A Seminar Topic On

BOUNDARY LAYER

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Introduction

- In August of 1904 Ludwig Prandtl,a 29-year old professor presented a remarkable paper on BOUNDARY LAYER at the 3rd International Mathematical Congress in Heidelberg.

- The condition of zero fluid velocity at the solid surface is referred to as 'no slip' and the layer of fluid between the surface and the free stream fluid is termed BOUNDARY LAYER.

Boundary Layer History

- 1904 Prandtl

Fluid Motion with Very Small Friction

2-D boundary layer equations

- 1908 Blasius

The Boundary Layers in Fluids with Little Friction

Solution for laminar, 0-pressure gradient flow

- 1921 von Karman

Integral form of boundary layer equations

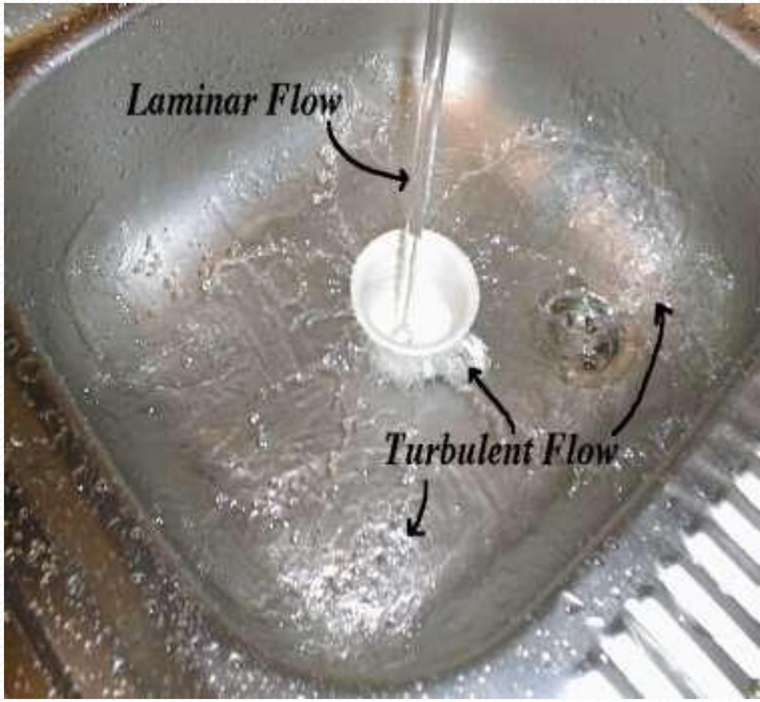
Laminar Flow

❖ Each liquid particle has a definite path.

❖ The paths of individual particles do not cross each other.

❖ All the molecules in the fluid move in the same direction and at the same speed.

❖ It also called as stream line flow.

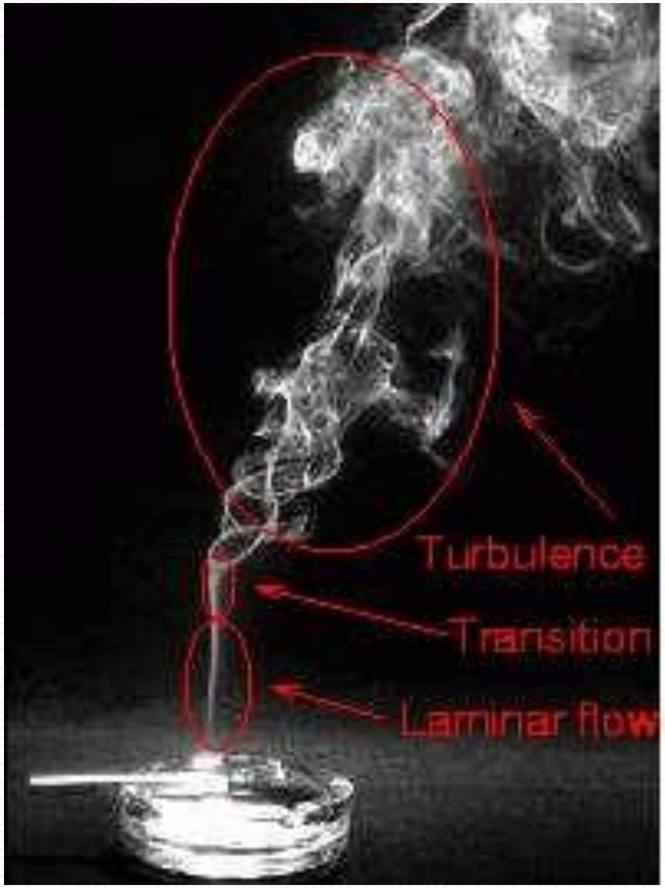


Turbulent Flow

- Each liquid particle do not have a definite path.

- The path of individual particle also cross each other.

- The molecules in the fluid move in different directions and at different speeds.



Critical Velocity

- A velocity at which the flow changes from the laminar flow to turbulent flow.

- The critical velocity may be further classified into the following two types :1.Lower Critical Velocity

  2.Upper Critical Velocity

Reynold's Number

Re =Inertia forces/viscus forces

$=(\rho v^2)/(\mu v/d)$

$=\rho vd/\mu$

$=vd/V$ (as $\rho/\mu=V$)

$$Re = \frac{\text{Mean velocity of liquid} \times \text{Diameter of pipe}}{\text{Kinematic velocity of liquid}}$$

- Re < 2000 ; Laminar flow
- 2000 < Re < 2800 ;Transition flow
- 2800 < Re ; Turbulent flow

