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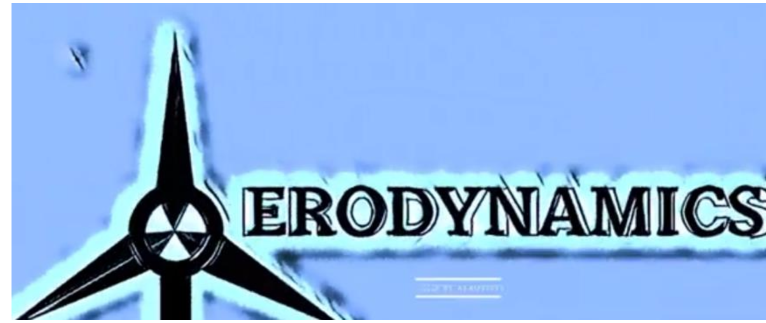

MEE1004-FLUID MECHANICS

Boundary Layer Flow

Lecture 1

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Flow Separation

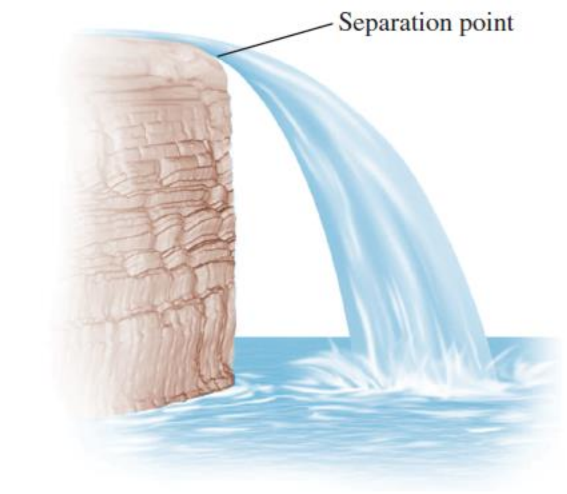
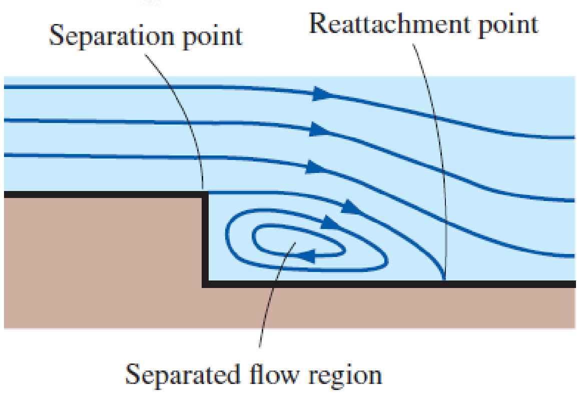
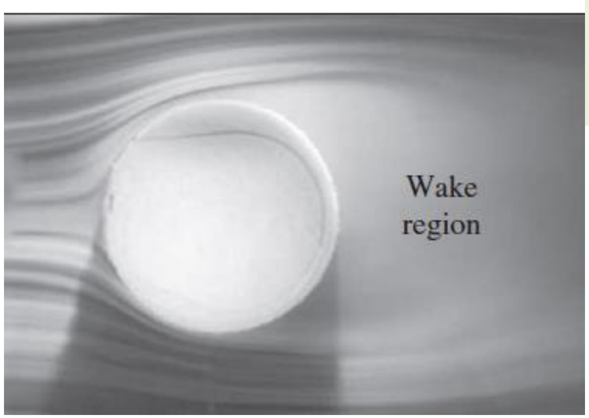


FIGURE 11–13
Flow separation in a waterfall.

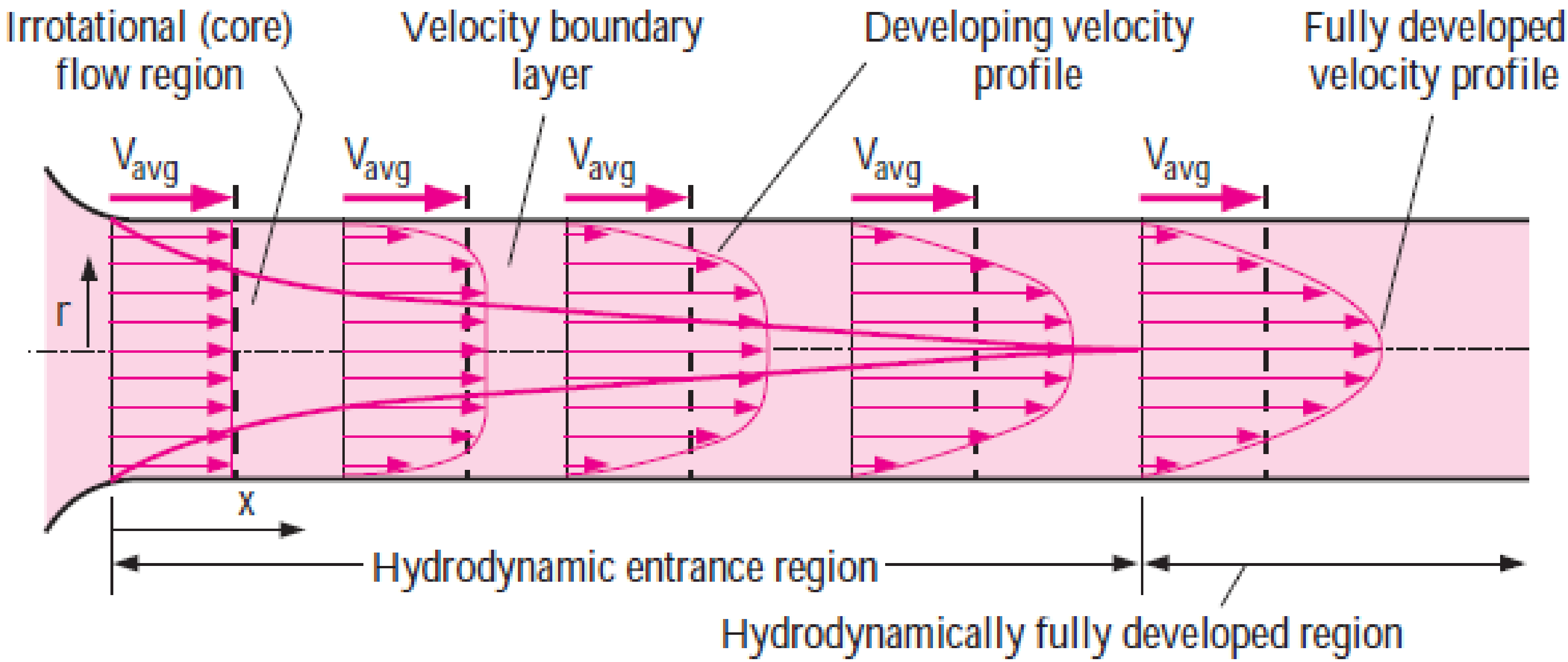




A fluid follows the front portion of the curved surface with no problem, but it has difficulty remaining attached to the surface on the back side. At sufficiently high velocities, the fluid stream detaches itself from the surface of the body. This is called **flow separation**

