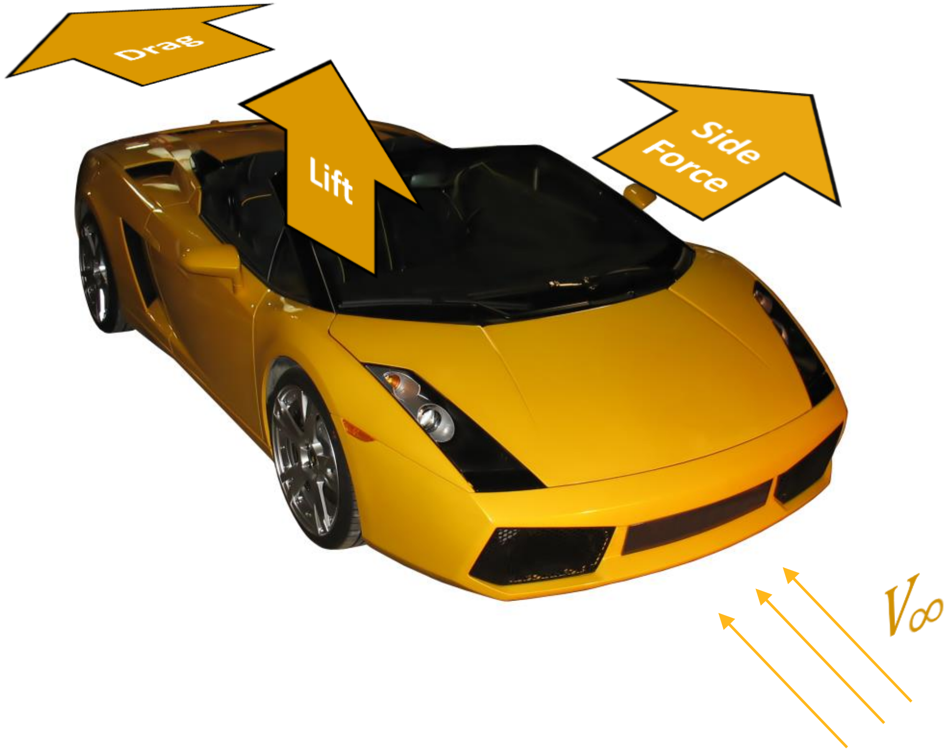
Drag Forces in External Flows

Real External Flows – Lesson 2

Forces in External Flows

- We briefly discussed forces acting on immersed bodies.
- As an object is moving in a fluid (or the fluid flows over an object), it is subjected to forces arising from the interaction of the flow and the object.
- Locally, the fluid flow exerts stresses on the object: tangential wall shear stress τ_w due to viscosity and normal stresses due to the pressure p. Once integrated over the entire surface, viscous and pressure contributions can be combined into the total force acting on the object, $\vec{F} = \vec{F}_p + \vec{F}_v$.
- This total force is typically described in terms of its drag and lift components:
  - The drag force F_{drag} (or simply drag) acts in the direction of the upstream velocity.
  - The lift force F_{lift} (or simply lift) acts normal to the flow direction.
- In 3D flows, there could also be a side force F_{side} component acting in the direction normal to lift – drag plane.
- In general, drag, lift and side force have contributions from pressure and viscous stresses, but these contributions are different for each component.

Forces in External Flows (cont.)



Lift coefficient

$$F_{lift} = C_L A \frac{\rho V_\infty^2}{2}$$

Drag coefficient

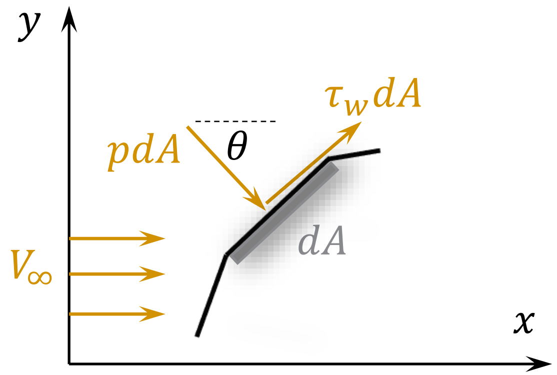
$$F_{drag} = C_D A \frac{\rho V_\infty^2}{2}$$

Forces in External Flows (cont.)