Boundary Layer Theory

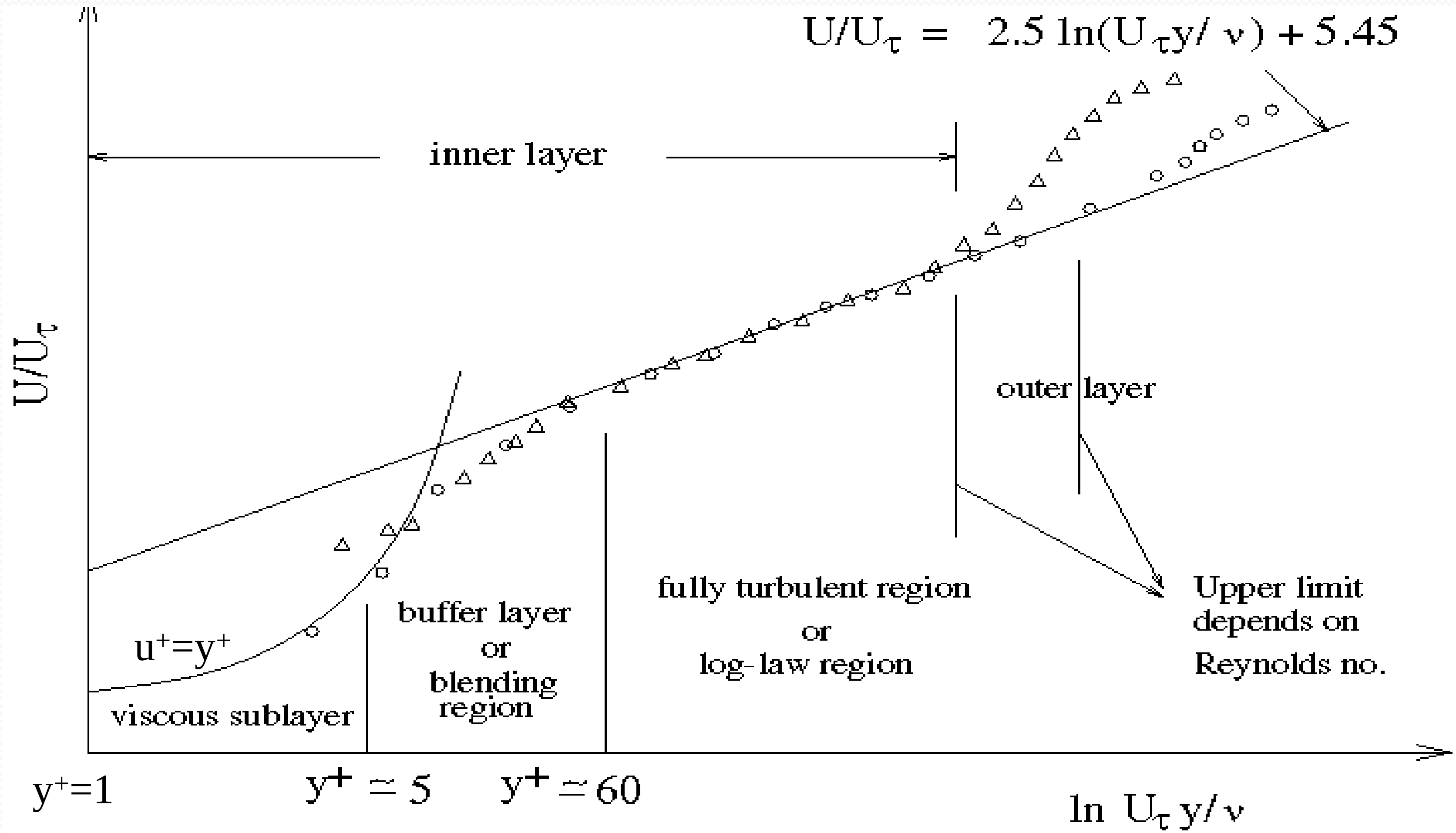
- A thin layer of fluid acts in such a way ,as if it's inner surface is fixed to the boundary of the body.

- Velocity of flow at boundary layer is zero.

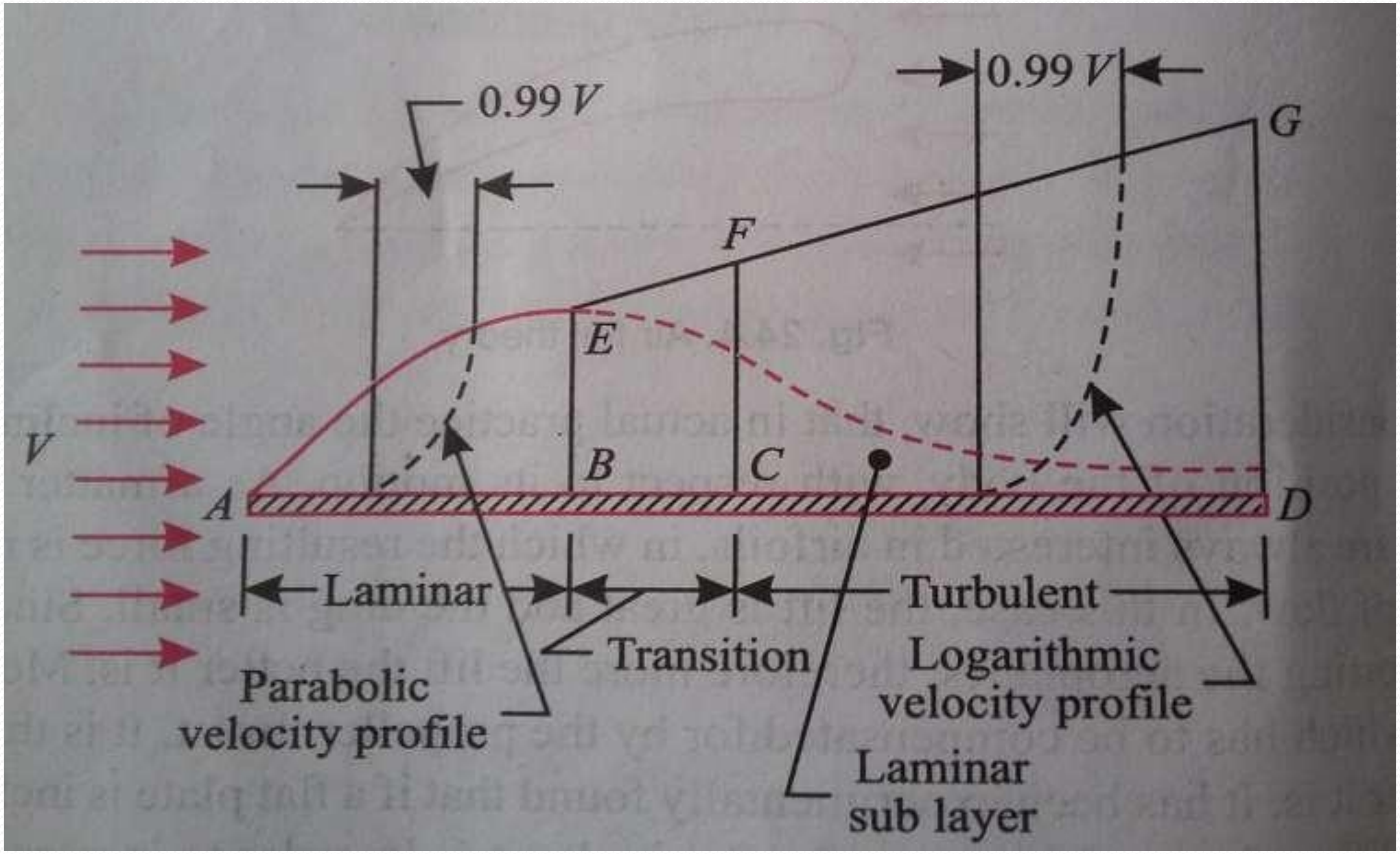
- The velocity of flow will go on increasing rapidly till at the extreme layer.