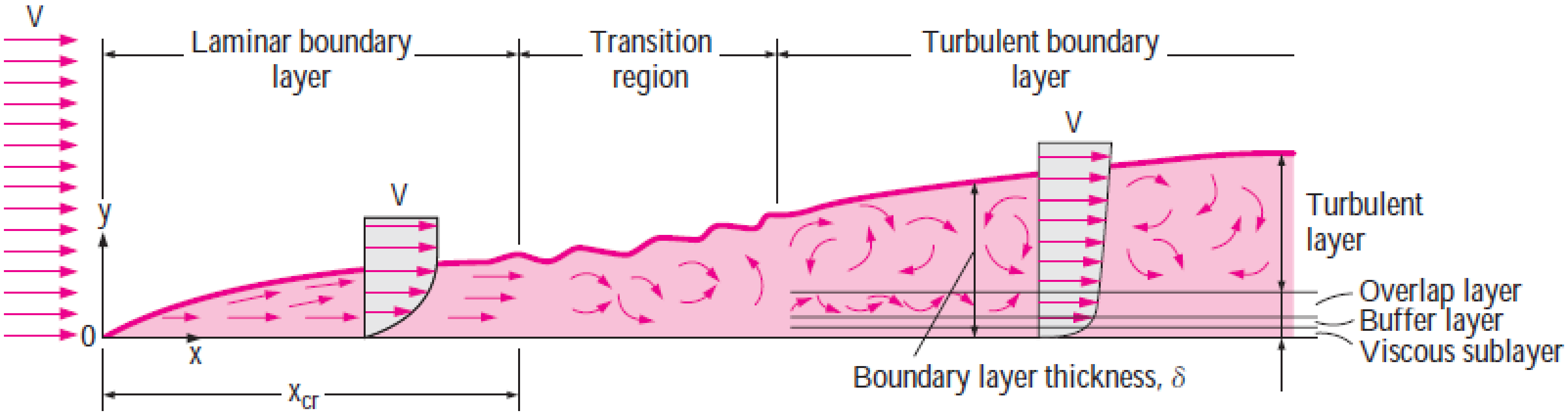
When a fluid separates from a body, it forms a separated region between the body and the fluid stream. This low-pressure region behind the body where recirculating and backflows occur is called the **separated region.**

The region of flow trailing the body where the effects of the body on velocity are felt is called the **wake.** The separated region comes to an end when the two flow streams reattach.

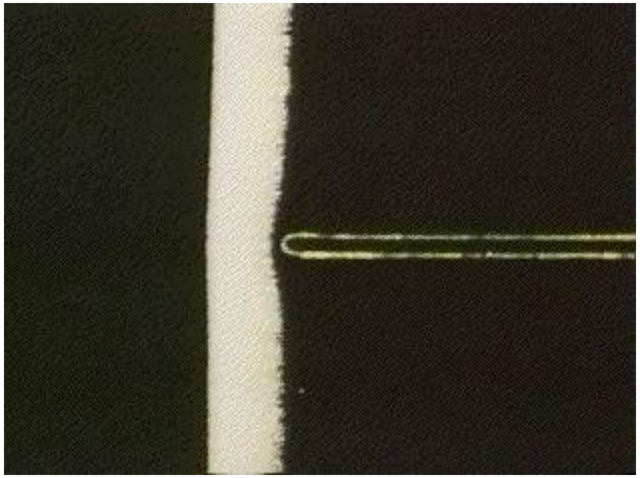

Irrotational (core)
flow region
Velocity boundary
layer
Developing velocity
profile
Fully developed
velocity profile
V_{avg}
V_{avg}
V_{avg}
V_{avg}
V_{avg}
r
x
Hydrodynamic entrance region
Hydrodynamically fully developed region

PARALLEL FLOW OVER FLAT PLATES

The region of the flow above the plate bounded by δ in which the effects of the viscous shearing forces caused by fluid viscosity are felt is called the **velocity boundary layer.** The boundary layer thickness δ is typically defined as the distance y from the surface at which $u = 0.99V$.



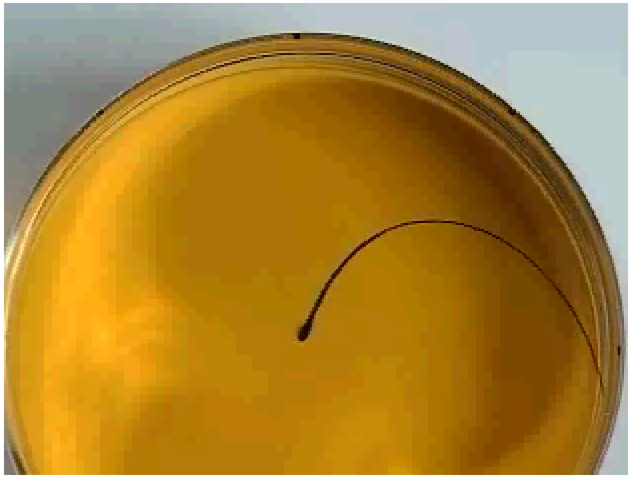
Viscous boundary layer



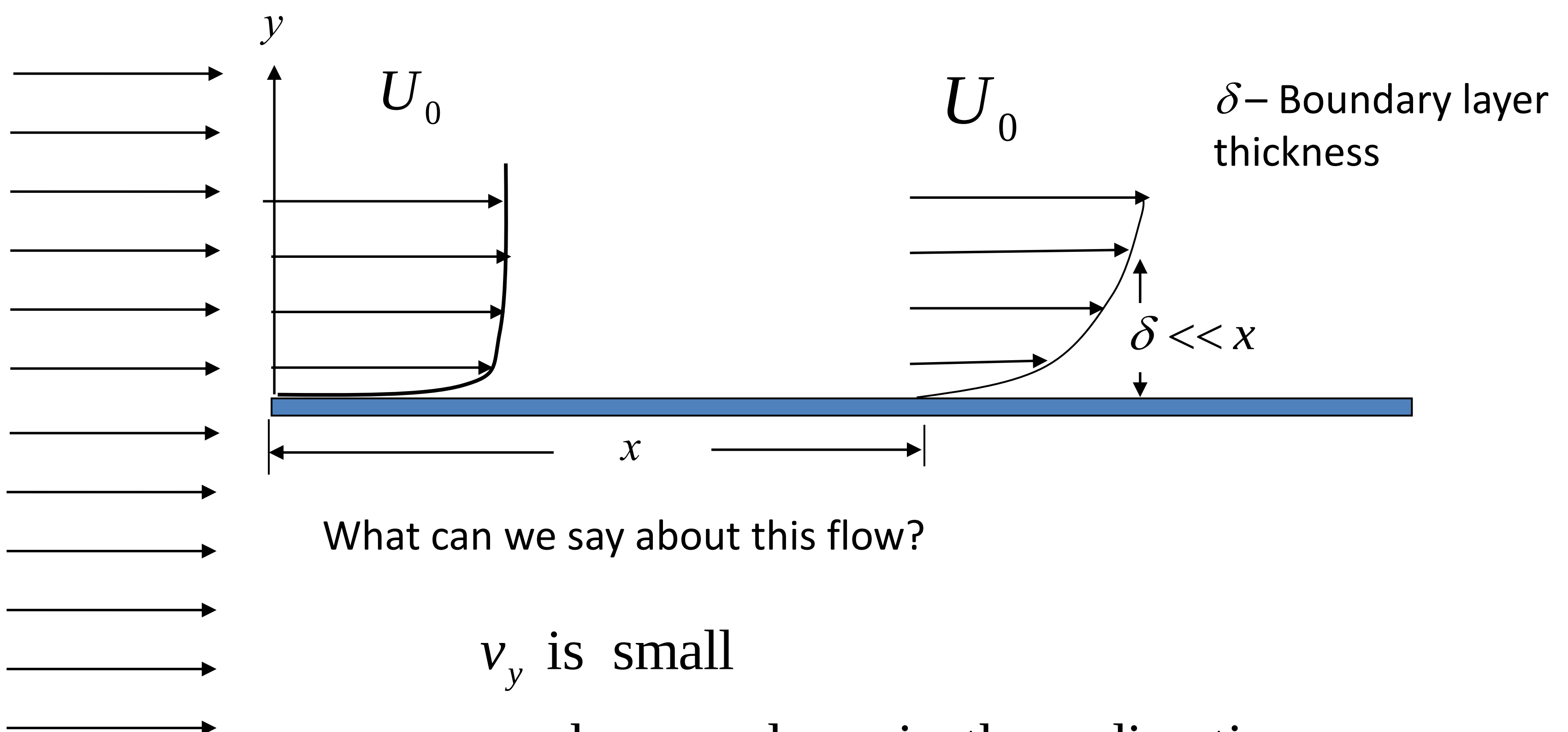
- An originally laminar flow is affected by the presence of the walls.
- Flow over flat plate is visualized by introducing bubbles that follow the local fluid velocity.
- Most of the flow is unaffected by the presence of the plate.
- However, in the region closest to the wall, the velocity decreases to zero.
- The flow away from the walls can be treated as inviscid, and can sometimes be approximated as potential flow.
- The region near the wall where the viscous forces are of the same order as the inertial forces is termed the boundary layer.
- The distance over which the viscous forces have an effect is termed the boundary layer thickness.
- The thickness is a function of the ratio between the inertial forces and the viscous forces, i.e. the Reynolds number. As Re increases, the thickness decreases.

