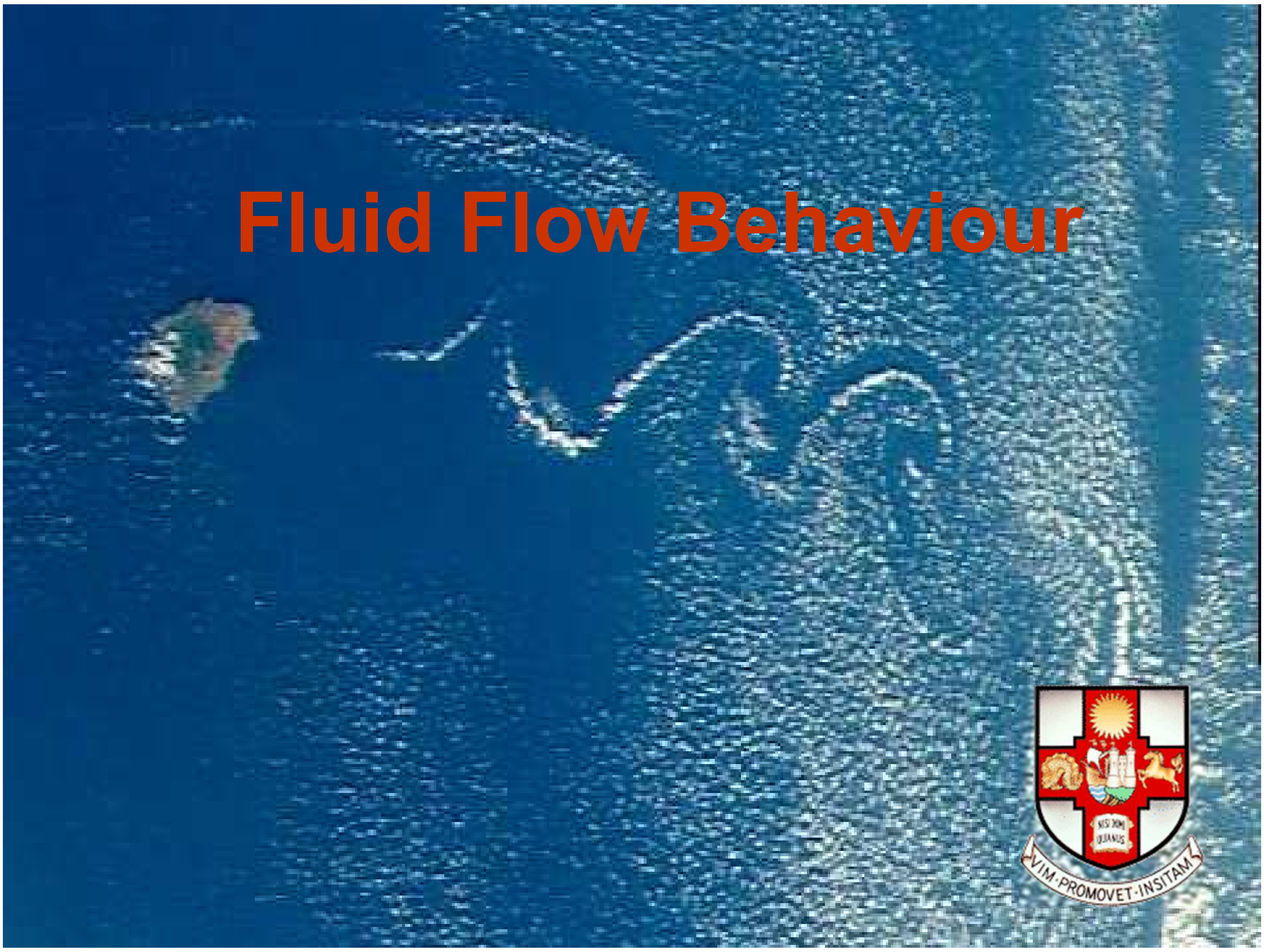
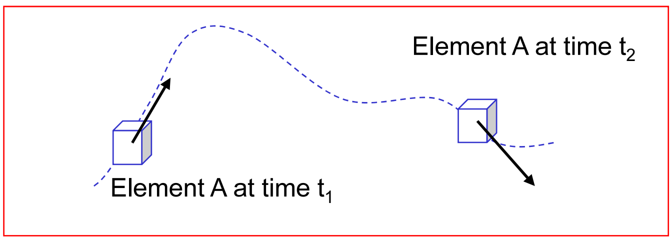
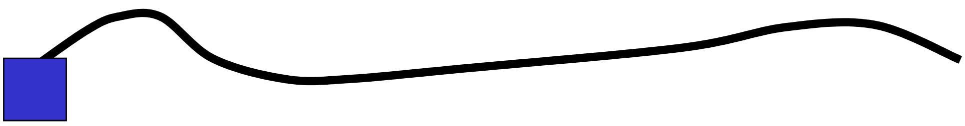


Flow Pictures

- It is useful to be able to visualise the physics of a fluid flow i.e. to understand “where the flow is going”.
- Common ways that are used are:
  - Pathlines
  - Streaklines
  - Streamlines

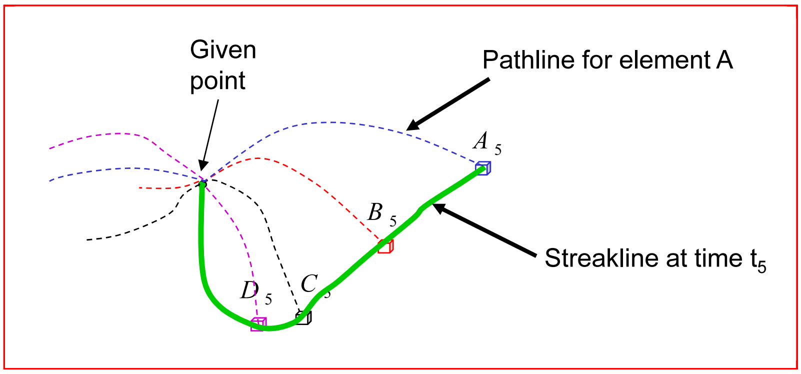
Pathline: the path traced by an element of fluid over an interval in time

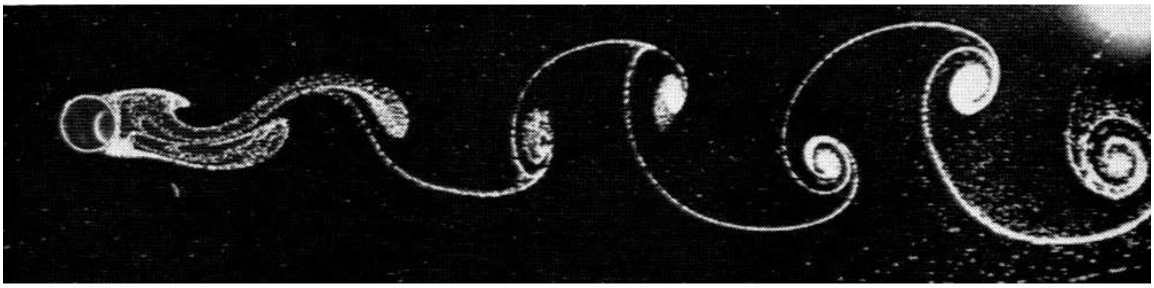




Flow Pictures 2

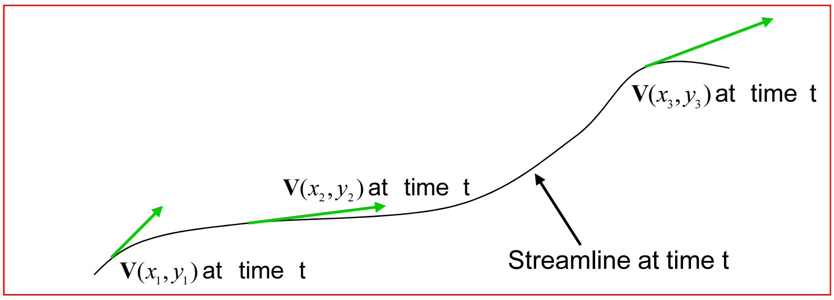
Streakline: the trace joining the instantaneous positions of fluid elements which have passed through a given point i.e. shown by smoke or dye injection