- The portion which is outside the boundary layer has a high value of Reynold's Number, because of the high velocity of flow

Boundary layer structure



Thickness Of Boundary Layer



- The distance from surface of the body ,to a place where the velocity of flow is 0.99 times of the maximum velocity of flow ,is known as thickness of boundary layer.

- It is usually denoted by δ(delta).

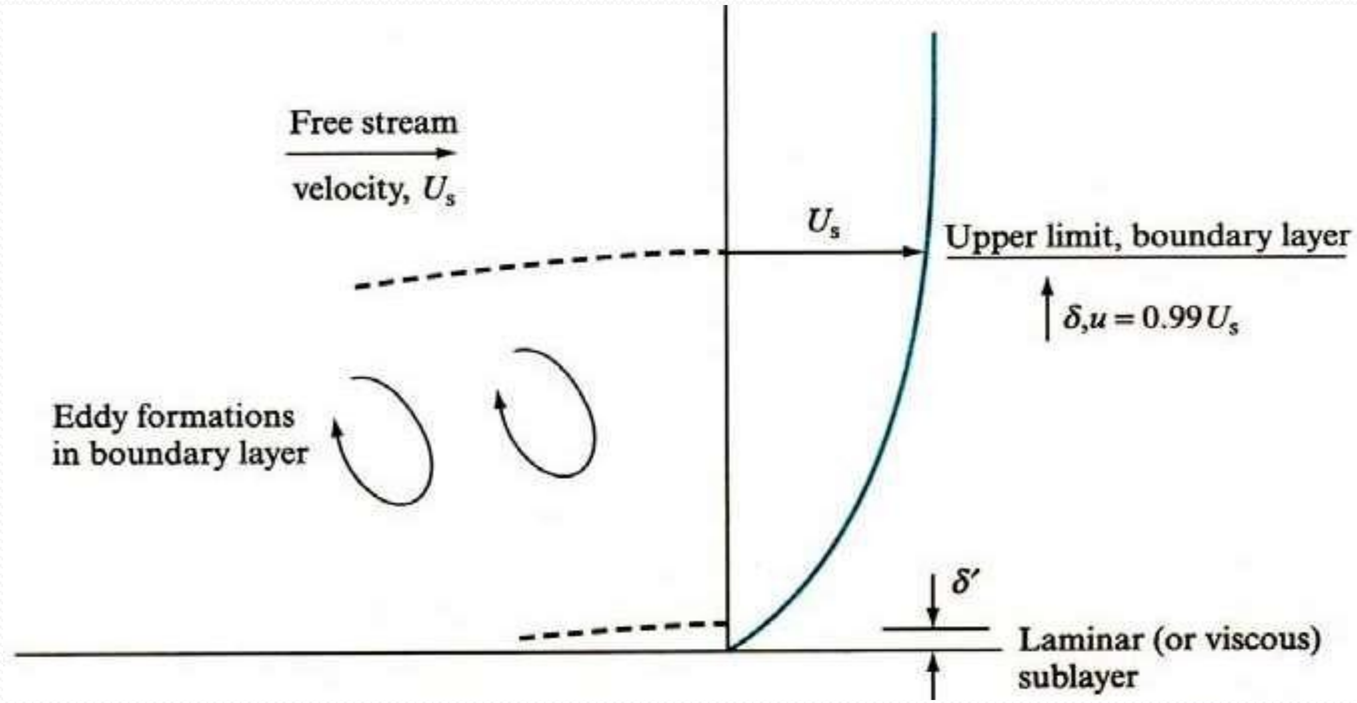
- R_{NX}= Vx/v

  where, V=Velocity of fluid

  v=Kinematic velocity of fluid

  x= Distance b/w the leading edge of the plate and the section

Boundary Layer Thickness, δ



Boundary layer thickness is defined as that distance from the surface where the local velocity equals 99% of the free stream velocity.

$$\delta = y_{(u=0.99U_s)}$$

Thickness Of Boundary Layer In A Laminar Flow

- It has been experimentally found, that the thickness of the boundary layer is zero at the leading edge A, and increases to the trailing edge , the flow is laminar.

- According to Pohlhausenin

$$\delta_{lam} = 5.835x/\sqrt{Rnx}$$

- According to Prandtl-Blassius

$$\delta_{lam} = 5x/\sqrt{Rnx}$$

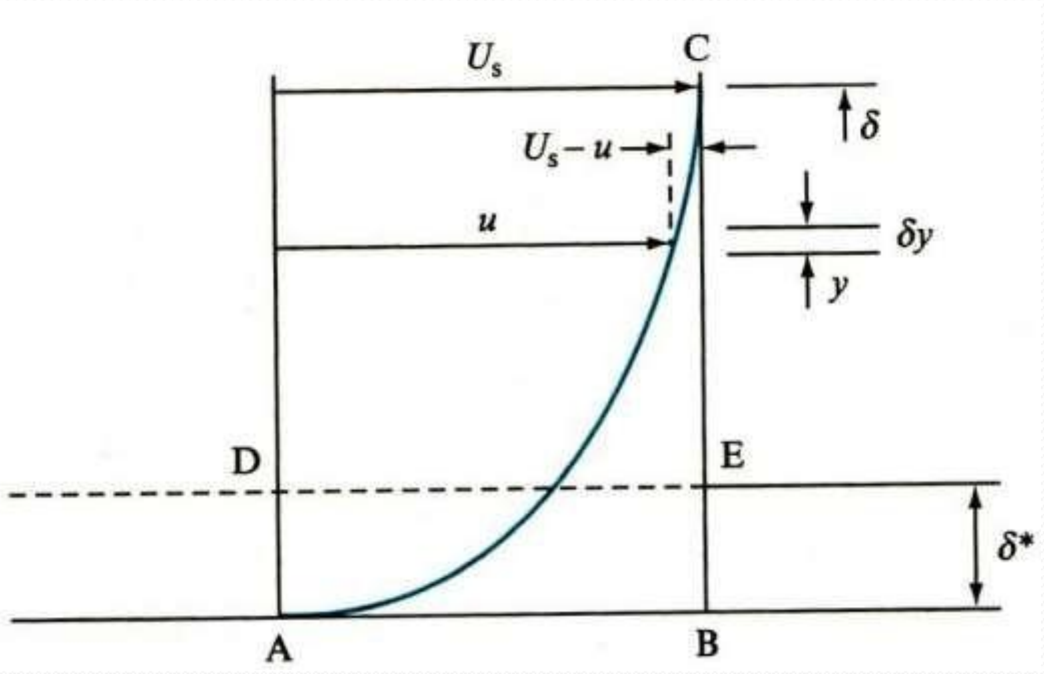
Thickness Of Boundary Layer In A Turbulent Flow

- As the boundary layer continuous further downstream, it expands and the transition flow changes into turbulent flow and the transition boundary layer changes into turbulent boundary layer, which continuous over the remaining length of the plate.

