ES 202
Fluid and Thermal Systems

Lecture 26:
Friction Drag on a Flat Plate
(2/11/2003)

Road Map of Lecture 26

Knowledge items:

- Origin of viscous drag
  - recall fluid friction (*i.e.* viscosity)
  - no-slip condition at boundaries (kinematic condition)
  - concept of boundary layer (region of significant viscous effects)
- Laminar-turbulent transition in boundary layer
- Drag on a flat plate

Visual learning:

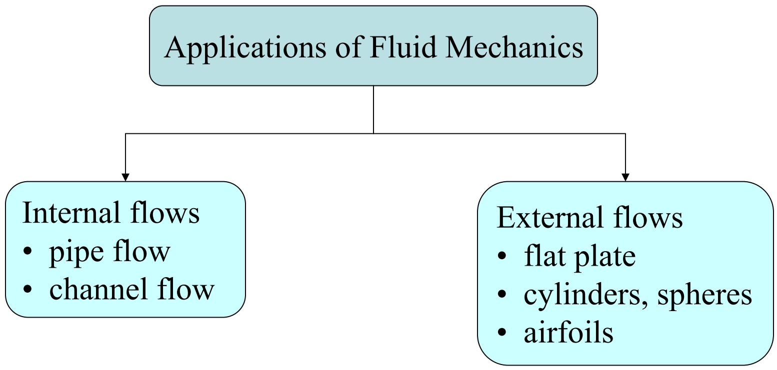
- Visualizations from MMFM

Applications:

- Dimensional analysis of boundary layer thickness on flat plate
- Control volume analysis of flat plate boundary layer

Internal Versus External Flows

- Application of fluid mechanics can be broadly classified into two categories:



Recall Fluid Friction

- Fluid friction
  - also termed "viscosity"
  - basketball-tennis-ball demonstration
  - exchange of momentum at the molecular scales
  - no-slip conditions at the solid surface (imagine thin layers of fluid moving relative to one another)
  - concept of boundary layer
  - stress-strain relation in a Newtonian fluid

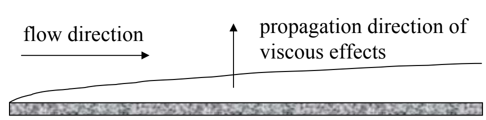
stress = viscosity X strain rate ⟶ $$\tau = \mu \frac{du}{dy}$$

Concept of Boundary Layer

- Due to the no-slip boundary condition (a kinematic condition), the layer of fluid immediately adjacent to the flat plate is not moving.
- The fluid which is far away from the flat plate does not "feel" the presence of the plate and travels at the free-stream speed *(U)*.
- Between the plate surface and free-stream, the fluid velocity changes from zero (plate surface) to the free-stream speed over a thin region.
- Show MMFM visualization
- This thin region is termed the "boundary layer".

Features of Boundary Layer

- Due to the "thinness" of the boundary layer, the velocity gradient is LARGE.
- Hence, viscous effects are important there. Why?
- Never apply Bernoulli's equation in the boundary layer. Why?
- Effects in two different directions:
  - flow is convected in the streamwise direction
  - presence of the flat plate is propagated in the normal direction into the fluid
  - <u>Result:</u> boundary layer thickness grows in the streamwise direction.



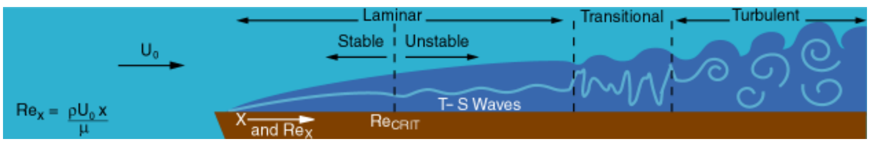
- <u>Exercise:</u> Perform dimensional analysis on boundary layer thickness.

Laminar-Turbulent Transition

- Similar to the laminar-turbulent transition in pipe flow, the flow over a flat plat also experiences a transition from laminar state to turbulent state when the local Reynolds number (Re_x) exceeds a critical number.
- The critical value can be taken to be

$$\mathrm{Re}_x \approx 5 \times 10^5$$

- In reality, the nominal critical Reynolds number depends on a host of different factors like level of free-stream disturbance, surface roughness, *etc.* Its exact value can vary over a large range.



Taken from Multi-Media Fluid Mechanics (Homsy *et al.*)

Significance of Reynolds Number

- Definition of Reynolds number:

$$Re_L = \frac{\rho V L}{\mu}$$

- The Reynolds number can be interpreted as the ratio of inertial to viscous effects (one of many interpretations)
- At low Reynolds number,
  - viscous effect is comparable to inertial effect
  - flow behaves in orderly manner (laminar flow)
- At high Reynolds number,
  - viscous effect is insignificant compared with inertial effect.
  - flow pattern is irregular, unsteady and random (turbulent flow)

Scaling of Boundary Layer Thickness

- In the laminar regime (close to the leading edge),

$$\frac{\delta_{\text{lam}}}{x} \propto \frac{1}{\text{Re}_x^{1/2}}$$

- In the turbulent regime (beyond transition point):

$$\frac{\delta_{\text{turb}}}{x} \propto \frac{1}{\text{Re}_x^{1/5}}$$

Drag on a Flat Plate

- Due to viscous (fluid friction) effects, the flat plate will experience a force in the downstream direction. The force is termed "Drag".
- Think of it as an action-reaction pair of force:
  - the fluid experiences a force in the upstream direction to slow it down;
  - the same force (in magnitude) acts on the flat plate in opposite direction.
- Exercise: Perform a control volume analysis on a flat plate to find out its total drag.
- Suggest another way to find the drag on a flat plate.