- Let's consider pressure and viscous stresses acting on a small element of a moving object. Drag and lift forces acting on this element are given by:

$$dF_{drag} = \mathrm{p}\cos\theta dA + \tau_w \sin\theta \, dA$$

$$dF_{lift} = -\mathrm{p}\sin\theta dA + \tau_w \cos\theta \, dA$$



- Total drag and lift integrated over the surface are:

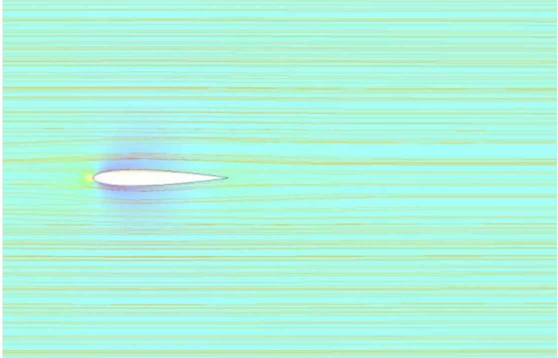
$$F_{drag} = \iint \mathrm{p}\cos\theta dA + \iint \tau_w \sin\theta \, dA$$

$$F_{lift} = -\iint \mathrm{p}\sin\theta dA + \iint \tau_w \cos\theta \, dA$$

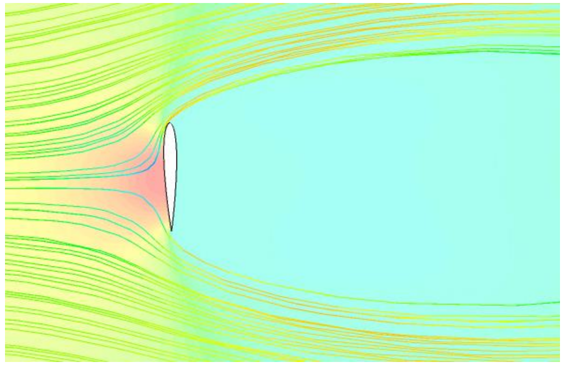
- While carrying out integration requires knowledge of pressure and shear stress distributions and the body shape, these expressions show that in general lift and drag on an external body comprise pressure and shear stress contributions.

Drag

- For the rest of this lesson, we will focus on discussing the drag component of the fluid force.
- Drag is influenced by the shape of the object, the Reynolds number, surface roughness and other parameters such as the Mach and Froude numbers.
- The drag acts in the direction parallel to the free-stream fluid motion.
- The tangential shear stresses acting on the object produce friction drag (or viscous drag). Friction drag is dominant in flows past thin streamline bodies like airfoils or wings
- Pressure drag results from the normal stress exerted by the pressure forces, and it becomes dominant in flows past bluff bodies. It is often called form drag because of its strong dependency on the shape of the body.
- Drag is always non-zero in real viscous flows.