Flow Pictures 3

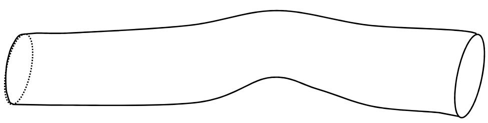
Streamline: The curve drawn from the flow field at an instant in time, whose tangent at any point is in the direction of the velocity vector at that point



Hence: no flow perpendicular to a streamline; streamlines can only cross at stagnation points (where velocity is zero) as the velocity at any point has only one value or direction

Pathlines, streaklines and streamlines are identical in **steady** flow but in general unsteady flows are different.

Streamtube is the 3D equivalent of the streamline



Steady Inviscid incompressible flow

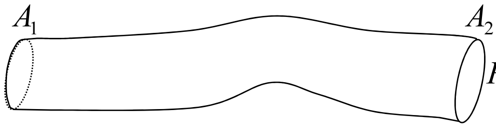
We will see later in the course: Along a streamline in steady inviscid incompressible flow the total pressure, P_o, defined by Bernoulli's equation, is constant

$$\underbrace{P_0}_{\substack{\text{Total}\\ \text{pressure}}} = \underbrace{p}_{\substack{\text{Static}\\ \text{pressure}}} + \underbrace{\tfrac{1}{2}\rho V^2}_{\substack{\text{Dynamic}\\ \text{pressure}}} + \underbrace{\rho g z}_{\substack{\text{Hydrostatic}\\ \text{pressure}}} = \text{constant}$$

for gases where hydrostatic term negligible $\quad P_0 = p + \tfrac{1}{2}\rho V^2$

Hence fluid velocity and static pressure simply related along a streamline:

$$P_0 = p_1 + \tfrac{1}{2}\rho V_1^2 + \rho g z_1$$



$$P_0 = p_2 + \tfrac{1}{2}\rho V_2^2 + \rho g z_2$$

If height unchanged (hydrostatic term unchanged) $\quad p_2 - p_1 = \tfrac{1}{2}\rho\left(V_1^2 - V_2^2\right)$

$V\uparrow\ p\downarrow$ *and* $V\downarrow\ p\uparrow$

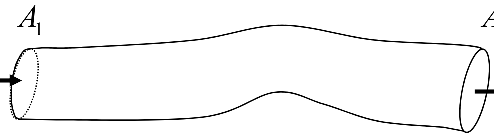
For compressible flow we still have the idea of total pressure which is of the same form as the incompressible equation above. However the dynamic & hydrostatic pressure changes

remember "pressure" means static pressure

Steady Inviscid incompressible flow (2)

As no flow across streamlines (and streamtubes) then mass flow rate in must equal mass flow rate out. principle of mass conservation or "continuity"

$$\frac{dm_1}{dt} = \rho A_1 V_1$$

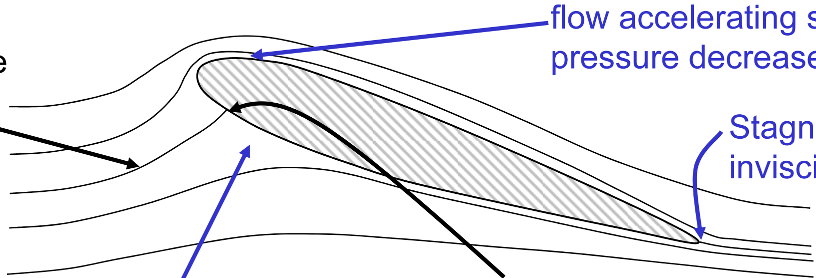


$$\frac{dm_2}{dt} = \rho A_2 V_2$$

$$\frac{dm_1}{dt} = \frac{dm_2}{dt} \quad \rightarrow \quad \rho A_1 V_1 = \rho A_2 V_2 \quad \rightarrow \quad A_1 V_1 = A_2 V_2$$

Hence, streamlines getting closer together implies a flow velocity increase and streamlines getting further apart implies the flow slows down

dividing streamline separating flows over upper and lower surfaces



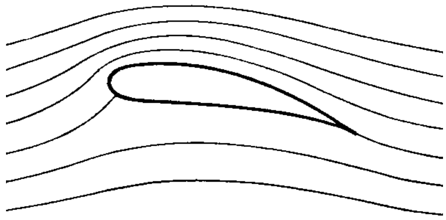
flow accelerating so pressure decrease

Stagnation point for inviscid flow models

flow slowing so pressure increase

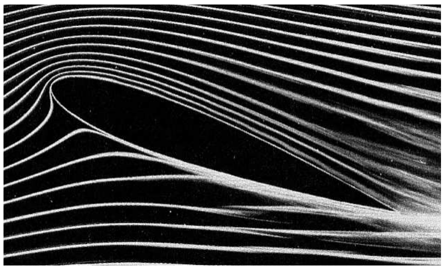
Stagnation point, velocity becomes zero, so static pressure here equals free-stream total pressure

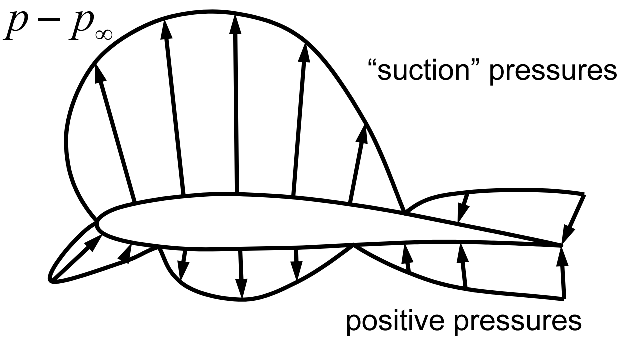
Pressure over streamlined bodies



Idealised streamlines for a 2D streamlined body where the effect of viscosity is neglected.