- According to Prandtl-Blassious,

$$\delta_{tur} = 0.377x/(R_{NX})^{1/5}$$

Displacement Thickness, δ*



The displacement thickness for the boundary layer is defined as the distance the surface would have to move in the y-direction to reduce the flow passing by a volume equivalent to the real effect of the boundary layer.

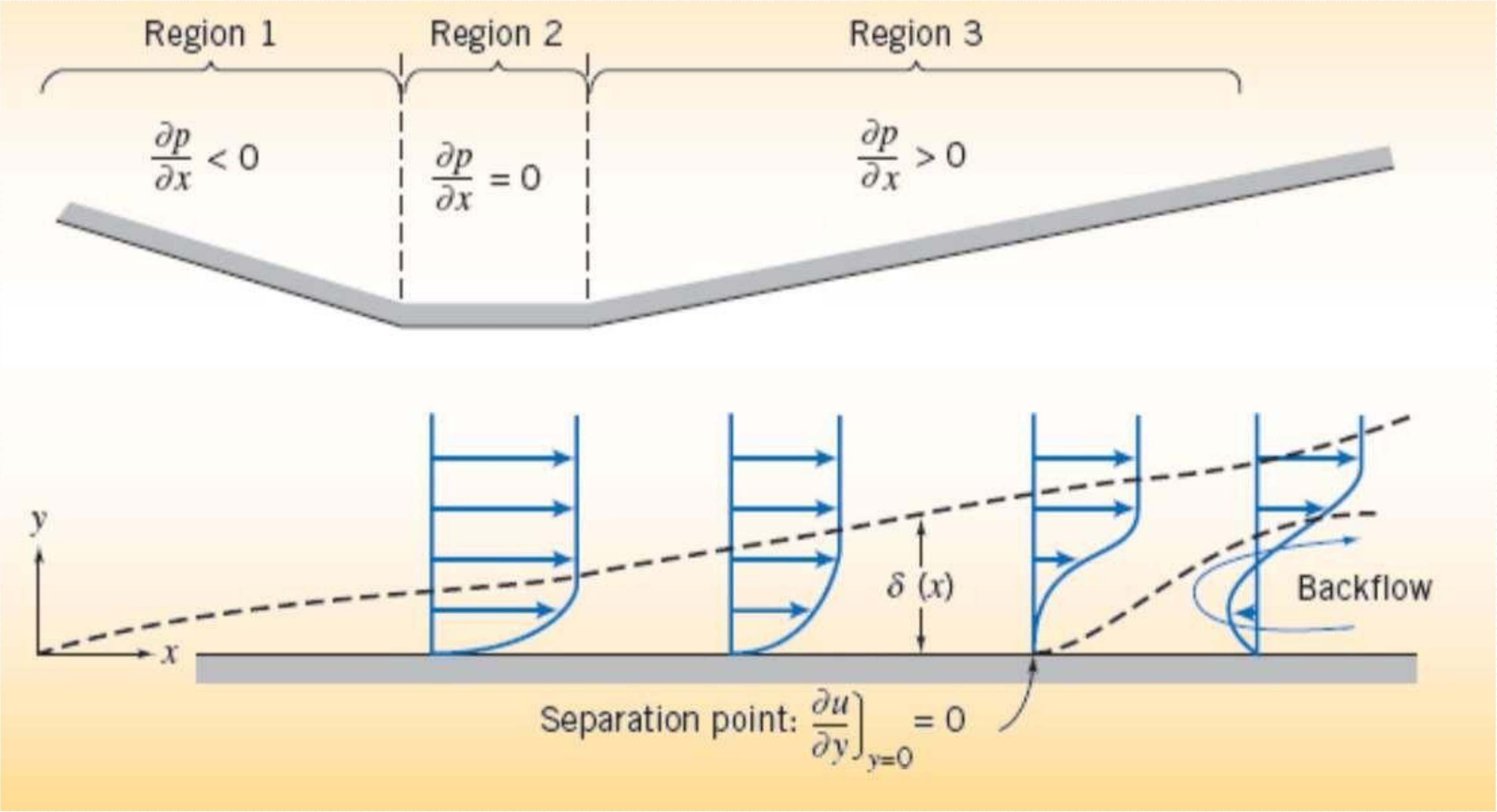
$$\delta^* = \int_0^{\delta} (1 - u/Us)\,dy$$

Momentum Thickness, θ

Momentum thickness is the distance that, when multiplied by the square of the free stream velocity, equals the integral of the momentum defect. Alternatively, the total loss of momentum flux is equivalent to the removal of momentum through a distance θ. It is a theoretical length scale to quantify the effects of fluid viscosity near a physical boundary.

$$\theta = \int_0^{\delta} u/Us(1 - u/Us)\mathrm{dy}$$

Pressure Gradients In Boundary Layer Flow



Applications Of Boundary Layer Theory

- ❖ *Aerodynamics* (Airplanes, Rockets, Projectiles)
- ❖ *Hydrodynamics* (Ships, Submarines, Torpedoes)
- ❖ *Transportation* (Automobiles, Trucks, Cycles)
- ❖ *Wind Engineering* (Buildings, Bridges, Water Towers)
- ❖ *Ocean Engineering* (Buoys, breakwaters, Cables).