Airfoil at 0 deg AOA



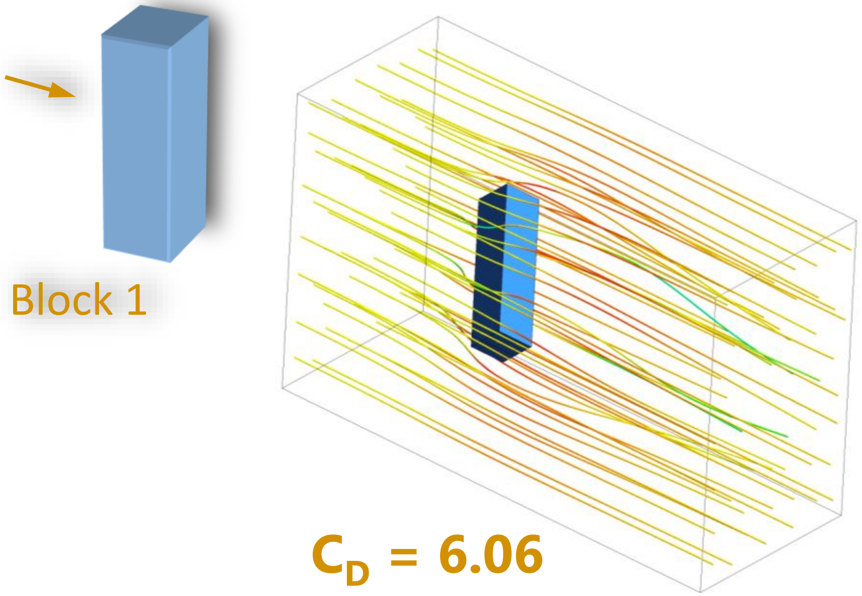
Airfoil at 90 deg AOA

Importance of Drag

- Drag in fluid flows can be either a hindrance or a benefit depending on specific needs of fluids applications.
- Overcoming aerodynamic drag by flying aircraft or moving automobiles comes at a cost of fuel/ energy consumption, and minimizing drag is a major focus in aerodynamics applications.
  - Aircraft drag is normally measured in drag counts, where one drag count is equal to 1e-04 of the drag coefficient.
  - A drag count between 200 and 400 is typical for a commercial airliner in cruise flight.
  - A decrease in drag force by only one drag count will enable the airplane to use 3% to 4% less fuel to fly the same distance, which adds up to significant savings in fuel costs during the lifespan of the aircraft.
- On the other hand, a sailboat cannot sail without wind exerting drag on its sails, and a parachute will not work without creating drag upon its descent.

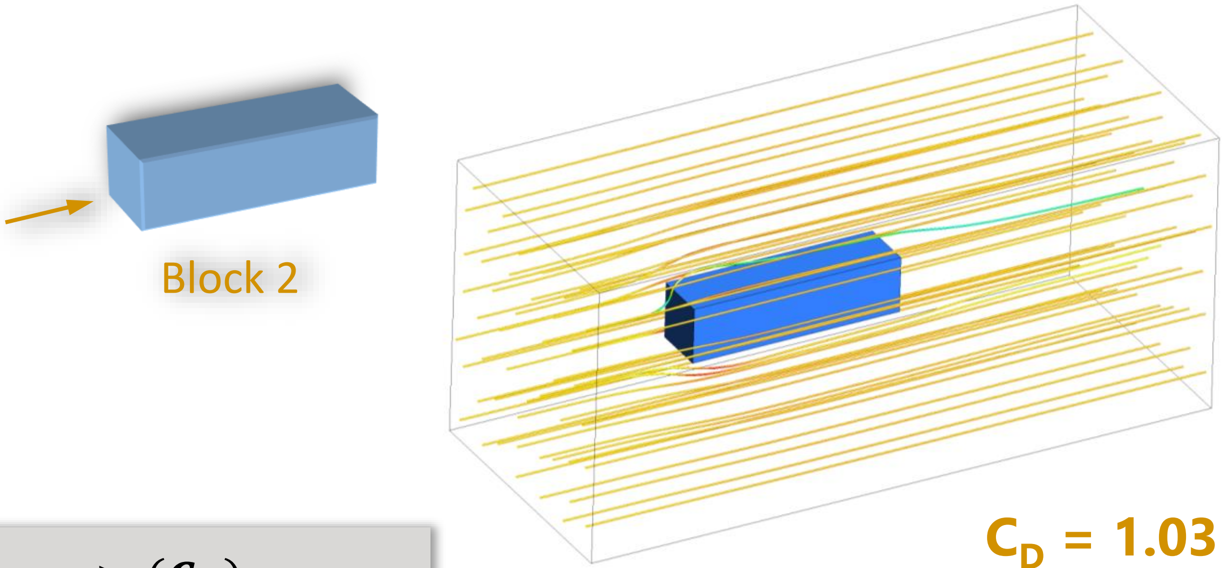
Influence of Object Shape on Drag

- The less streamlined the object the greater the influence of pressure drag. Pressure drag is increased by flow separation which occurs with an adverse pressure gradient in the direction of flow.
- The pressure drag can be reduced over the object by making a gradual taper toward the rear portion of the object. The increased length also increases the skin friction. Design is a compromise between friction drag and pressure drag.