Flow visualisation using smoke injection to show streaklines (equivalent to streamlines if flow steady)

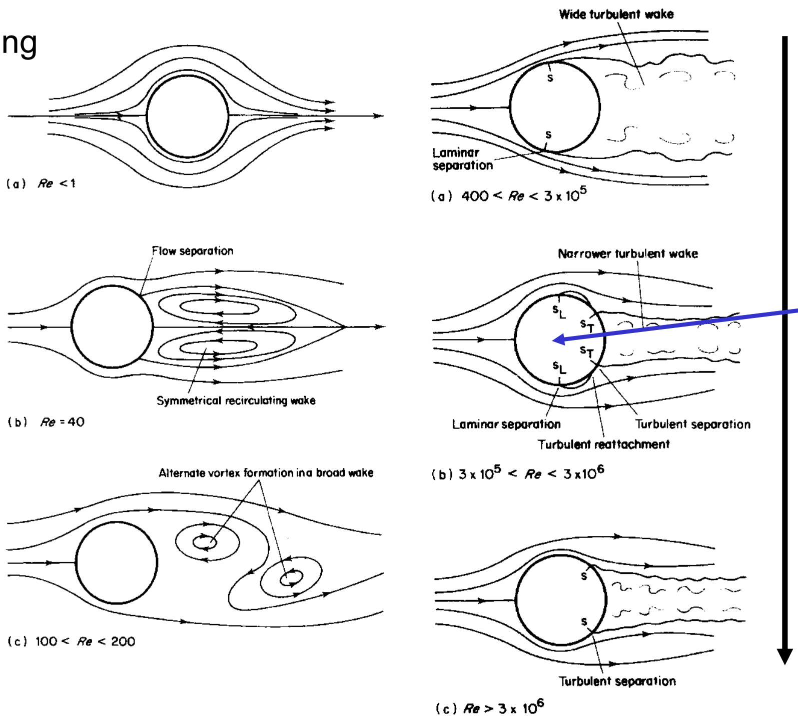




The lift and drag are functions of both pressure and the viscous shear stress but for streamlined bodies the viscous stress can be small and occasionally ignored when calculating lift.

Streamlines over smooth bluff bodies (eg sphere)

Creeping flow



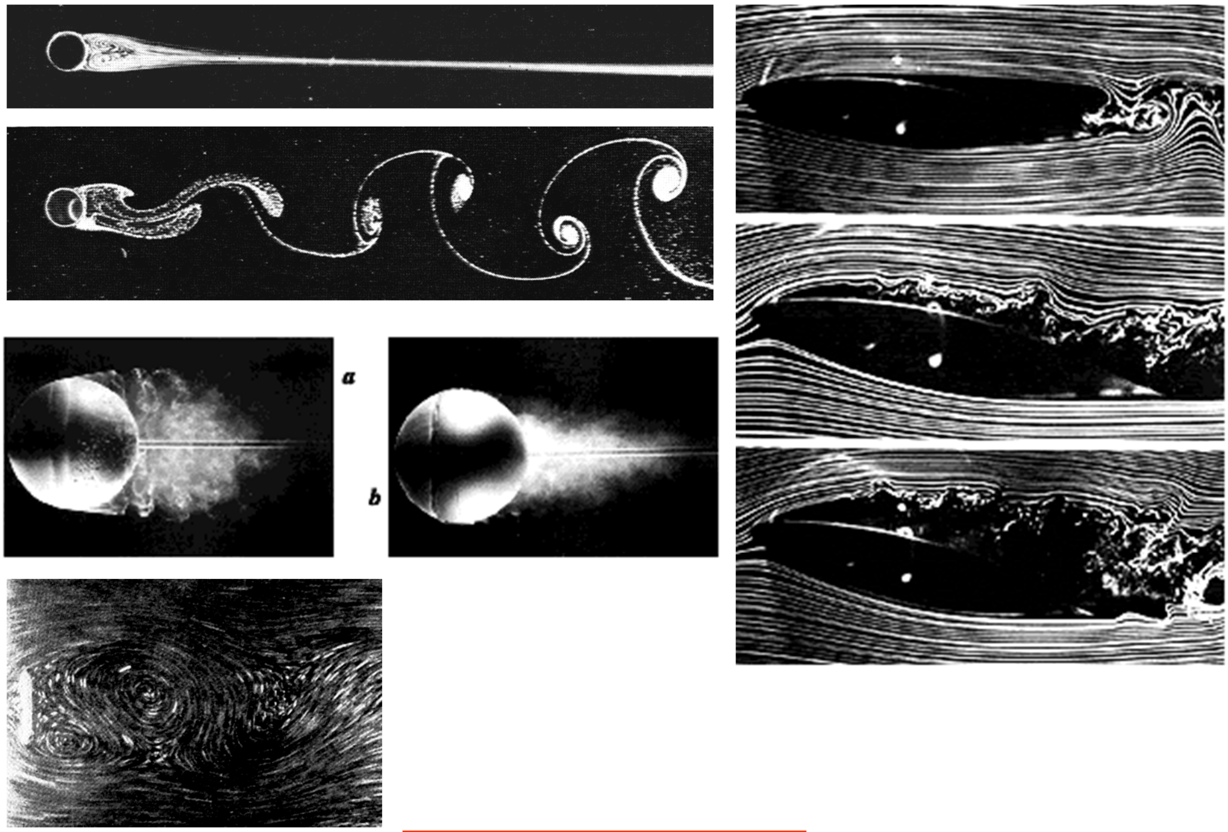
Velocity increasing

See later definition of Reynolds Number

"smooth cricket ball" in air, at speeds of 70km/h to 700 km/h

Obviously significantly more complex than the previous streamlined body.To understand what is happening we must appreciate the effect of viscosity.

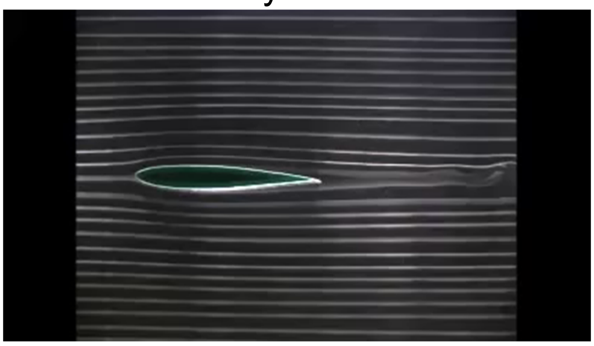
Streaklines over real bodies



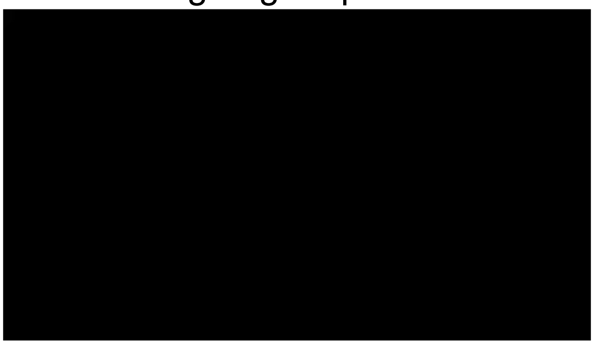
Background, not in exam

2D & 3D Behaviour

- 2D aerofoil, streamlined to bluff body behaviour as incidence changes

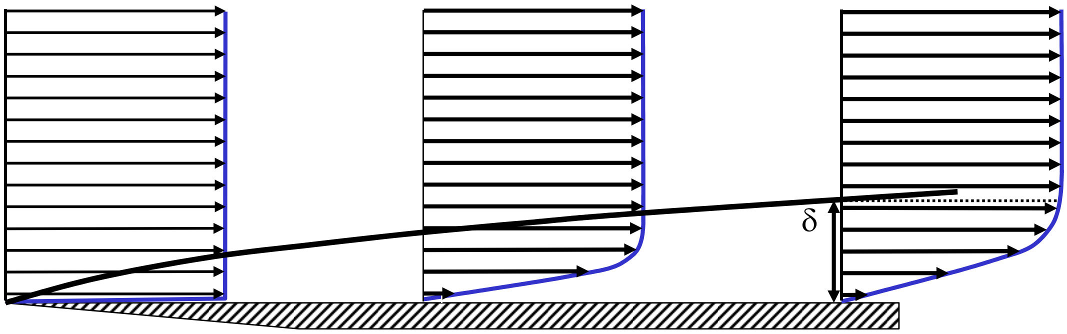


- 3D: Pressure differences on the top and bottom surfaces of the aerofoil cause a swirling flow at the wing edge "tip vortex"