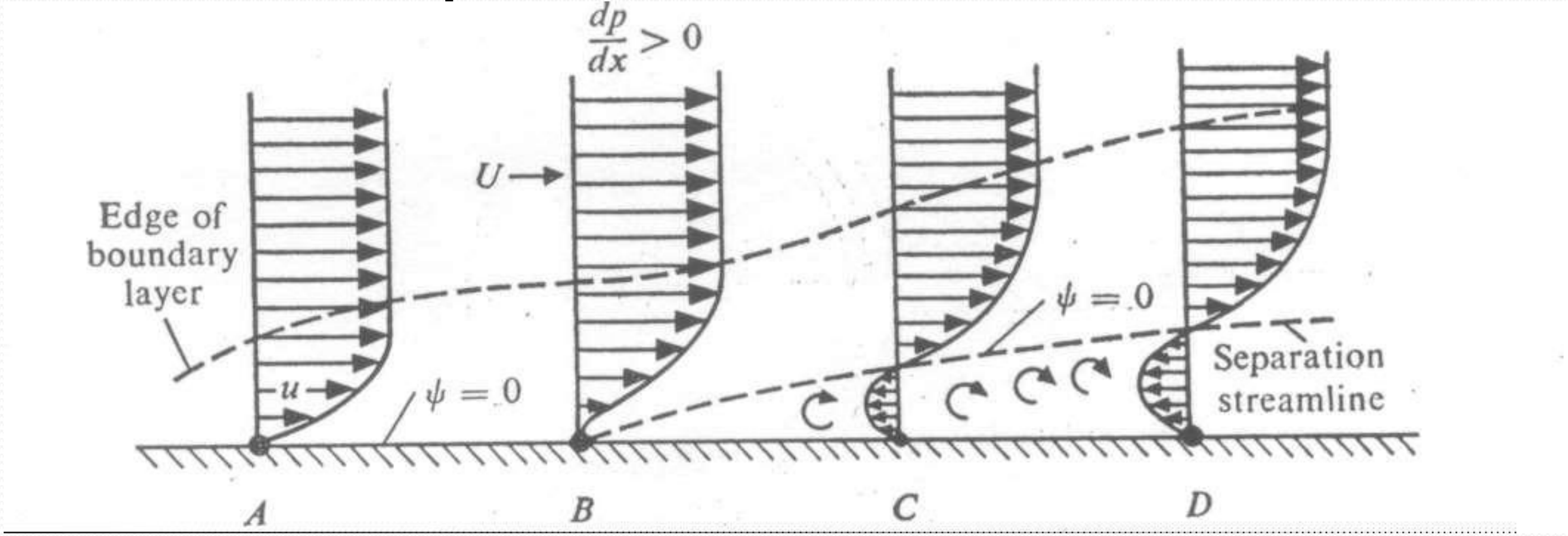
Boundary Layer Separation

- The increasing downstream pressure slows down the wall flow and can make it go backward-flow separation.

- *dp/dx* >0 adverse pressure gradient, flow separation may occur.

- *dp/dx* < 0 favourable gradient, flow is very resistant to separation.

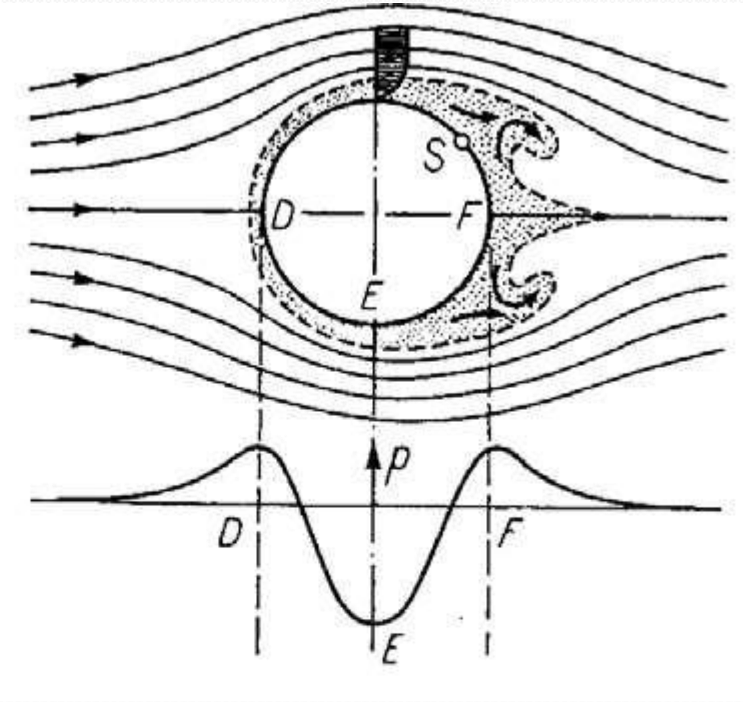
BL Separation Condition



❖Due to backflow close to the wall, a strong thickening of the BL takes place and BL mass is transported away into the outer flow.

❖At the point of separation, the streamlines leave the wall at a certain angle.

Separation Of BL At A Circular Cylinder



Separation of the boundary layer and vortex formation a circular cylinder (schematic). S=separation point

- D to E, pressure drop, pressure is transformed into kinetic energy.

- From E to F, kinetic energy is transformed into pressure.

- A fluid particle directly at the wall in the boundary layer is also acted upon by the same pressure distribution as in the outer flow(inviscid).

- Due to the strong friction forces in the BL, a BL particle loses so much of its kinetic energy that is cannot manage to get over the “pressure gradient” from E to F.

- The following figure shows the time sequence of this process:

- Reversed motion begun at the trailing edge.

- Boundary layer has been thickened, and start of the reversed motion has moved forward considerably.

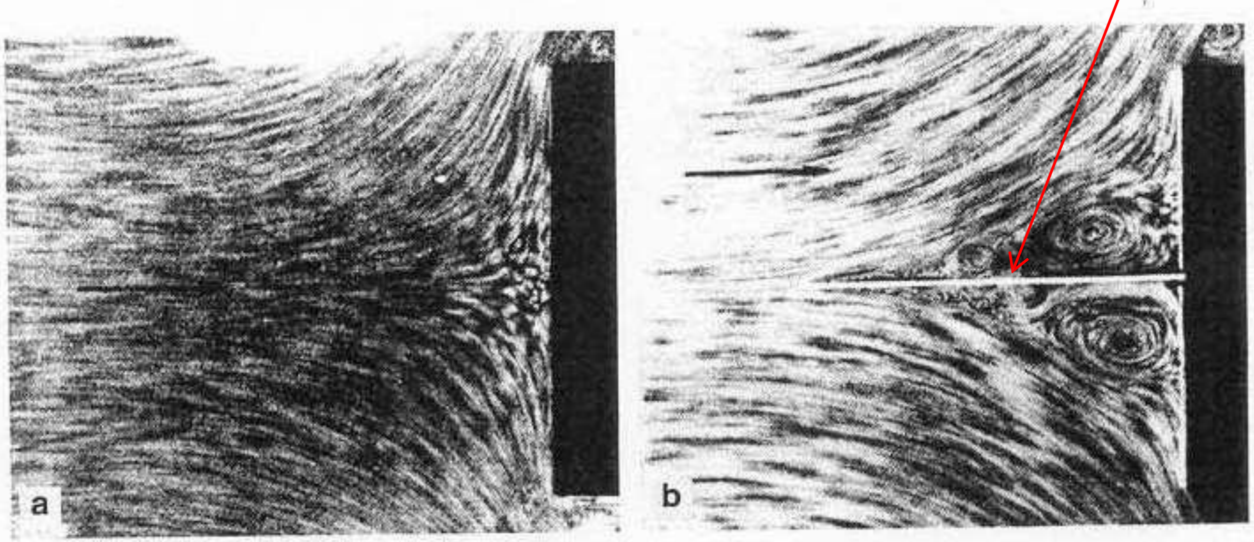
- And d. a large vortex formed from the backflow and then soon separates from the body.

Examples of Boundary Layer Separations (in 2D)

Features:

The entire boundary layer flow breaks away at the point of zero wall shear stress and, having no way to diverge left or right, has to go up and over the resulting separation bubble or wake.