Block 1

$C_D = 6.06$



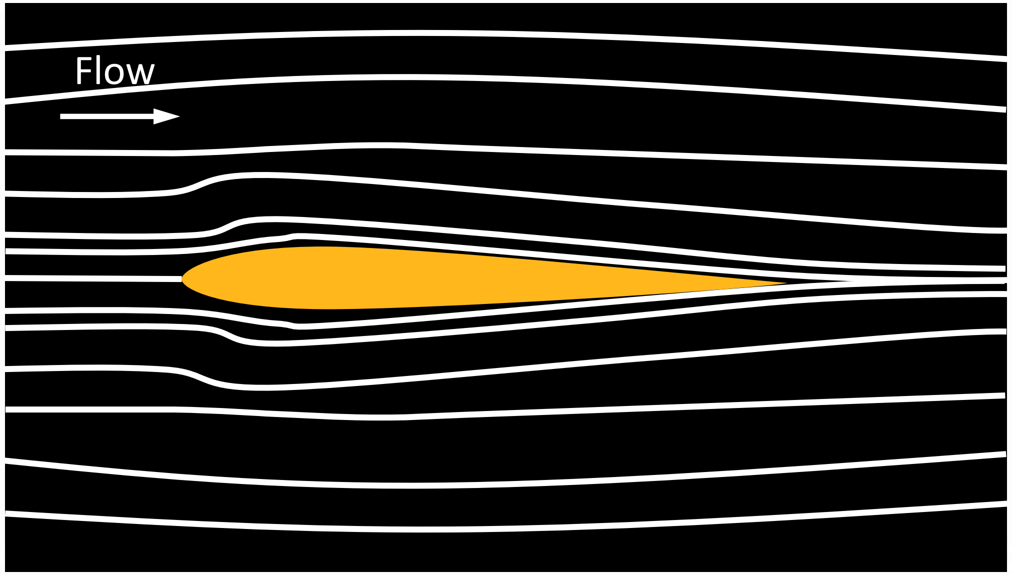
Block 2

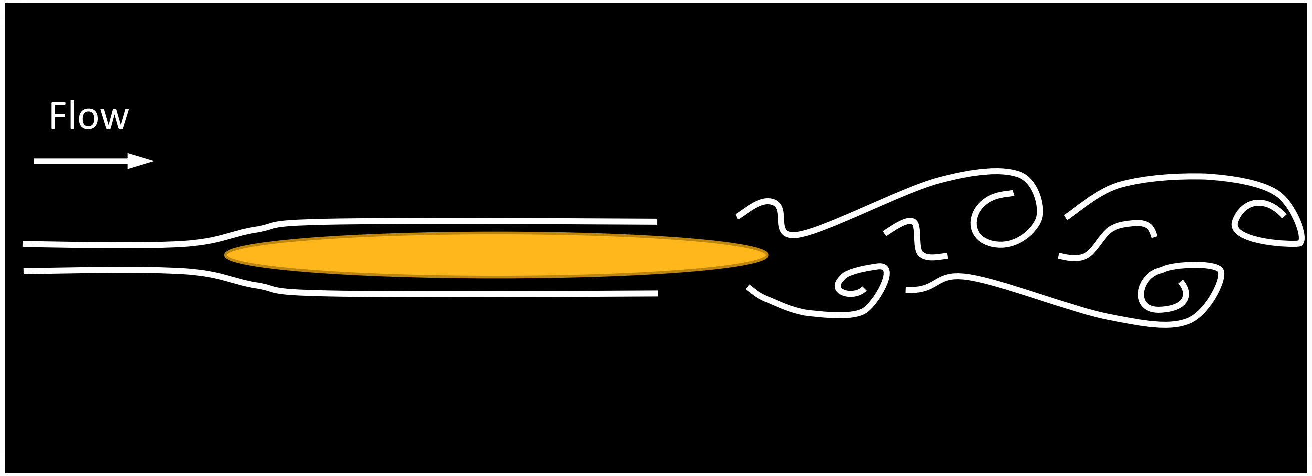
$C_D = 1.03$

$$(C_D)_{Block1} > (C_D)_{Block2}$$

Drag – Effect of Streamlined Shape

- The more abrupt tail of the thin ellipse on the right creates an adverse pressure gradient resulting in flow separation. The separation also allows for some of the kinetic energy contained in the fluid to be dissipated by viscous effects.