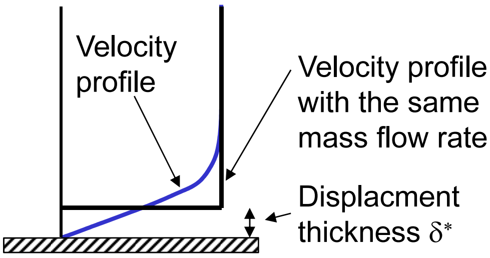
Flow over a flat plate: Laminar viscous flow

Consider a smooth steady uniform flow as it reaches the leading edge of a flat plate. Viscosity means the flow will be zero at the surface and the resulting shear stress will cause a region of smoothly retarded flow to develop (the boundary layer)



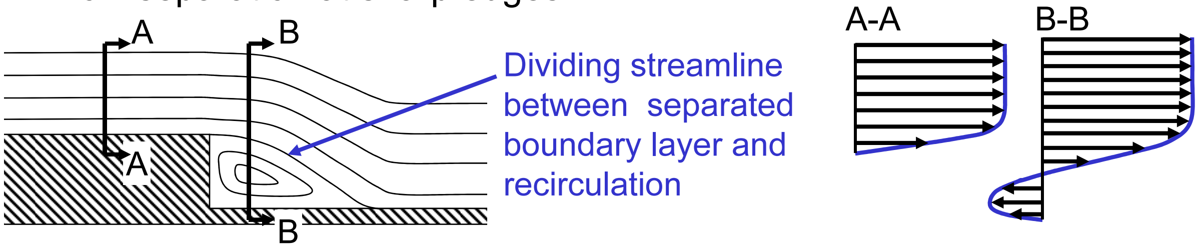
The boundary layer thickness (usually δ) is defined as the height above the surface where the velocity is 99% of the free stream value. Simple here, but can be very difficult to work out in complex flows.

More useful definitions of the boundary layer height include the "displacement thickness", which represents the displacement of a uniform flow with the same mass flow rate.



Practical Consequences of Viscosity

- leads to 'no-slip' velocity condition at surfaces
- → 'skin friction' drag
- → formation of 'boundary layer' adjacent to surface
- effectively 'prohibits' flow around sharp corners
  - flow around small radii leads to high local velocities and high local velocity gradients – no problem in inviscid fluid … but …
  - with viscosity, very high shear forces result – which in turn tend to prevent the flow 'turning the corner'
- → flow separation at sharp edges



- Viscosity damps out flow instabilities
- → transition from laminar to <u>turbulent</u> flow

Viscous Effects & Reynolds Number

'kinematic' viscosity $\nu = \mu/\rho$

$$Re = \frac{\rho V L}{\mu} = \frac{VL}{\nu} = \frac{inertia\ force}{viscous\ force}$$

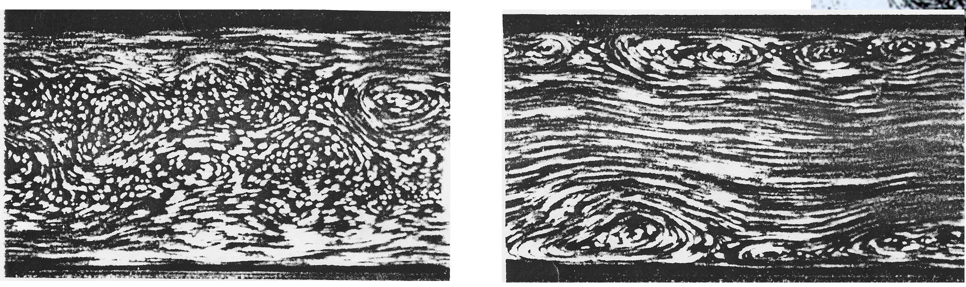
	μ ($Nm^{-2}s$)	ν (m^2s^{-1})
air	**1.8×10^{-5}**	**1.47×10^{-5}**
water	**1.14×10^{-3}**	**1.14×10^{-6}**

- *L* is an arbitrary (but usually physically significant) reference length, eg
  - diameter d for pipe flows
  - distance from the leading edge, x, for flows along surfaces
  - chord c for aerofoils and wings
  - depth δ for boundary layer flows
  - length scale used often indicated by subscript, eg Re_x
- low Re – viscous forces are important over entire flow
- high Re – significant viscous effects confined to thin region near body
- Transition Re – For any Re above some critical value viscous forces are no longer sufficient to damp disturbances and the flow becomes turbulent

Turbulent Flow – Basic Concepts

- turbulent flow can be considered to consist of a large number of *eddies* of varying sizes and frequencies, flowing with the stream and interacting with each other as they do so
  - analysis of turbulent motion remains *the* outstanding problem in fluid dynamics (indeed in all of applied mathematics) today

daVinci 1500



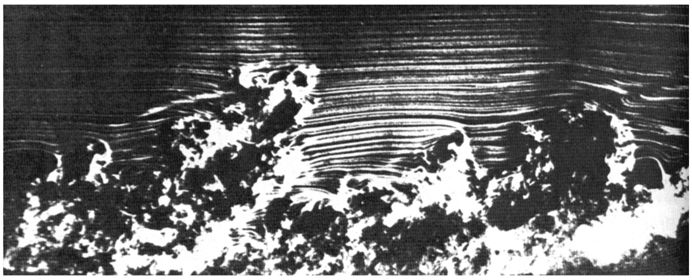
Pictures of eddies in a turbulent pipe flow taken by a camera moving with a) the average speed of the centreline flow and b) with the average speed of the flow near the walls.