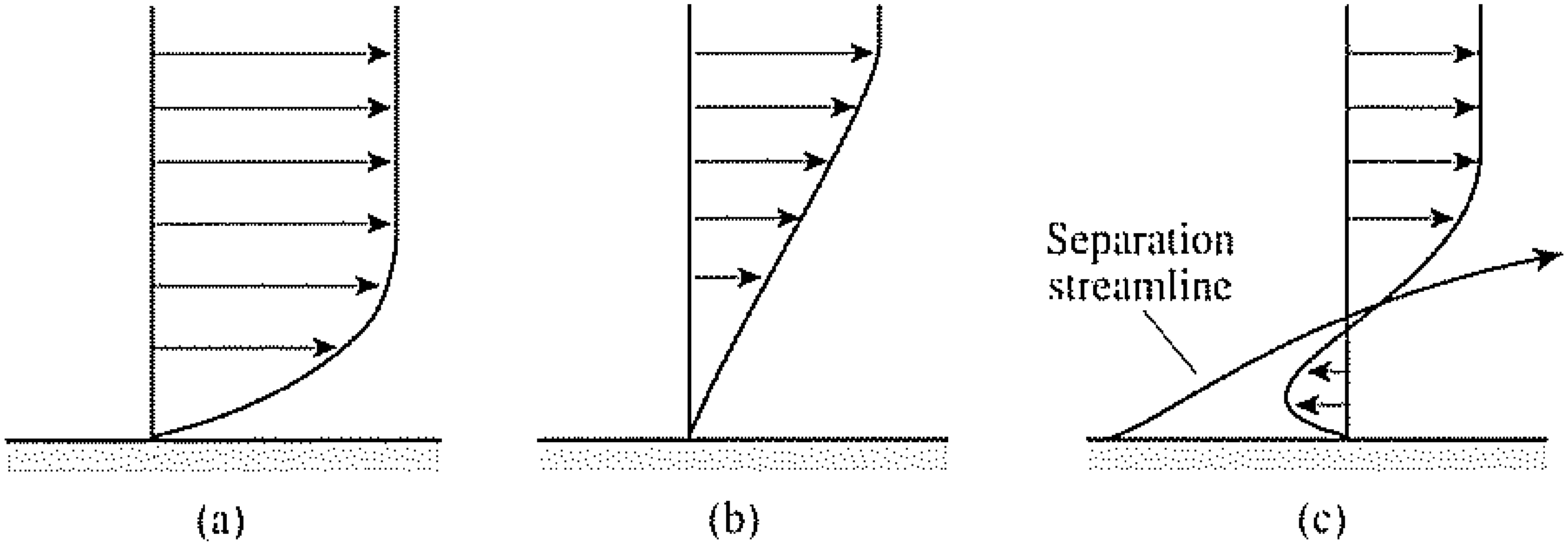
1. Plane wall(s)



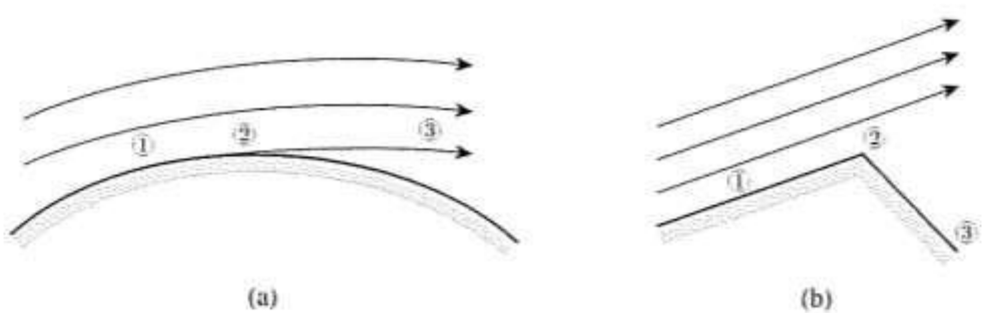
Stagnation point flow, after H Fottinger(1939)a)Free stagnation point flow without separation b)retarded stagnation point flow with separation (a). Plane stagnation-point flow: no separation on the streamlines of symmetry (no wall friction present), and no separation at the wall (favourable pressure gradient)

(b).Flat wall with right angle to the wall: flow separate.

EXAMPLE OF FLOW SEPARATION

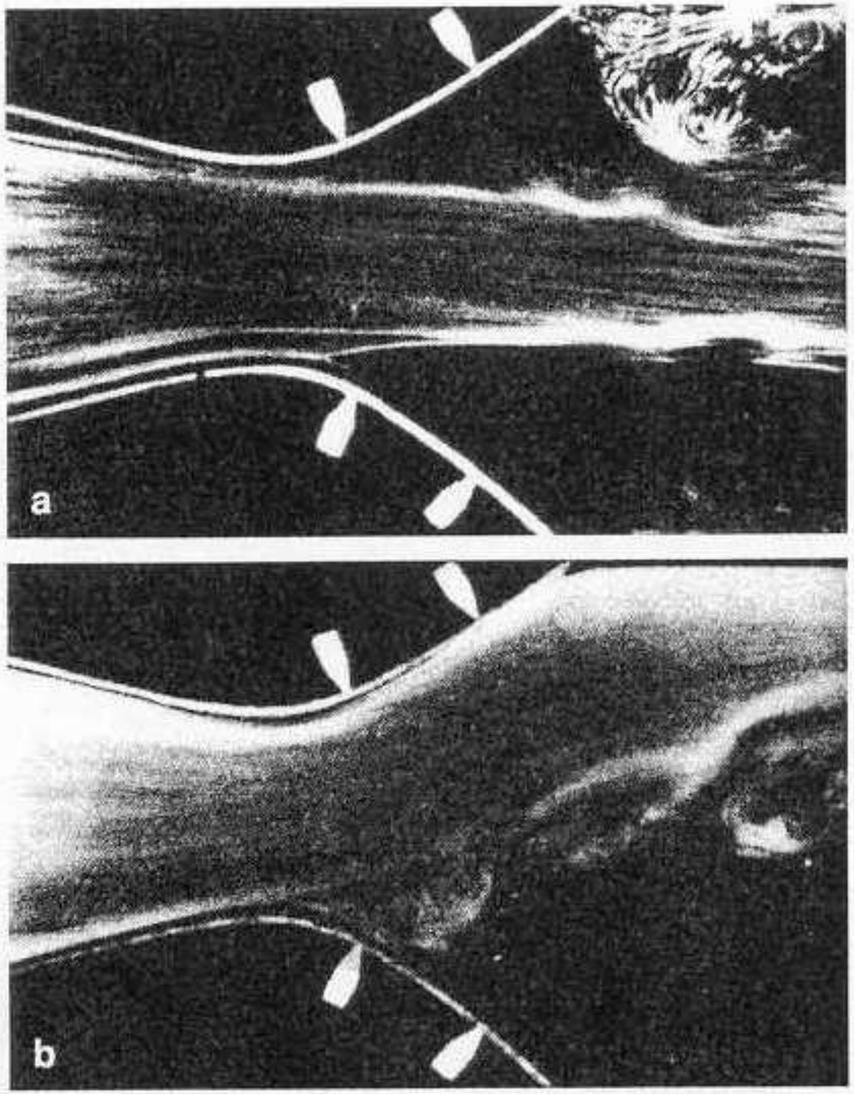


- Velocity profiles in a boundary layer subjected to a pressure rise
  - (a) start of pressure rise
  - (b) after a small pressure rise
  - (c) after separation
- Flow separation from a surface
  - (a) smooth body
  - (b) salient edge

