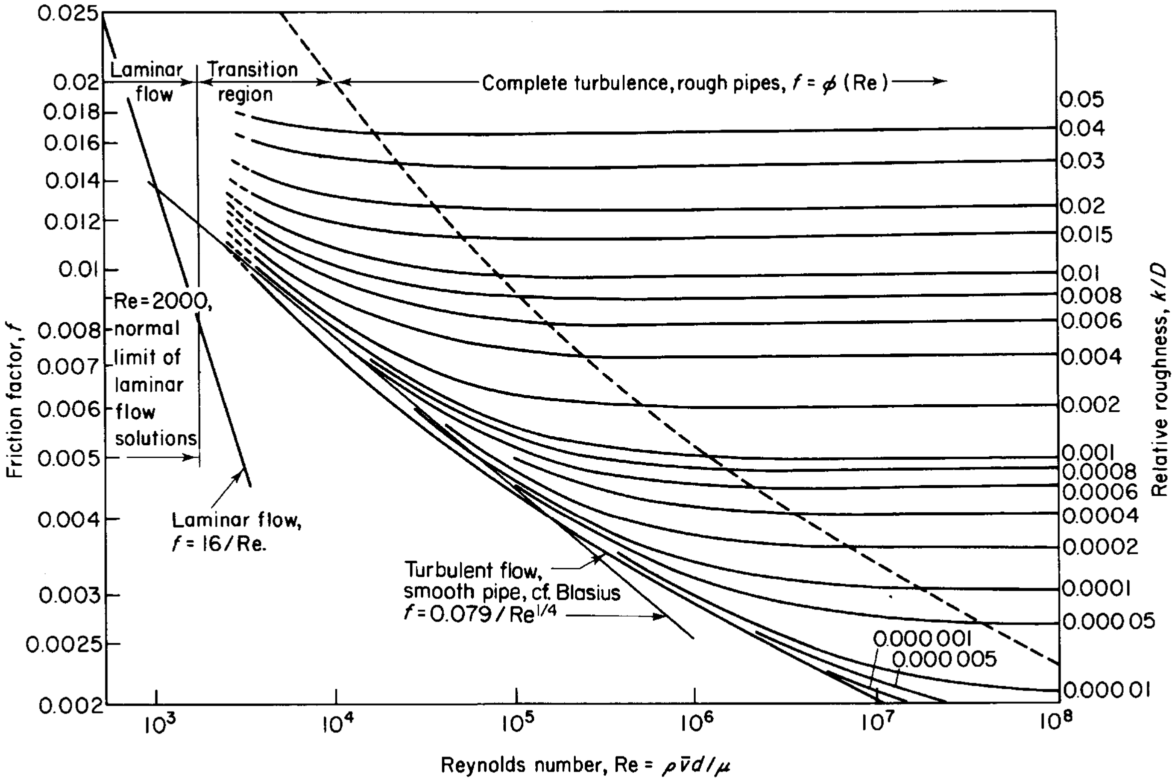
$$\boxed{\Delta p = 4f\left(\frac{l}{d}\right)\rho\overline{U}^2}$$

- $\overline{U}$ is the mean velocity in the pipe
- plotted on *Moody Diagram* as function of Re_d and relative roughness ε/d
- for turbulent flow in *smooth* pipes $f \approx 0.079\mathrm{Re}_d^{-0.25}$



Background, not in exam

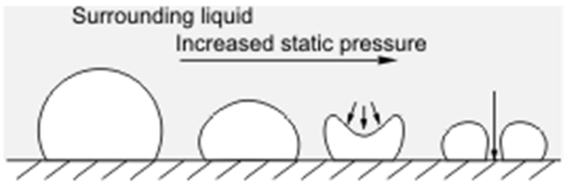
Moody Diagram

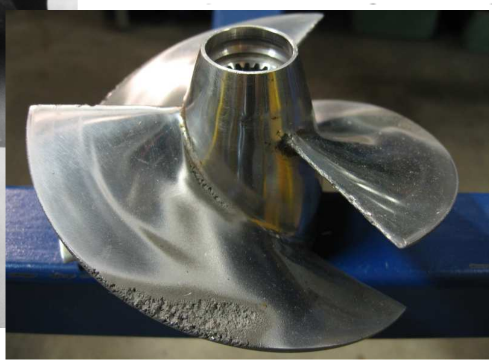


Background, not in exam

Complex Fluid Behaviour - Cavitation

- When the pressure in a liquid drops below the “vapour pressure” dissolved gases can come out of solution to initiate cavitation.
- Cavitation similar to but not the same as boiling –thermodynamics are very different
- Causes surface erosion problems in propellors, pumped pipe networks as well as large diesel engines .





Complex Fluid Behaviour Examples

- Free surface flows e.g. the Hydraulic Jump

- Compressible flows

Learning Outcomes: "What you should have learnt so far"

- Definition of streamlines, pathlines & streaklines
- The idea of total pressure and stagnation points
- Inverse relationship between pressure and velocity
- Streamlines expected around streamlined and bluff bodies
- The concept of the laminar boundary layer
- Reynolds number as a ratio of inertial and viscous forces
- The concept of the turbulent eddy and the transfer of momentum to & from the turbulent boundary layer
- Factors affecting turbulent transition
- The boundary layer and the concept of separation caused by adverse pressure gradient
- Definitions of Lift, Drag, Form Drag, Skin friction Drag & Lift/Drag coefficients
- Relationship between drag components for streamlined bodies