- in detail, turbulent flow is *unsteady, 3D* and (apparently) *random*
- when *time-averaged*, flow becomes *steady*

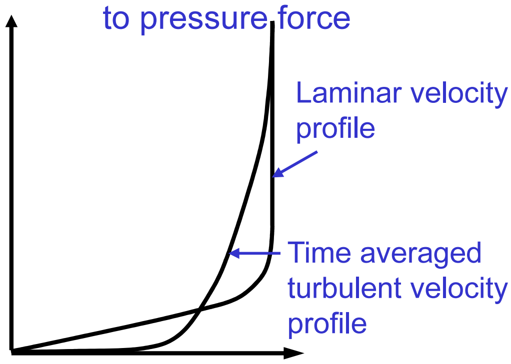
Turbulent Boundary Layer

- in *laminar* flow shear stress (viscosity) is due to lateral momentum transfer at the molecular level
- in *turbulent* flow 'large-scale' mixing provides an additional mechanism for lateral momentum transfer
  - effective shear stress greatly increased

+600% similar magnitude to pressure force



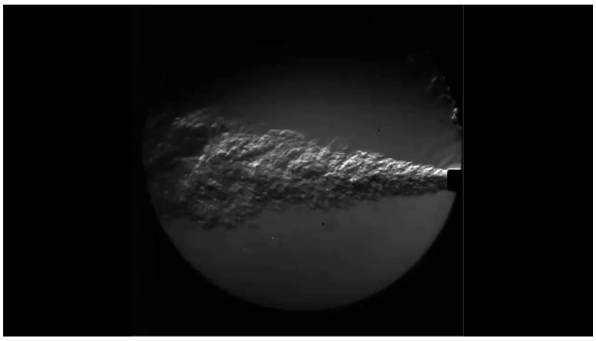
instantaneous boundary layer



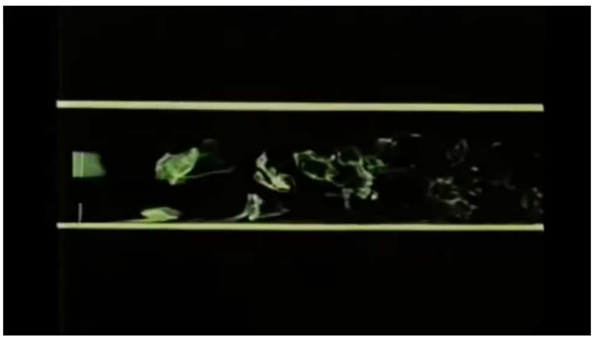
- Most analysis of turbulent boundary layers involves analysis of the time average flow.
- Boundary layer growth rate faster for turbulent flow

Examples of Turbulent Flow

- Schlieren video of hairdryer slowed x5



- Schlieren video of supersonic jet slowed x330. Showing unsteady shock pattern and final low speed exhaust.

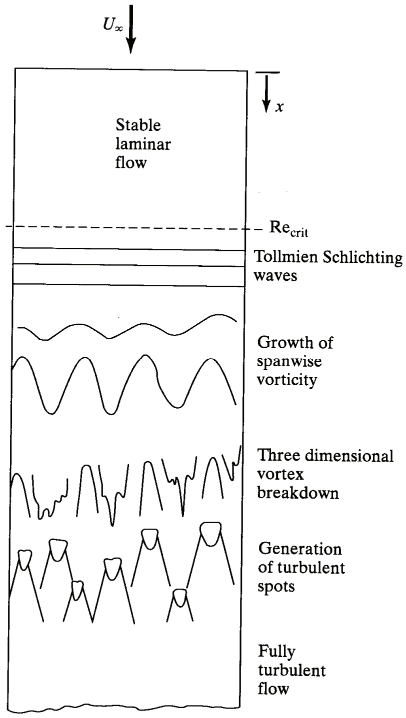


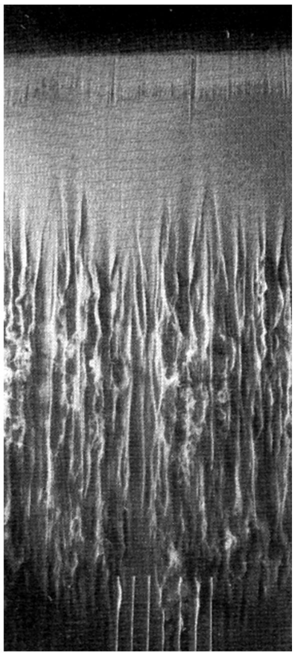
- Pulsed smoke visualisation of 2D pipe flow.

- Blue (centre) and red (wall) dye injected in turbulent flow in a roughened pipe

Turbulence Transition Mechanism

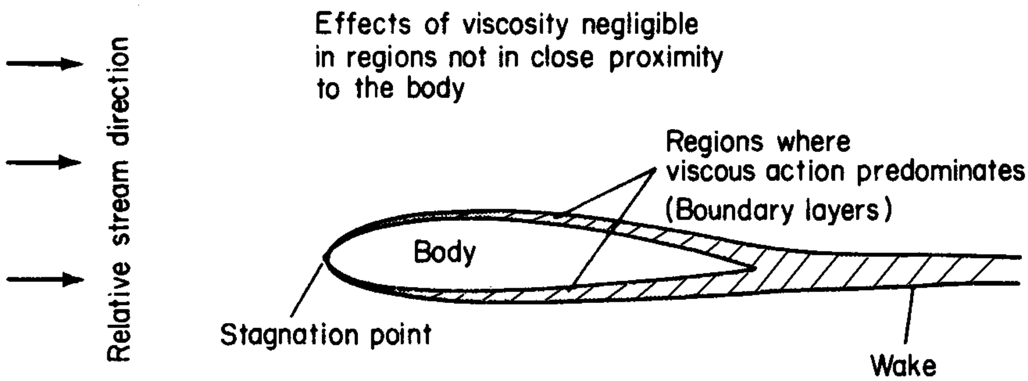
- Transition from laminar to turbulent flow idealised by the stages shown below (do not memorise), however in analysis transition often taken as instantaneous. Factors that have a strong effect on the onset and length of transition include: Reynolds Number; streamwise pressure gradient *(slowing flows 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



thickness of boundary layer exaggerated in picture - region is *very* thin, typically ~0.001 of streamwise length for an aerofoil

- 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

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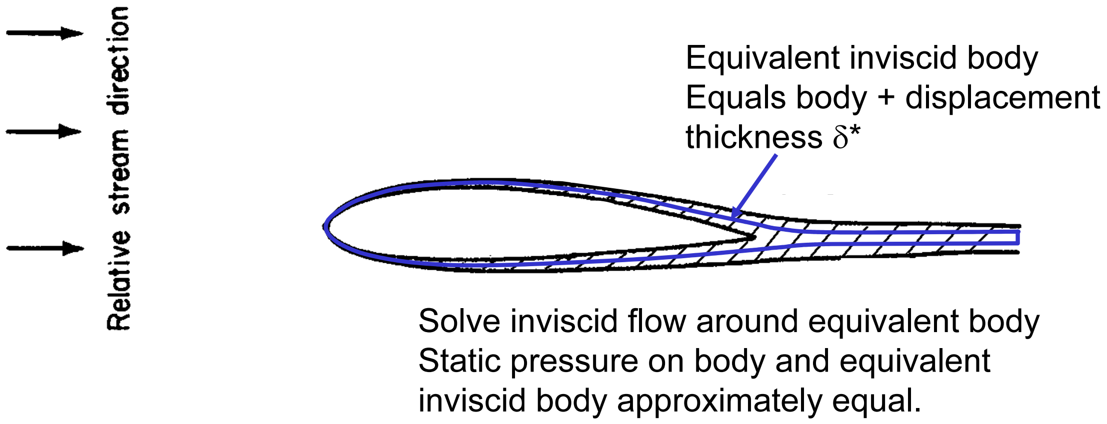
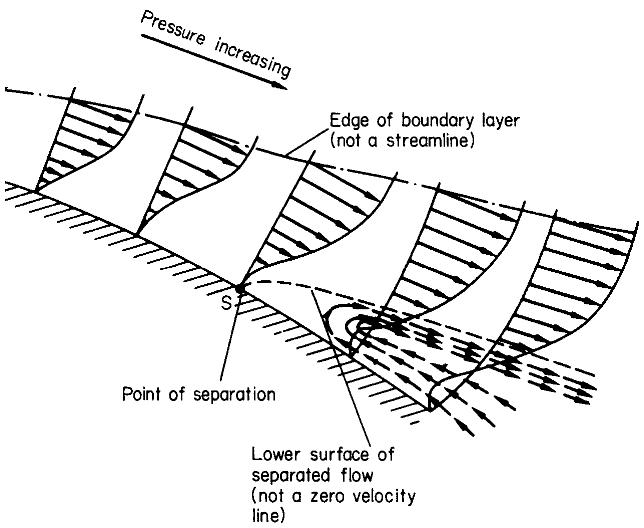