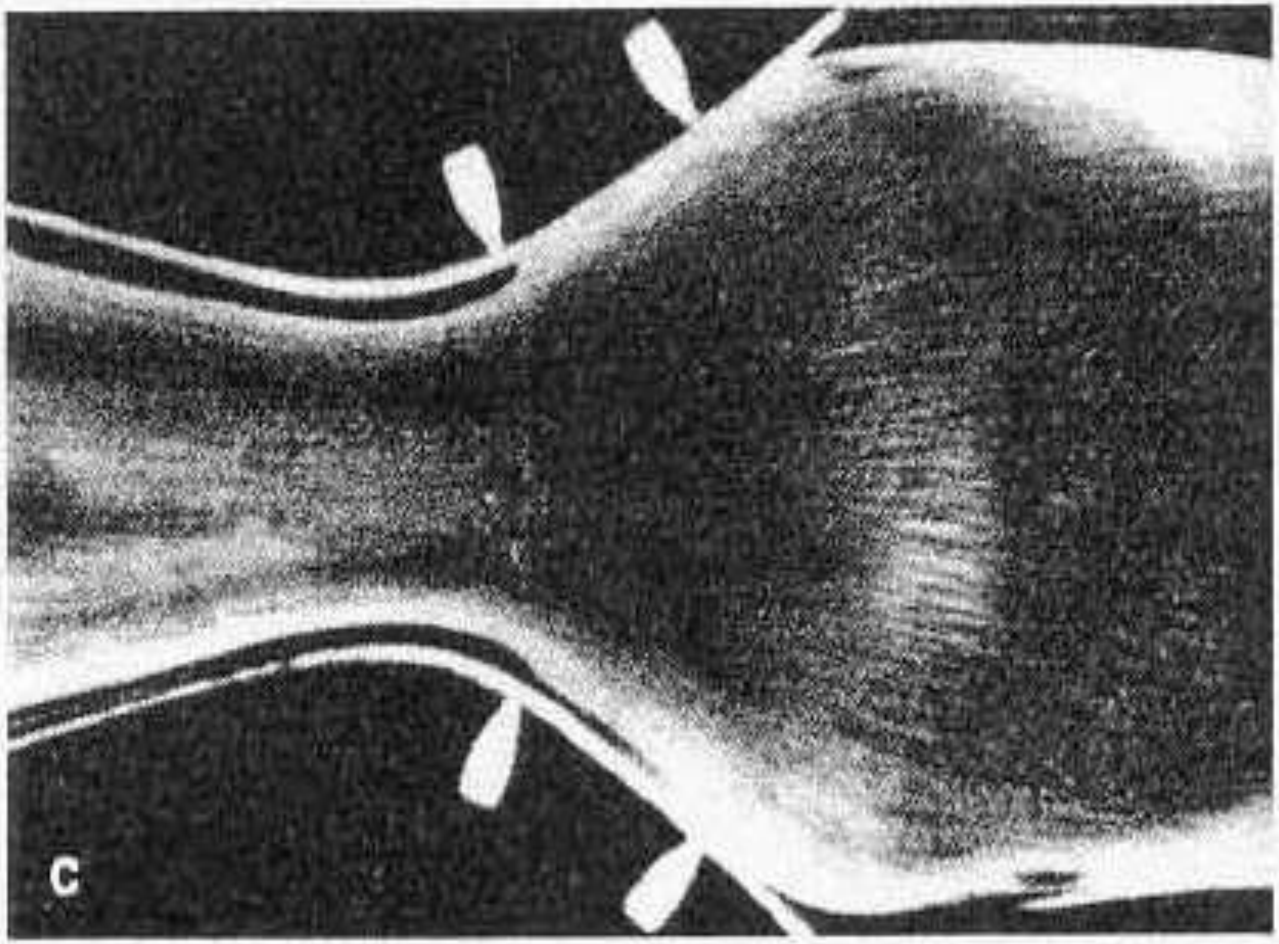


2. Diffuser flow:-

Flow in widening channel (Diffuser)
a)Separation in both diffuser walls
b)Suction of the boundary layer
at the upper diffuser walls

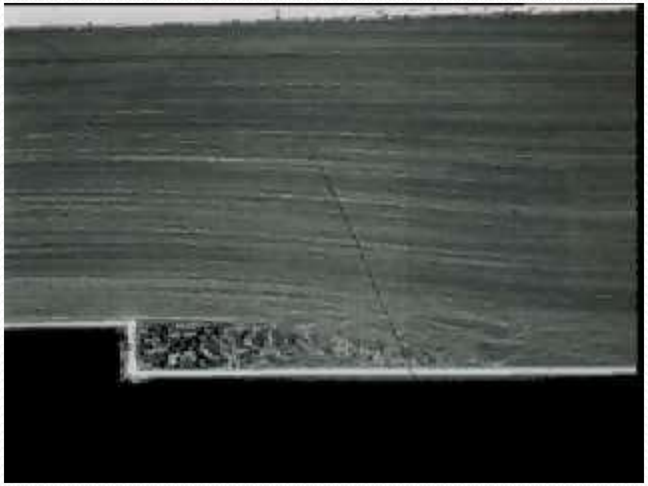


c)Suction at both diffuser walls (after L. Prandtl ;O. Tietjens(1931))



Separation at Sharp corners

- Corners, sharp turns and high angles of attack all represent sharply decelerating flow situations where the loss in energy in the boundary layer ends up leading to separation.



- Here we see how the boundary layer flow is unable to follow the turn in the sharp corner (which would require a very rapid acceleration), causing separation at the edge and recirculation in the aft region of the backward facing step.

Flow Over a Truck

- Flow over non-streamlined bodies such as trucks leads to considerable drag due to recirculation and separation zones.

- A recirculation zone is clear on the back of the cab, and another one around the edge of the trailer box.

- The addition of air shields to the cab roof ahead of the trailer helps organize the flow around the trailer and minimize losses, reducing drag by up to 10-15%.