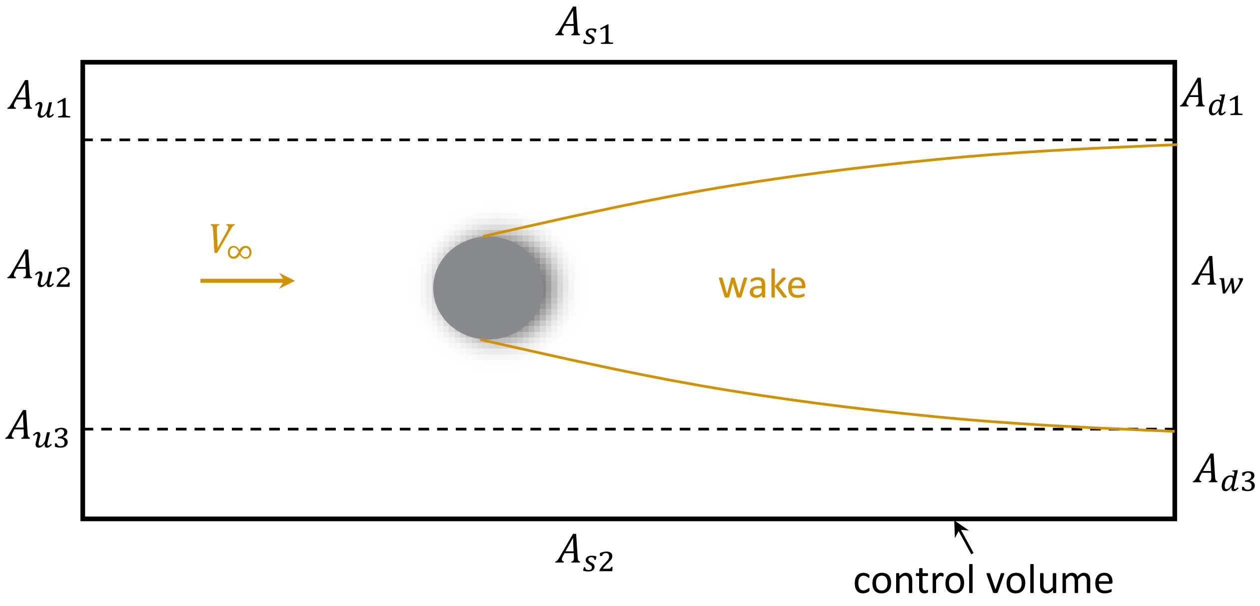




Wake Effect on Drag

- The example on the previous slide leads to an interesting observation that wakes behind bodies increase overall drag. This effect can be illustrated by our favorite control volume integral analysis of conservation equations.

- Consider a control volume in a flow over an object. All boundaries of the volume are far enough from the body so pressure and density on those boundaries are equal to freestream values.
- Velocities on upstream and downstream boundaries of the control volume except A_w are assumed to be equal to V_∞. Integrating conservation of mass and momentum equations gives:



$$\int_{A_w} \rho (V_\infty - u) dA = \int_{A_{s1}+A_{s2}} \rho u_n dA$$

continuity

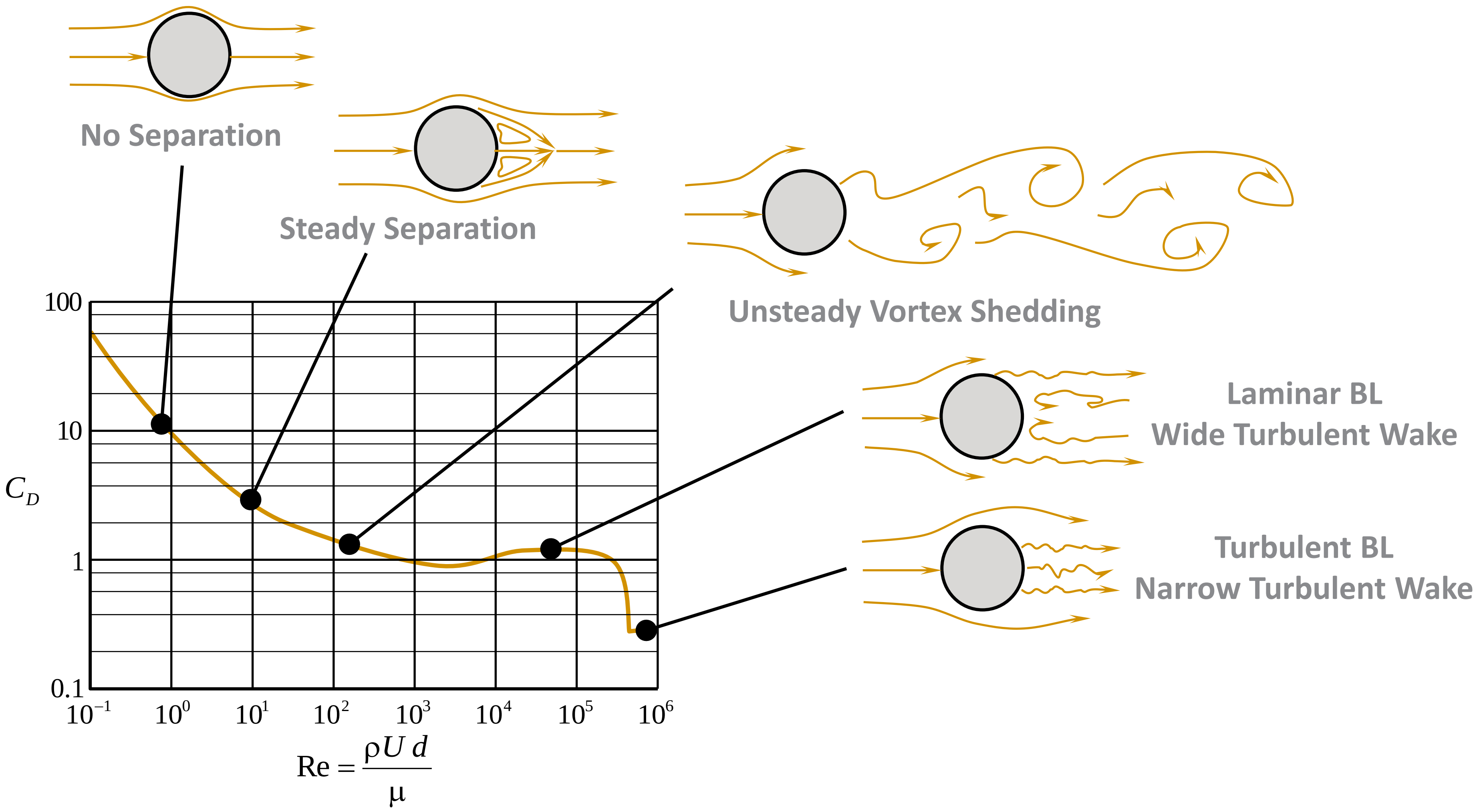
$$F = \int_{A_w} \rho (u^2 - V_\infty^2) dA + V_\infty \int_{A_{s1}+A_{s2}} \rho u_n dA$$