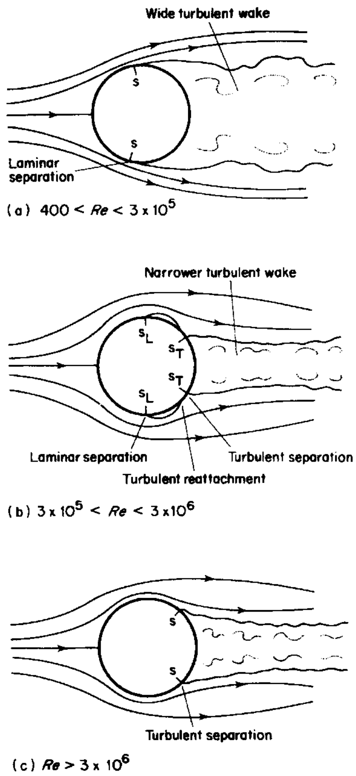
Background, not in exam

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.

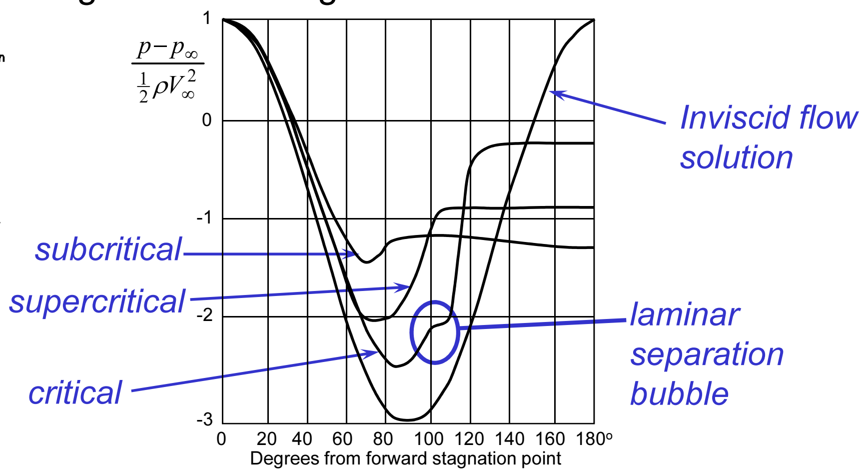


Streamlines over bluff bodies revisited



- 3 major categories high Re of flow

(a) *subcritical* ($Re_d \approx 4\text{x}10^2$ to $3\text{x}10^5$) early laminar separation
(b) *critical* ($Re_d \approx 3\text{x}10^5$ to $3\text{x}10^6$) laminar separation bubble, followed by delayed turbulent separation
(c) *supercritical* ($Re_d > 3\text{x}10^6$) turbulent separation
note region of constant pressure at the rear
– the wider the wake the higher the suction & the greater the drag

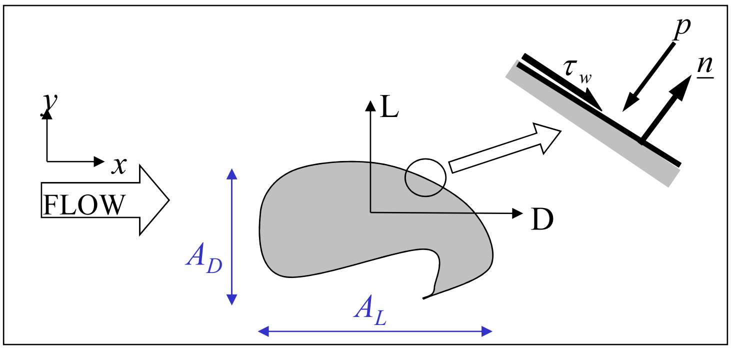


Lift and Drag Definitions

- 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

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

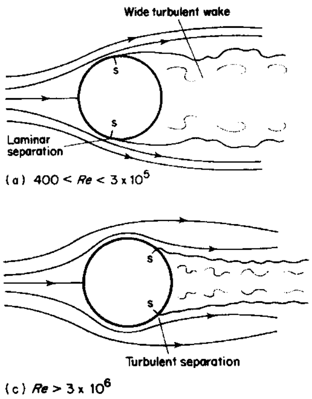
$$L = \int_{body} \tau_y dy - \int_{body} p n_y dx$$

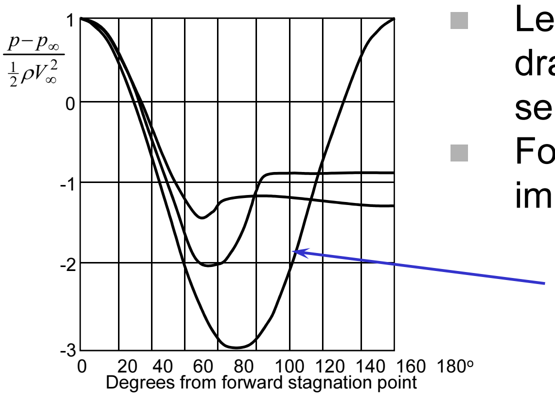


- The drag & lift coefficient is defined as the force normalised by an appropriate area and dynamic pressure. $C_D = \frac{D}{\frac{1}{2}\rho V_\infty^2 A_D}$ $C_L = \frac{L}{\frac{1}{2}\rho V_\infty^2 A_L}$

  definition of A_D & A_L can change
- For a particular shape it is assumed that the coefficients are universal, so "force = coefficient x dynamic pressure x Area" in all conditions.

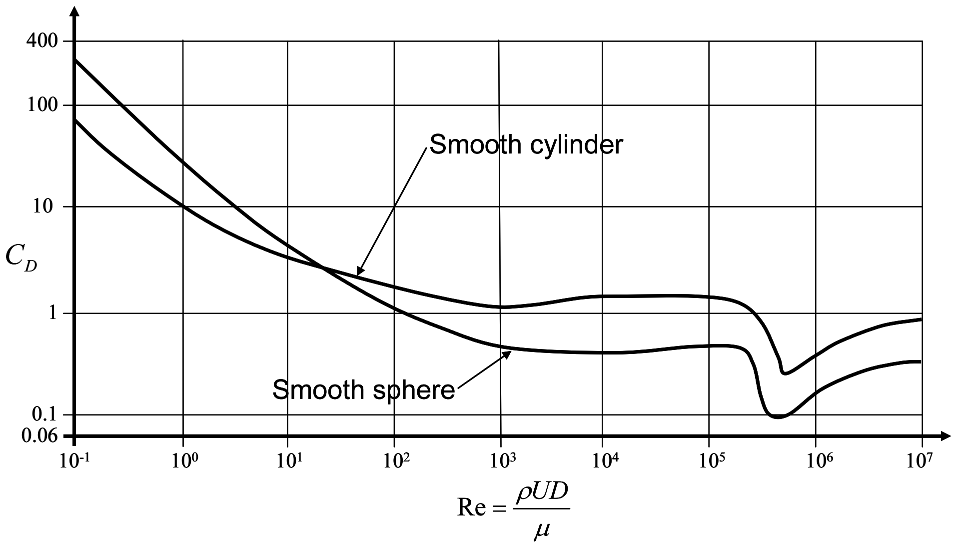
Drag around bluff bodies (cylinder example)