Examples of Boundary Layer Separations (in 3D)

Features:-

Unlike 2D separations, 3D separations allow many more options.

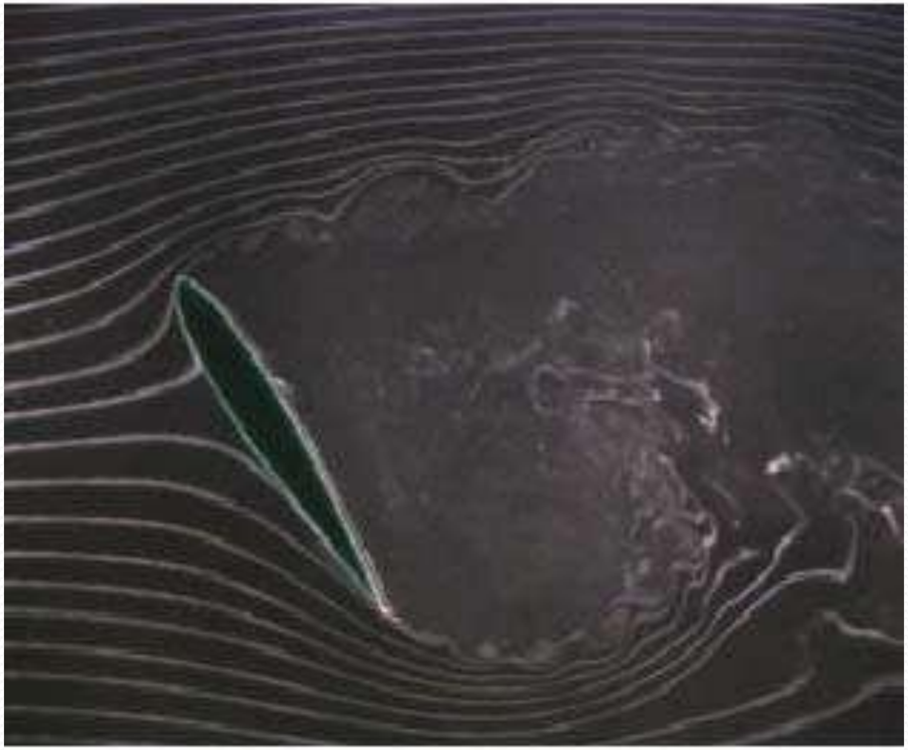
There are four different special points in separation:

- ❖ *A nodal Point*, where an infinite number of surface streamlines merged tangentially to the separation line.
- ❖ *A saddle point*, where only two surface streamlines intersect and all others divert to either side.
- ❖ *A focus, or spiral node*, which forms near a saddle point and around which an infinite number of surface streamlines swirl.
- ❖ *A three-dimensional singular point*, not on the wall, generally serving as the centre for a horseshoe vortex.

Video Library

(animations from “Multi-media Fluid Mechanics”, Homsy, G. M., etc.)

Conditions Producing Separation

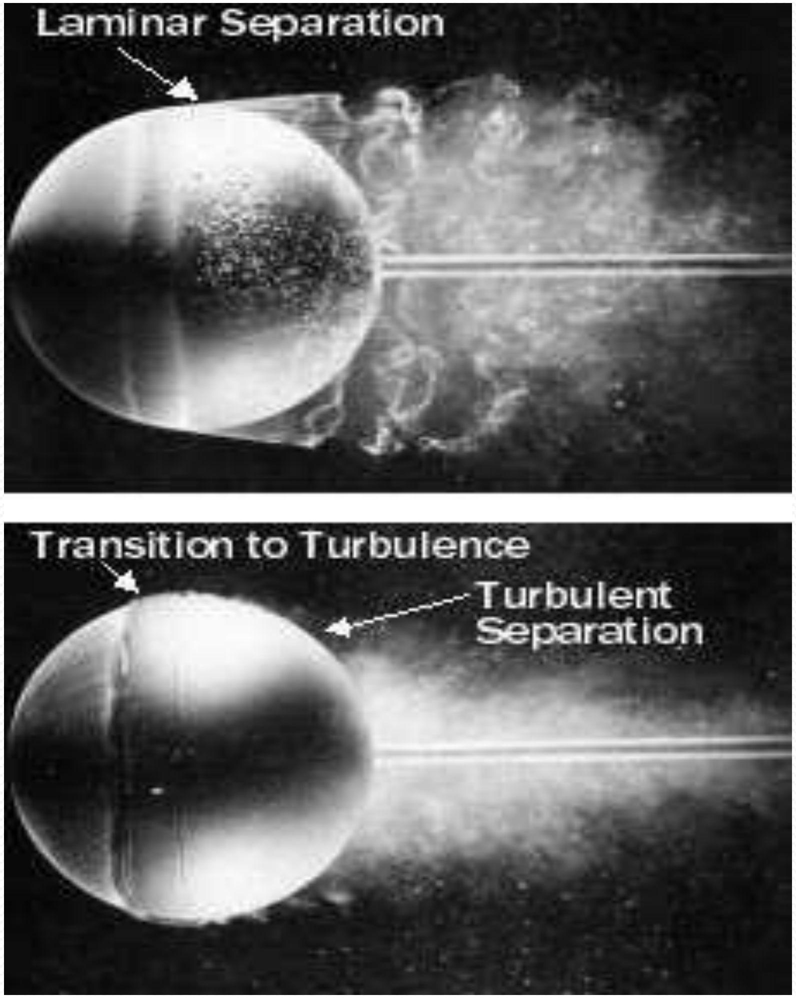


Separations on air foil (different attack angles)

Leading edge separation

Separations in diffuser

Effect of body shape on separation



Laminar and Turbulent separation

Reference

Books:-

- Hydraulics, Fluid Mechanics and Hydraulic Machines
  R.S. Khurmi & N. Khurmi
- Fluid Mechanics and Hydraulic Machines
  Dr. R. K. Bansal

Papers:-

- Laminar, Turbulent, Transition flow by Bhaskar Kumar, IIT Roorkee
- BIEN 501 by Seven A. Jones

Websites:-

- en.wikipedia.org/Boundary_layer
- www.nasa.gov/../boundlay.html
- www.thermopedia.com/content/595/
- Nptel.ac.in/../Course_home-9.htm

Conclusion

- The concept of the boundary layer was introduced.
- Boundary layers require special treatment in the CFD model.
- The influence of pressure gradient on boundary layer attachment showed that an adverse pressure gradient gives rise to flow separation.
- For accurate drag, lift, and torque predictions, the boundary layer and flow separation need to be modeled accurately.
- This requires the use of:-
  - A suitable grid.
  - A suitable turbulence model.
  - Higher order discretization.
  - Deep convergence using the force to be predicted as a convergence monitor.

THANK YOU

HAVE A NICE DAY