Effect of viscosity

- The layers closer to the wall start moving right away due to the no-slip boundary condition. The layers farther away from the wall start moving later.
- The distance from the wall that is affected by the motion is also called the viscous diffusion length. This distance increases as time goes on.
- The experiment shown on the left is performed with a higher viscosity fluid (100 mPa.s). On the right, a lower viscosity fluid (10 mPa.s) is shown.



Flow Over a Flat Plate



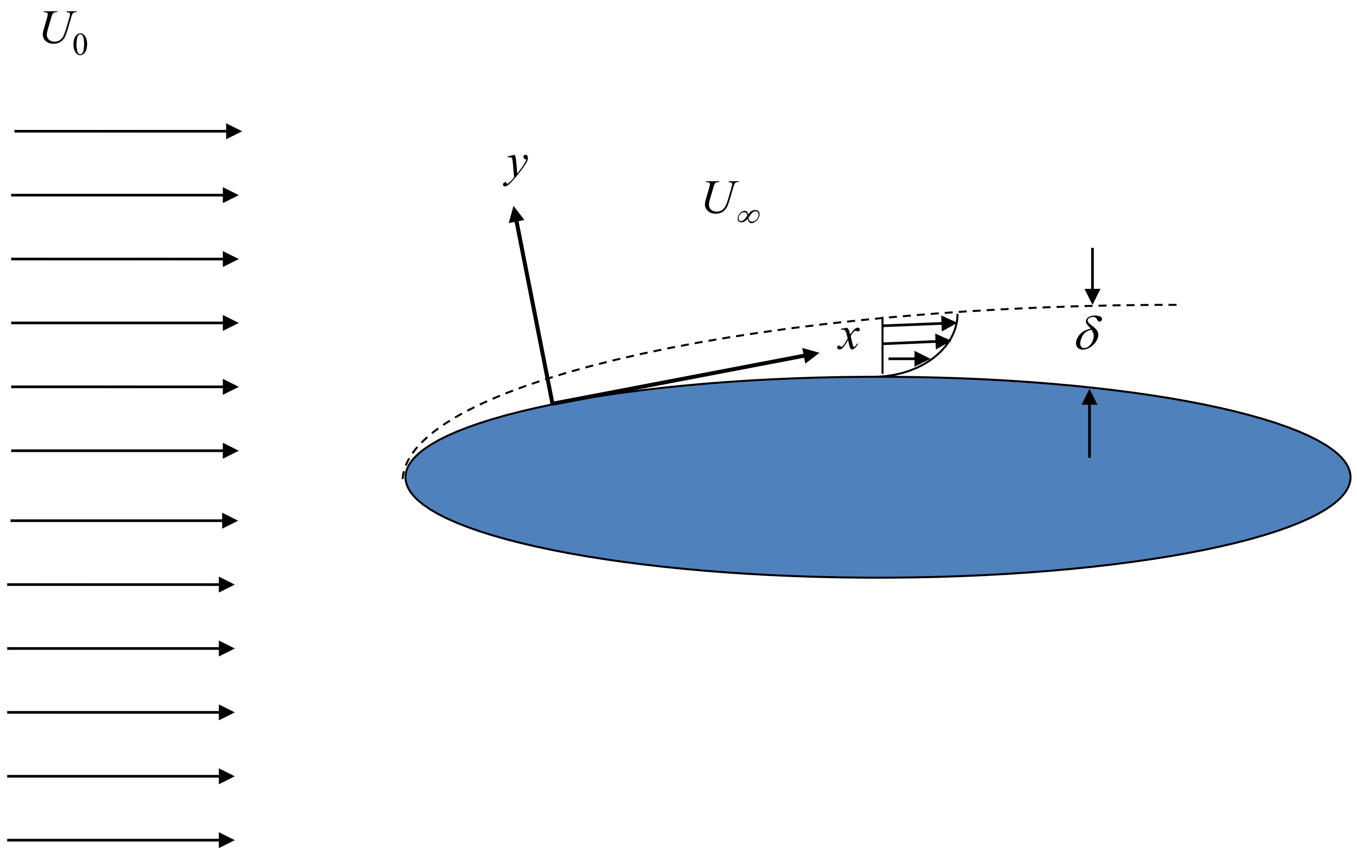
What can we say about this flow?