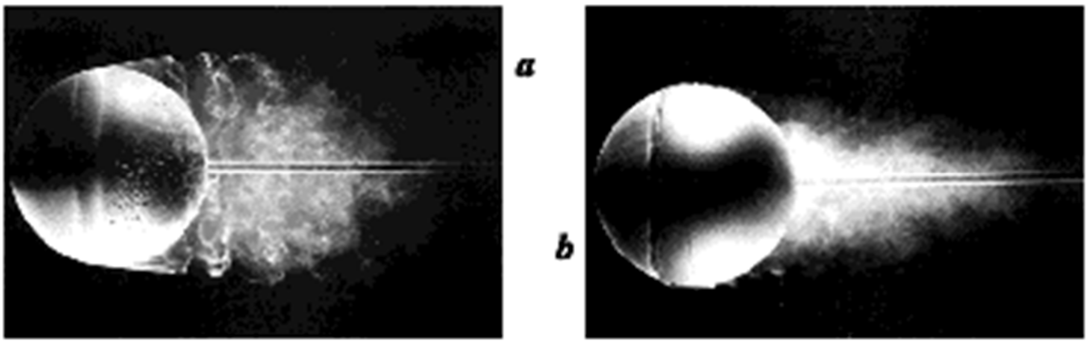




- Consider previous subcritical and supercritical flows around cylinders as examples of a bluff body flows.
- The drag is dominated by the pressure integral (Form Drag).
- The pressure aft of the separation is approximately constant. Furthermore the earlier the separation the lower the pressure.
- Leads 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)

Drag around cylinder as Re changes



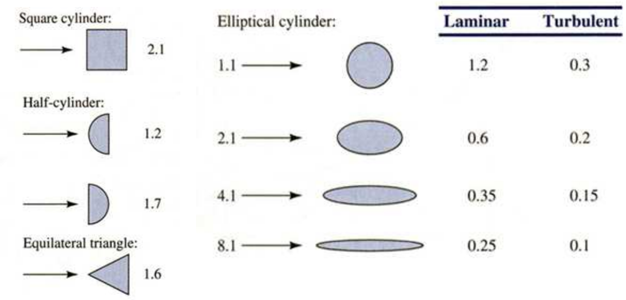


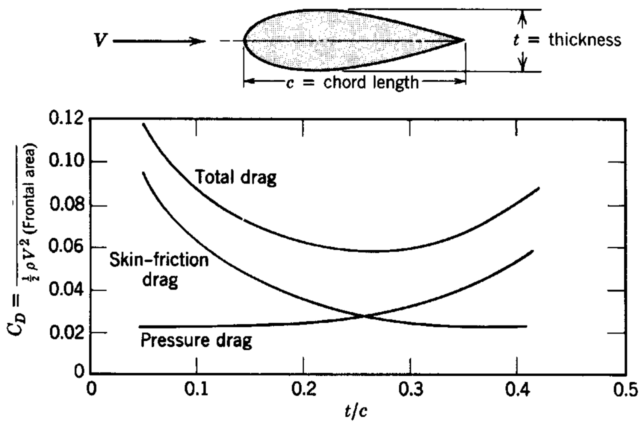
- Comparison of laminar separation around a sphere, a, with a flow that is “tripped” so that the attached boundary layer becomes fully turbulent, b.
- The laminar flow separates before it reaches maximum thickness. The tripped turbulent flow stays attached well beyond the maximum thickness.
- Separated 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

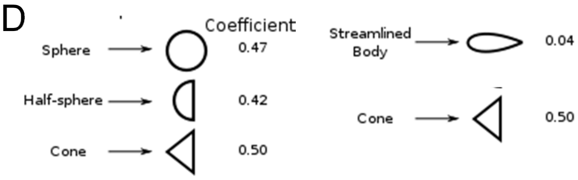
Typical Drag Coefficient Values

- 2D values





- 3D



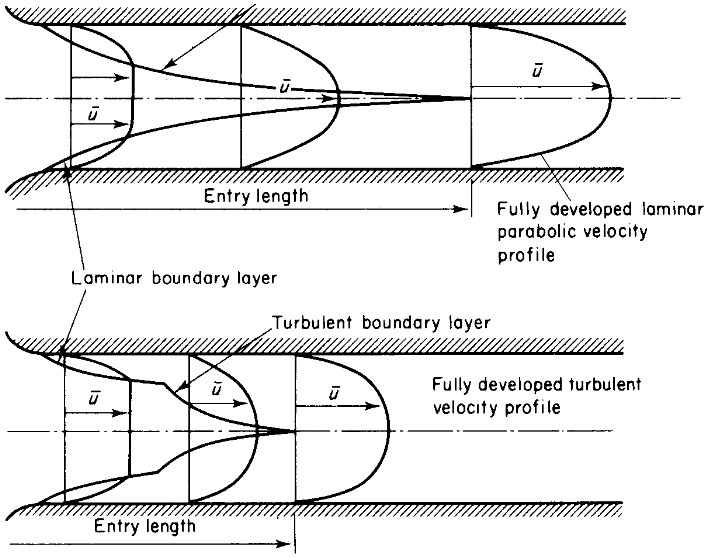
- Turbulent flow over streamlined bodies: skin friction ↑ form drag ↓
- reducing thickness/chord ratio reduces form drag
  - alleviates adverse pressure gradient on aft surfaces
- drag reduction most sensitive to changes in aft region
  - this is where separation occurs