v_y is small

v_x changes slowy in the x direction

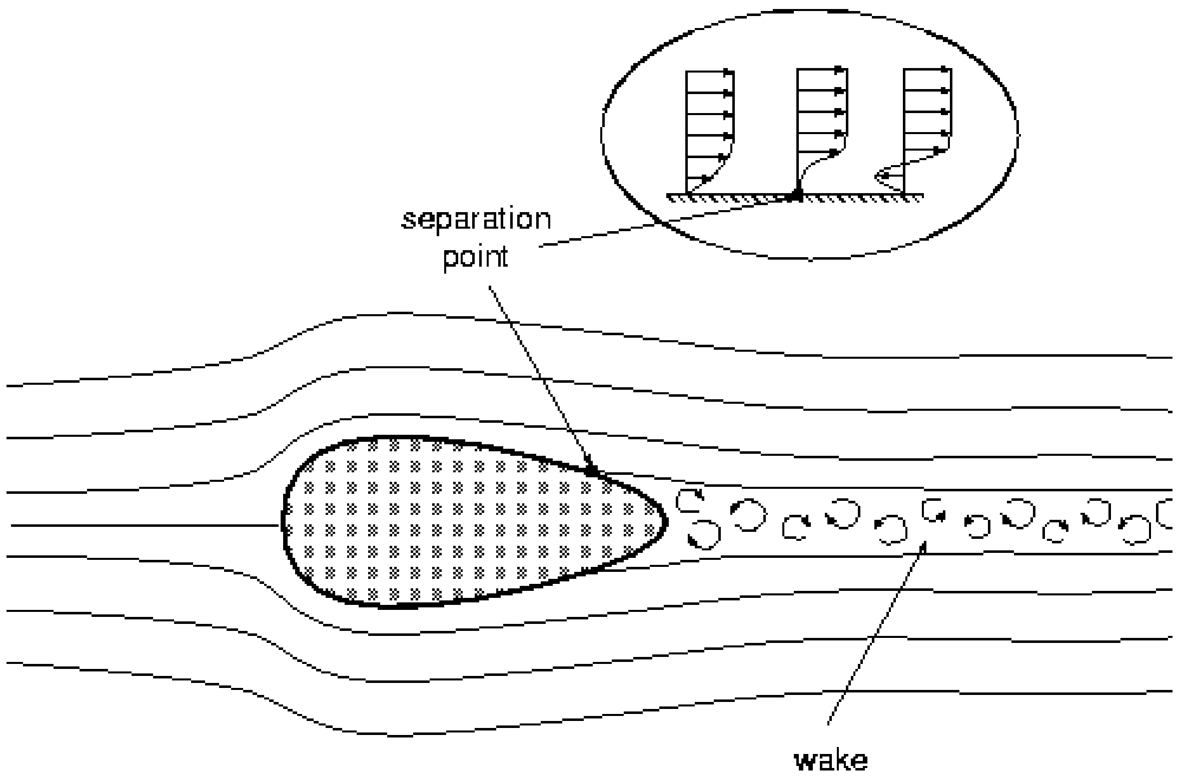
v_x changes rapidly in the y direction

Flow Over a Body



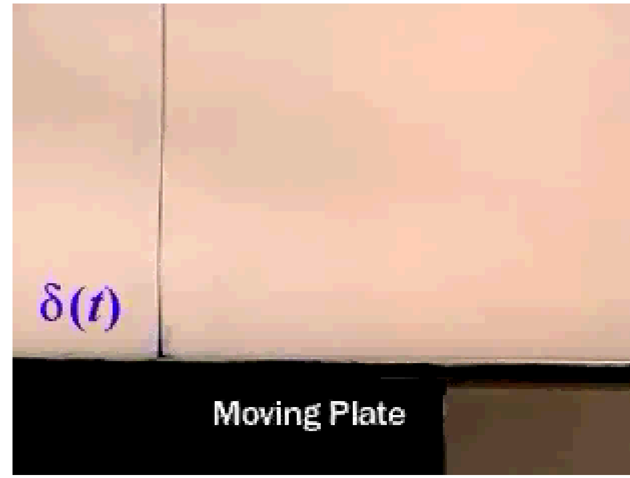
Flow separation

- Flow separation occurs when:
  - the velocity at the wall is zero or negative and an inflection point exists in the velocity profile,
  - and a positive or adverse pressure gradient occurs in the direction of flow.



Moving plate boundary layer

- An impulsively started plate in a stagnant fluid.
- When the wall in contact with the still fluid suddenly starts to move, the layers of fluid close to the wall are dragged along while the layers farther away from the wall move with a lower velocity.
- The viscous layer develops as a result of the no-slip boundary condition at the wall.



Viscous boundary layer thickness

- Exact equations for the velocity profile in the viscous boundary layer were derived by Stokes in 1881.
- Start with the Navier-Stokes equation:

$$\frac{\partial u}{\partial t} = \nu \frac{\partial^2 u}{\partial y^2}$$

- Derive exact solution for the velocity profile:

$$U = U_0\left(1 - erf\left(\frac{y}{2\sqrt{\nu t}}\right)\right)$$

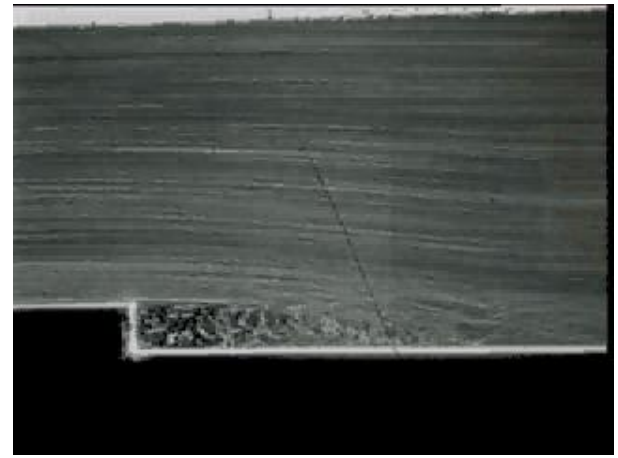
$$erf(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} dt$$

- erf is the error function:
- The boundary layer thickness can be approximated by:

$$\frac{\partial u}{\partial t} = \nu \frac{\partial^2 u}{\partial y^2} \Rightarrow \frac{U_0}{t} \approx \nu \frac{U_0}{\delta^2} \Rightarrow \delta \approx \sqrt{\nu t}$$

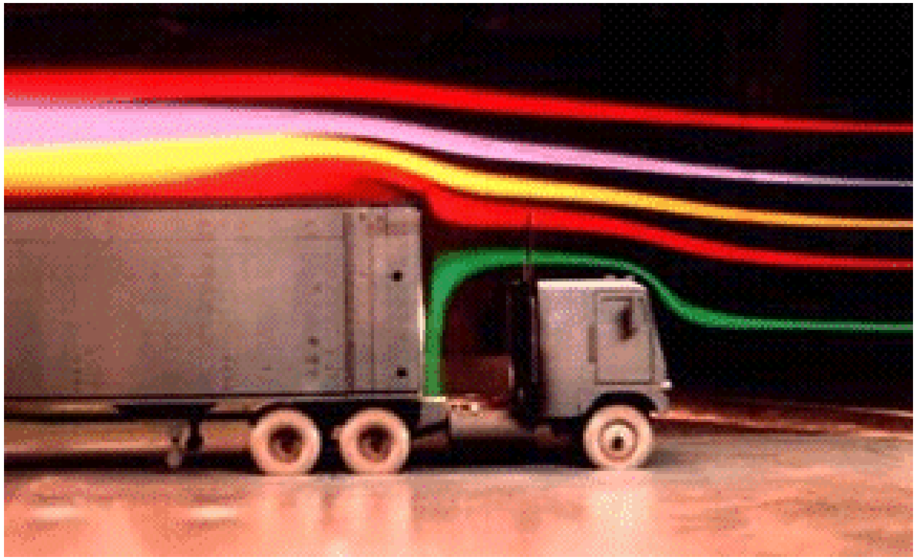
Separation at sharp corners

- 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.

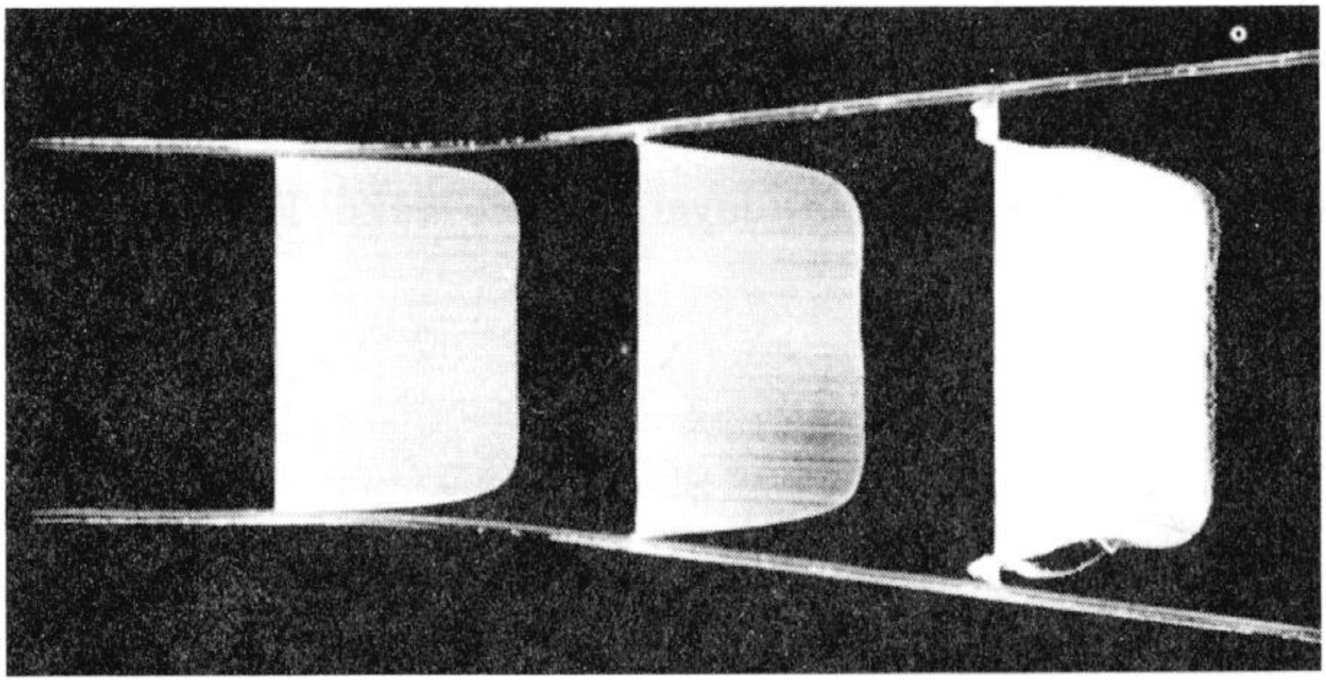


Flow around a truck

- 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%.

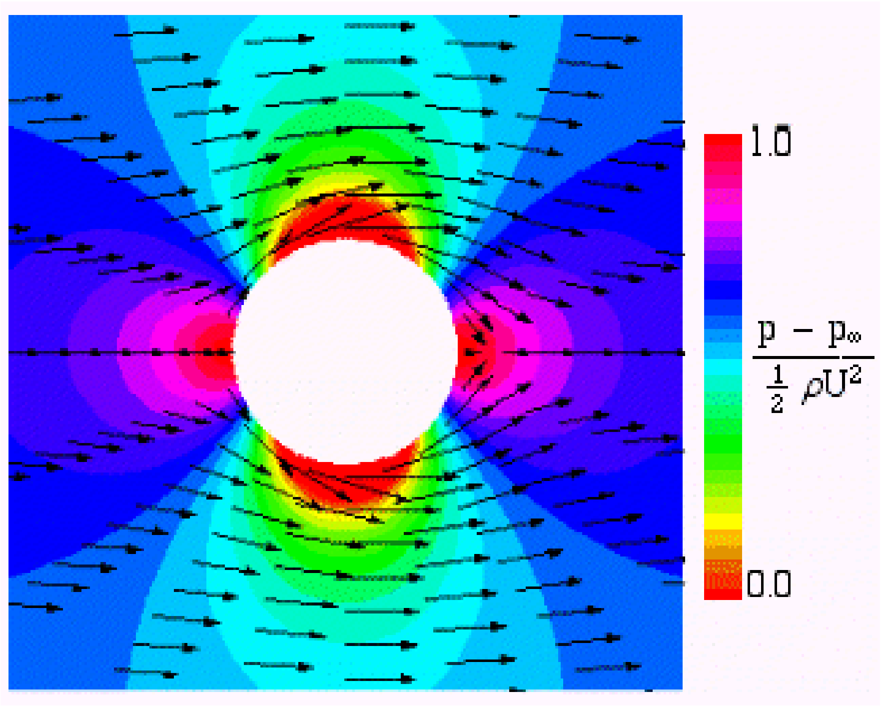


Flow separation in a diffuser with a large angle



Inviscid flow around a cylinder

- The origins of the flow separation from a surface are associated with the pressure gradients impressed on the boundary layer by the external flow.
- The image shows the predictions of inviscid, irrotational flow around a cylinder, with the arrows representing velocity and the color map representing pressure.
- The flow decelerates and stagnates upstream of the cylinder (high pressure zone).
- It then accelerates to the top of the cylinder (lowest pressure).

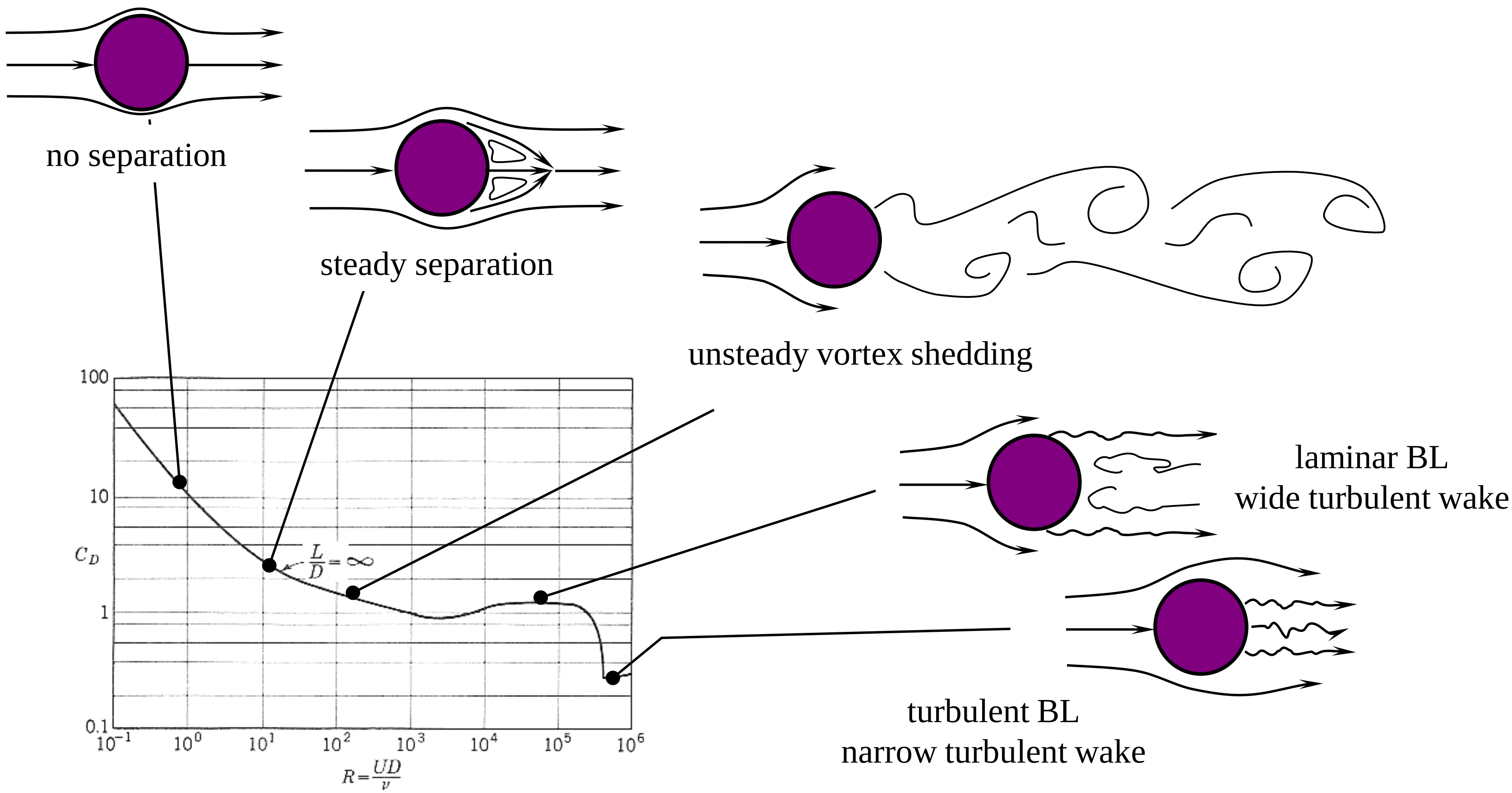


- Next it must decelerate against a high pressure at the rear stagnation point.