Viscous pipe flow

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

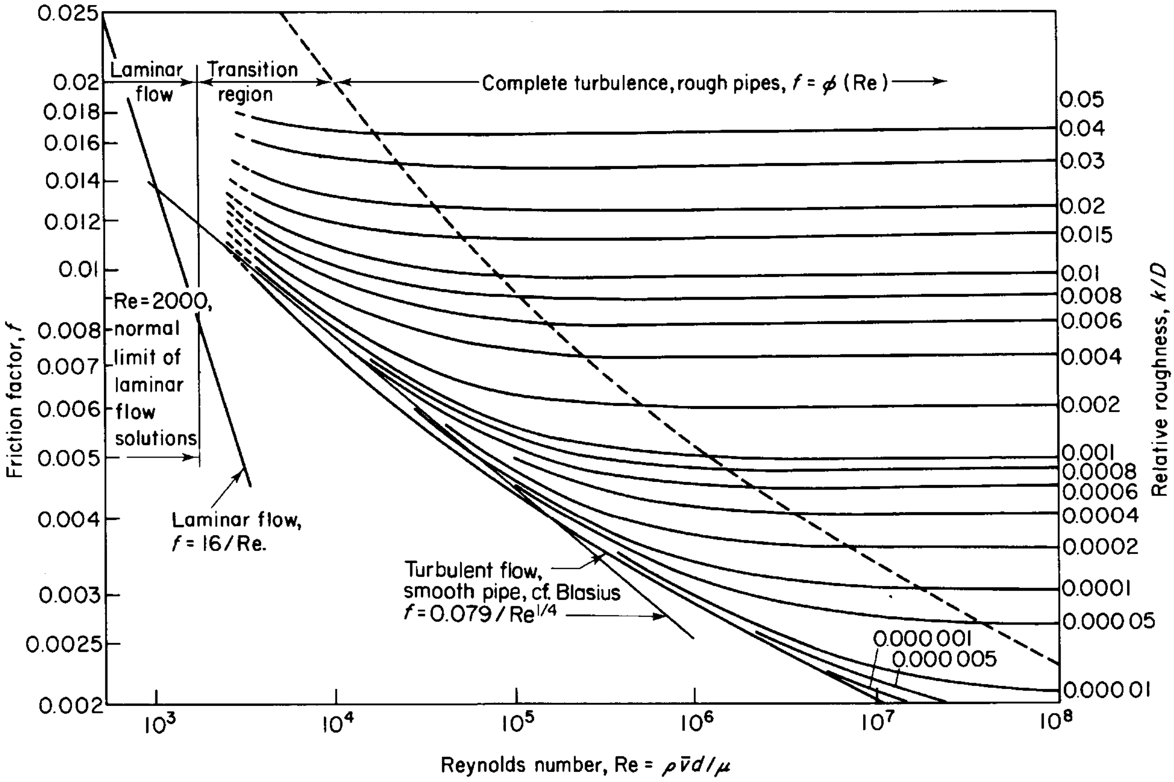
$$\boxed{\Delta p = 4f\left(\frac{l}{d}\right)\rho\overline{U}^2}$$

- $\overline{U}$ 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 $f \approx 0.079Re_d^{-0.25}$



Background, not in exam

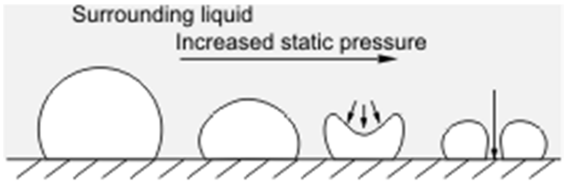
Moody Diagram

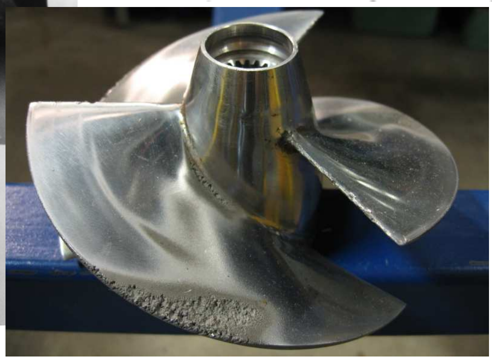


Background, not in exam

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 .

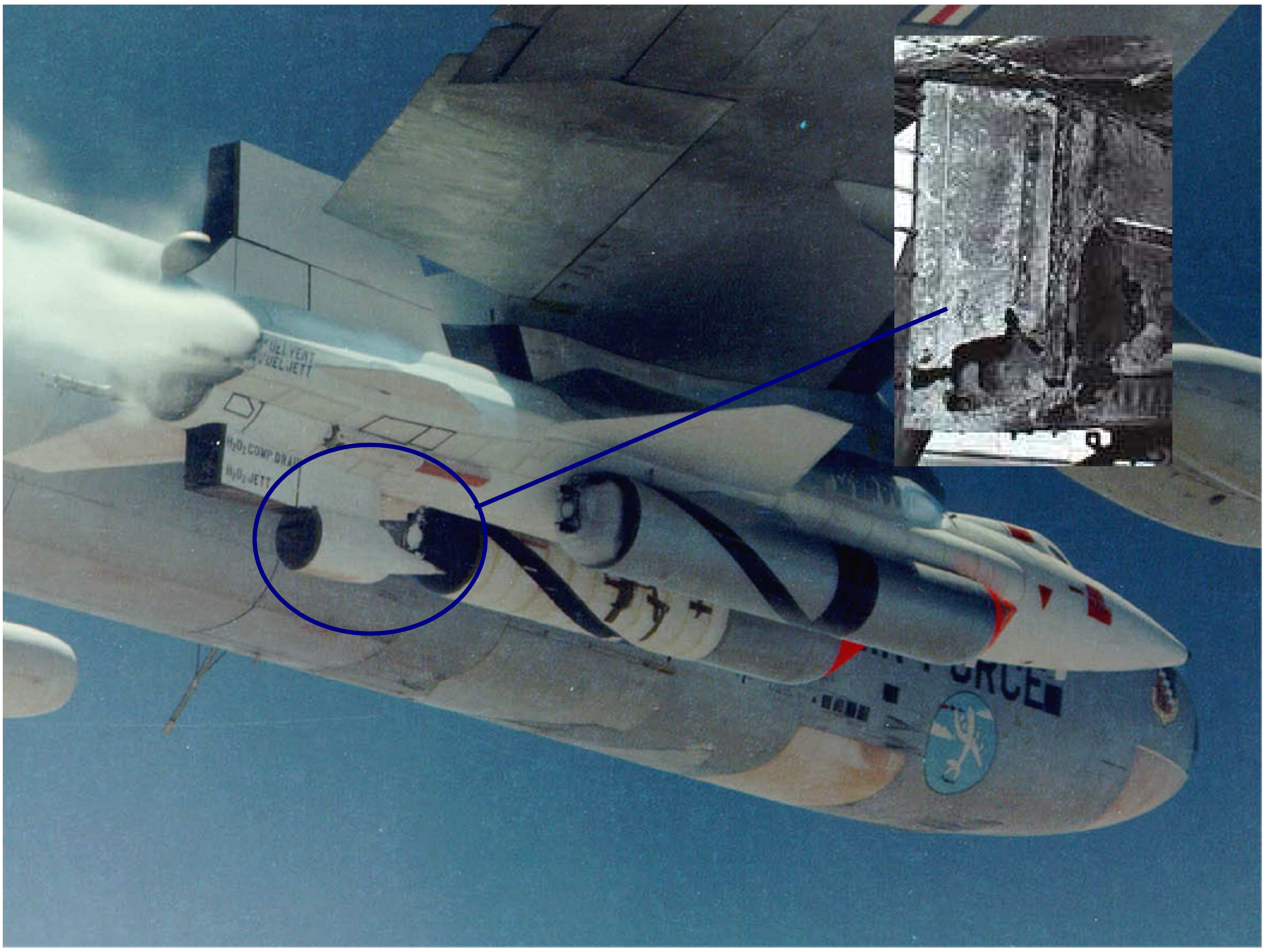




Complex Fluid Behaviour Examples

- 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

Fluids 1 labs: F1

- 4 experiments
  - Various bodies in an airstream
  - Variation of Drag Coefficient with Reynolds number
  - Flow visualisation
  - Pressure tapped aerofoil
- Time limited so: read notes beforehand, arrive on time
- Velocity Calculations are based on Bernoulli's eqn
  - Airbox velocity assumed negligible so static pressure variation equals dynamic pressure
- Results per group marked on the day – 30%
- Discussion section (maximum of 3 pages) uploaded to blackboard – up to two weeks after