Drag on a smooth circular cylinder

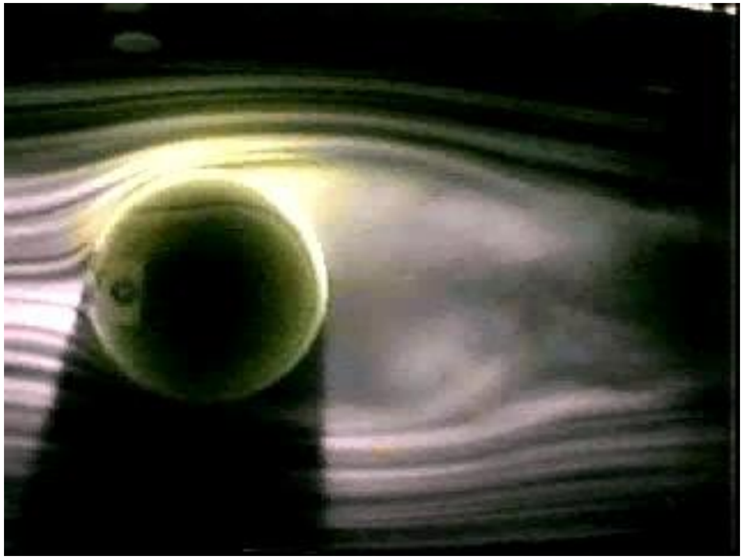
$$F_{drag} = C_D \, \tfrac{1}{2} \rho v^2 A_{\perp}$$

- The drag coefficient is defined as follows:



Separation - adverse pressure gradients

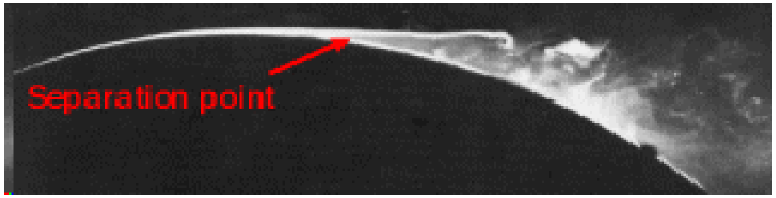
- Separation of the boundary layers occurs whenever the flow tries to decelerate quickly, that is whenever the outer pressure gradient is negative, or the pressure gradient is positive, sometimes referred to as an adverse pressure gradient.
- In the case of the tennis ball, the flow initially decelerates on the upstream side of the ball, while the local pressure increases in accord with Bernoulli's equation.
- Near the top of the ball the local external pressure decreases and the flow should accelerate as the potential energy of the pressure field is converted to kinetic energy.



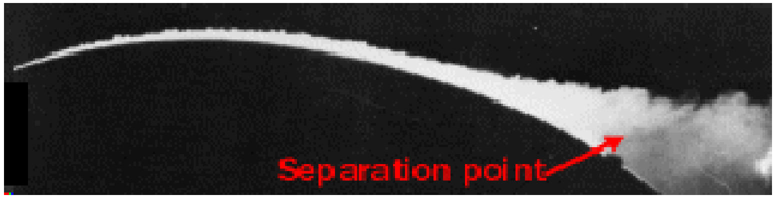
- However, because of viscous losses, not all kinetic energy is recovered and the flow reverses around the separation point.

Turbulent boundary layer

- Increased momentum transport due to turbulence from the free stream flow to the flow near the wall makes turbulent boundary layers more resistant to flow separation.
- The photographs depict the flow over a strongly curved surface, where there exists a strong adverse (positive) pressure gradient.
- The boundary layer has a high momentum deficit.
- In the case where the boundary layer is laminar, insufficient momentum exchange takes, the flow is unable to adjust to the increasing pressure and separates from the surface.
- In case where the flow is turbulent, the increased transport of momentum (due to the Reynolds stresses) from the free-stream to the wall increases the streamwise momentum in the boundary layer. This allows the flow to overcome the adverse pressure gradient. It eventually does separate nevertheless, but much further downstream.



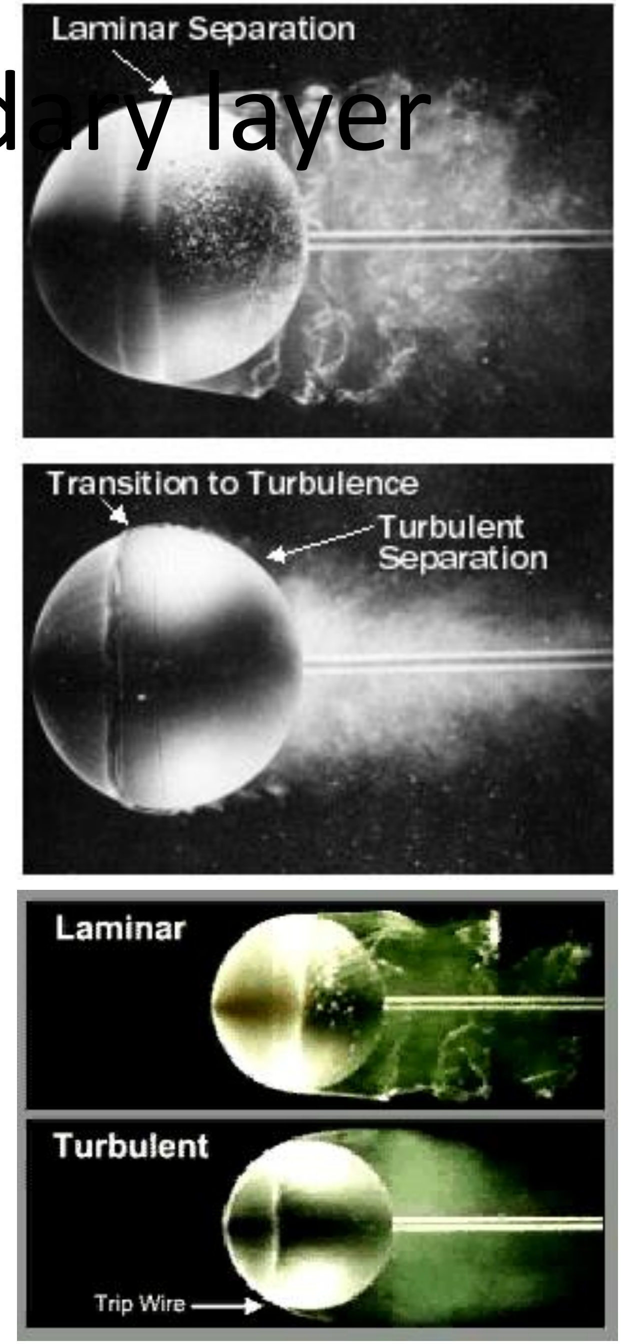
Laminar Separation



Turbulent Separation

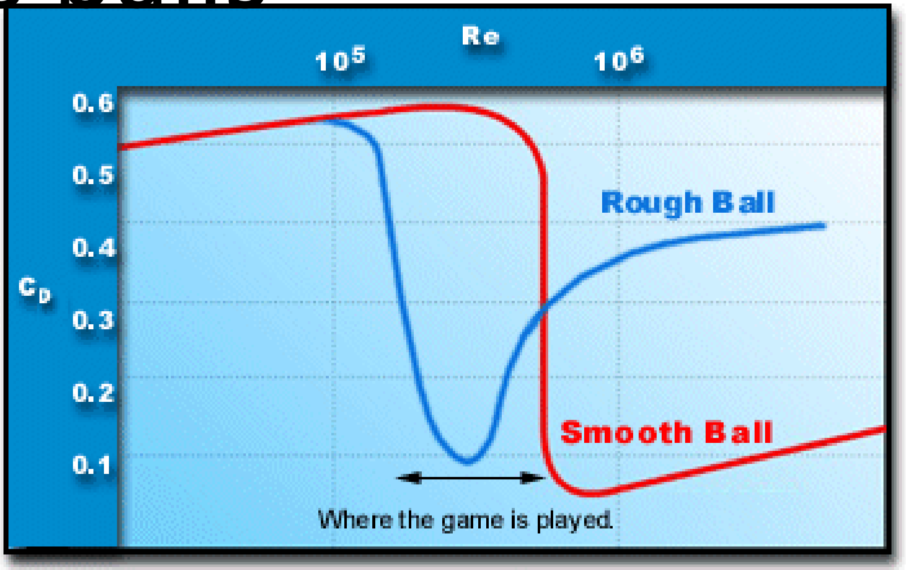
Tripping the boundary layer

- Here we see how the addition of a trip wire to induce transition to turbulence changes the separation line further to the rear of the sphere, reducing the size of the wake and thus drastically diminishing overall drag.
- This well-known fact can be taken advantage of in a number of applications, such as dimples in golf balls and turbulence generation devices on airfoils.



Sports balls

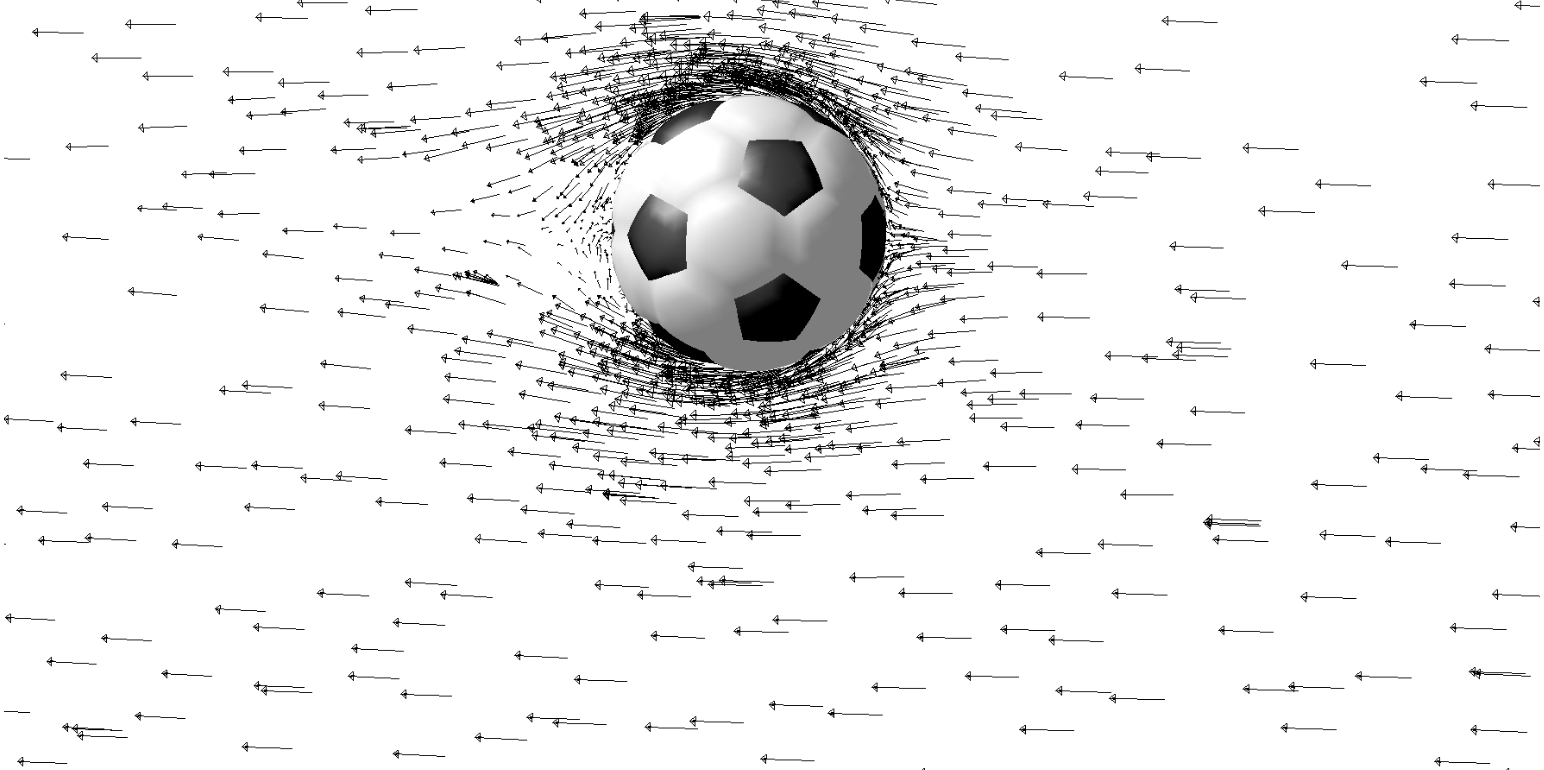
- Many games involve balls designed to use drag reduction brought about by surface roughness.
- Many sports balls have some type of surface roughness, such as the seams on baseballs or cricket balls and the fuzz on tennis balls.
- It is the Reynolds number (not the speed, per se) that determines whether the boundary layer is laminar or turbulent. Thus, the larger the ball, the lower the speed at which a rough surface can be of help in reducing the drag.



- Typically sports ball games that use surface roughness to promote an early transition of the boundary layer from a laminar to a turbulent flow are played over a Reynolds number range that is near the “trough” of the Cd versus Re curve, where drag is lowest.

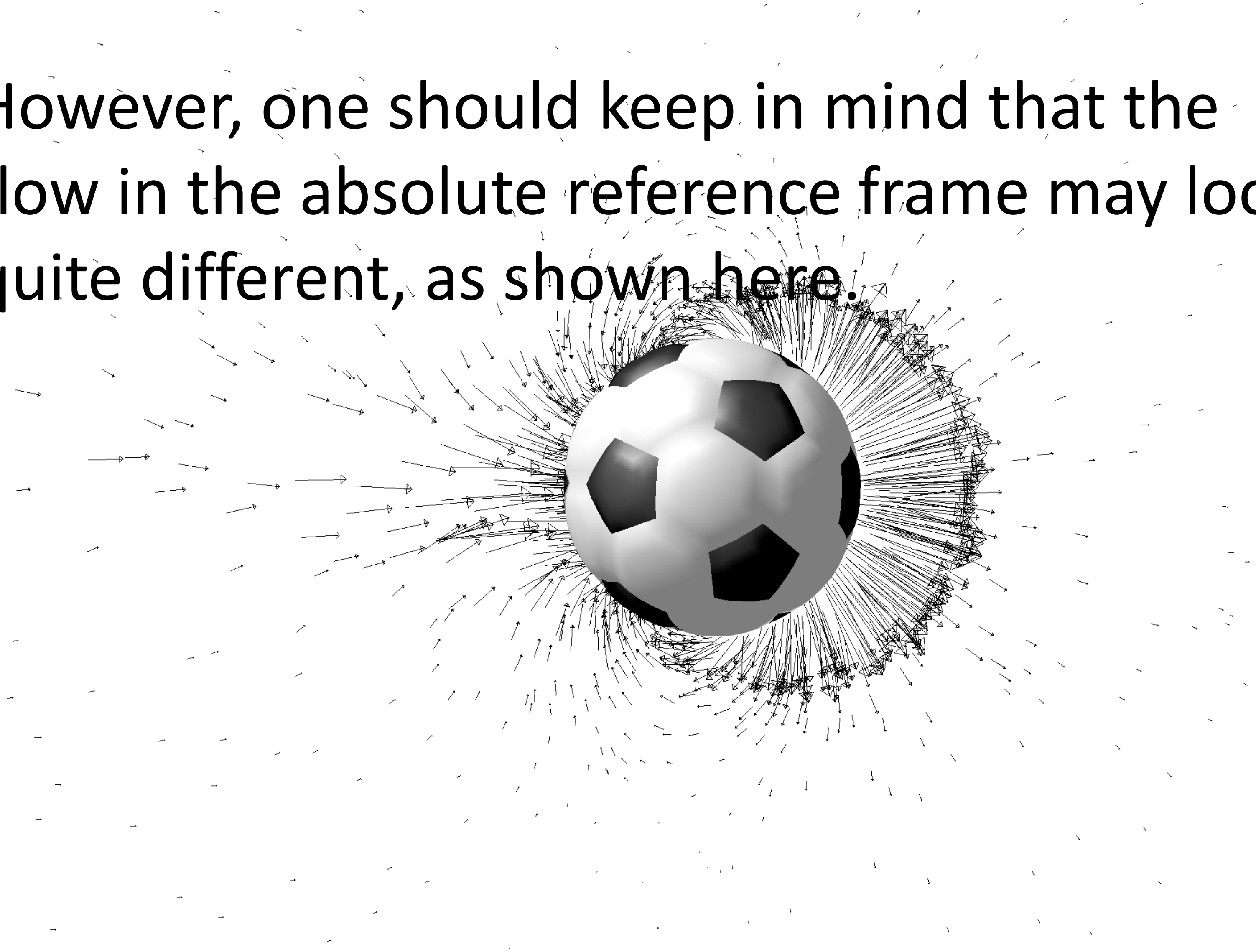
Flow in reference frame relative to the ball

- Note that we have been showing flow fields in the reference frame of the object, similar to the flow around the soccer ball shown here.



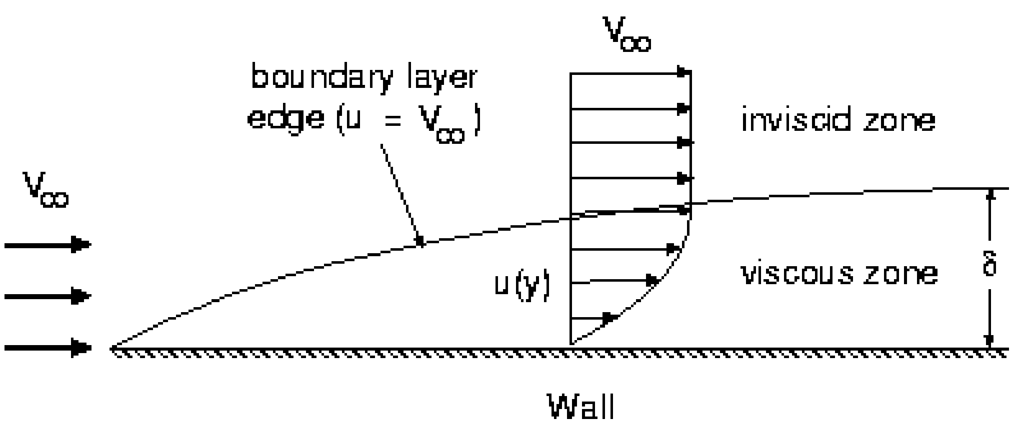
Flow in absolute reference frame

- However, one should keep in mind that the flow in the absolute reference frame may look quite different, as shown here.



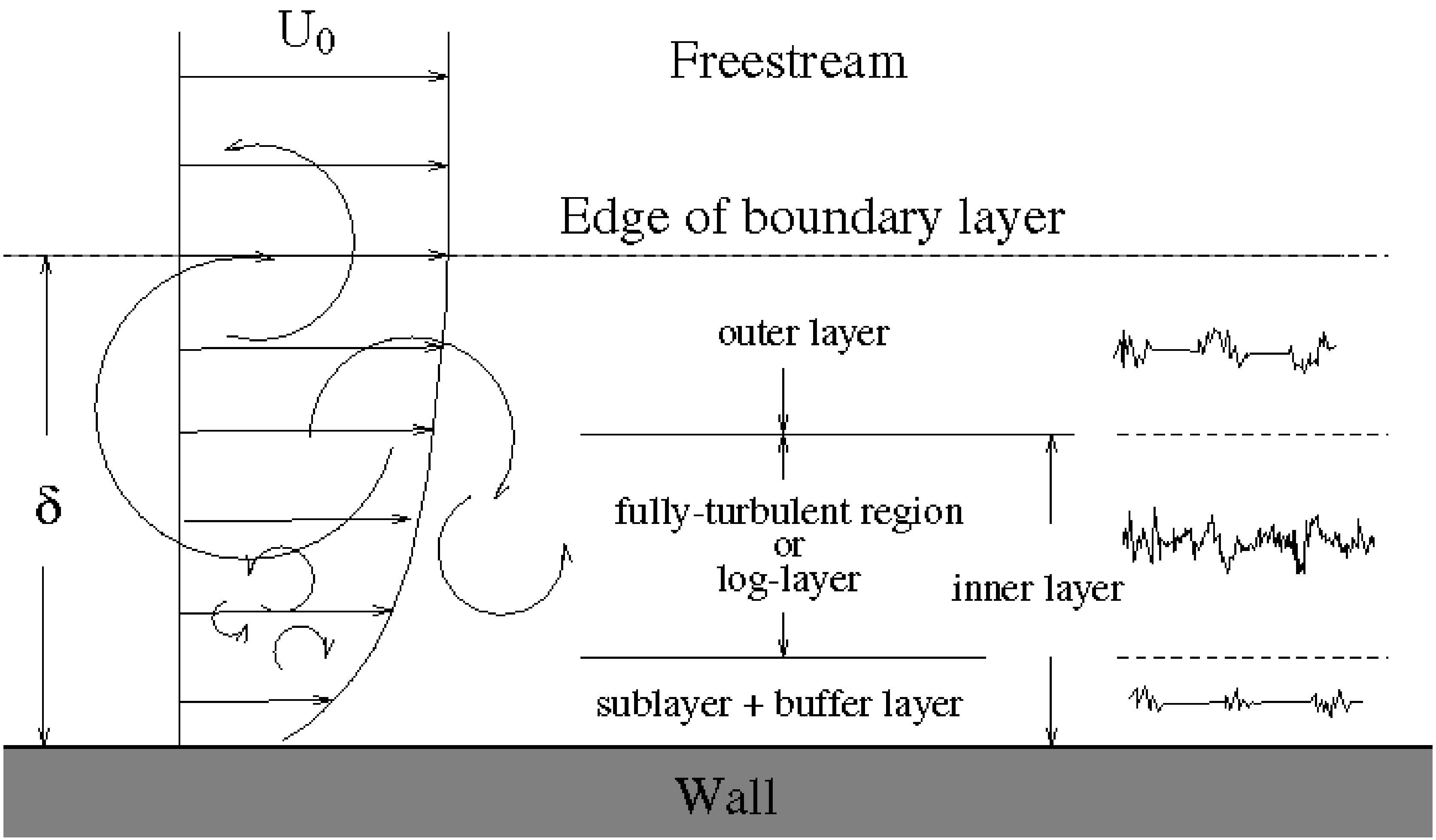
The turbulent boundary layer

- In turbulent flow, the boundary layer is defined as the thin region on the surface of a body in which viscous effects are important.
- The boundary layer allows the fluid to transition from the free stream velocity U_τ to a velocity of zero at the wall.
- The velocity component normal to the surface is much smaller than the velocity parallel to the surface: v << u.
- The gradients of the flow across the layer are much greater than the gradients in the flow direction.
- The boundary layer thickness δ is defined as the distance away from the surface where the velocity reaches 99% of the free-stream velocity.



$$\delta = y, \text{ where } u/U = 0.99$$

The turbulent boundary layer



Thank you !