momentum

$$\Longrightarrow \quad F_{drag} = \int_{A_w} \underbrace{\rho u (V_\infty - u)}_{\text{velocity defect in wake}} dA$$

$F_{drag} = 0$ if there is no wake ($u = V_\infty$)

Drag – Effect of Reynolds Number



$$\mathrm{Re} = \frac{\rho U d}{\mu}$$

No Separation

Steady Separation

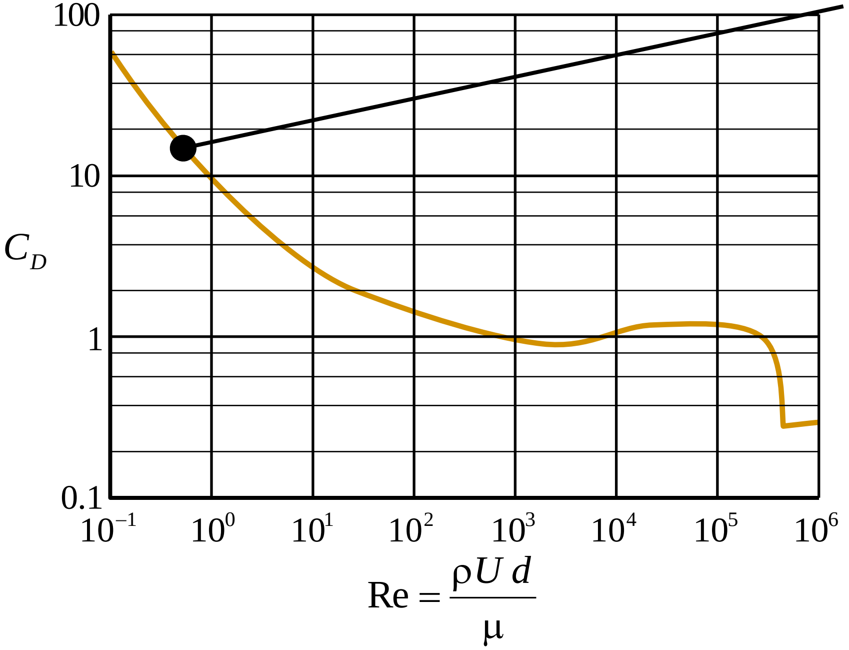
Unsteady Vortex Shedding

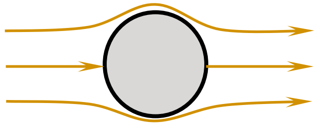
Laminar BL
Wide Turbulent Wake

Turbulent BL
Narrow Turbulent Wake

Drag – Effect of Reynolds Number (cont.)

- At low Reynolds numbers ($Re < 1$), the inertia effects are small relative to the viscous and pressure forces. In this flow regime the drag coefficient varies inversely with the Reynolds number. For example, the drag coefficient C_D for a sphere is equal to $24/Re$.

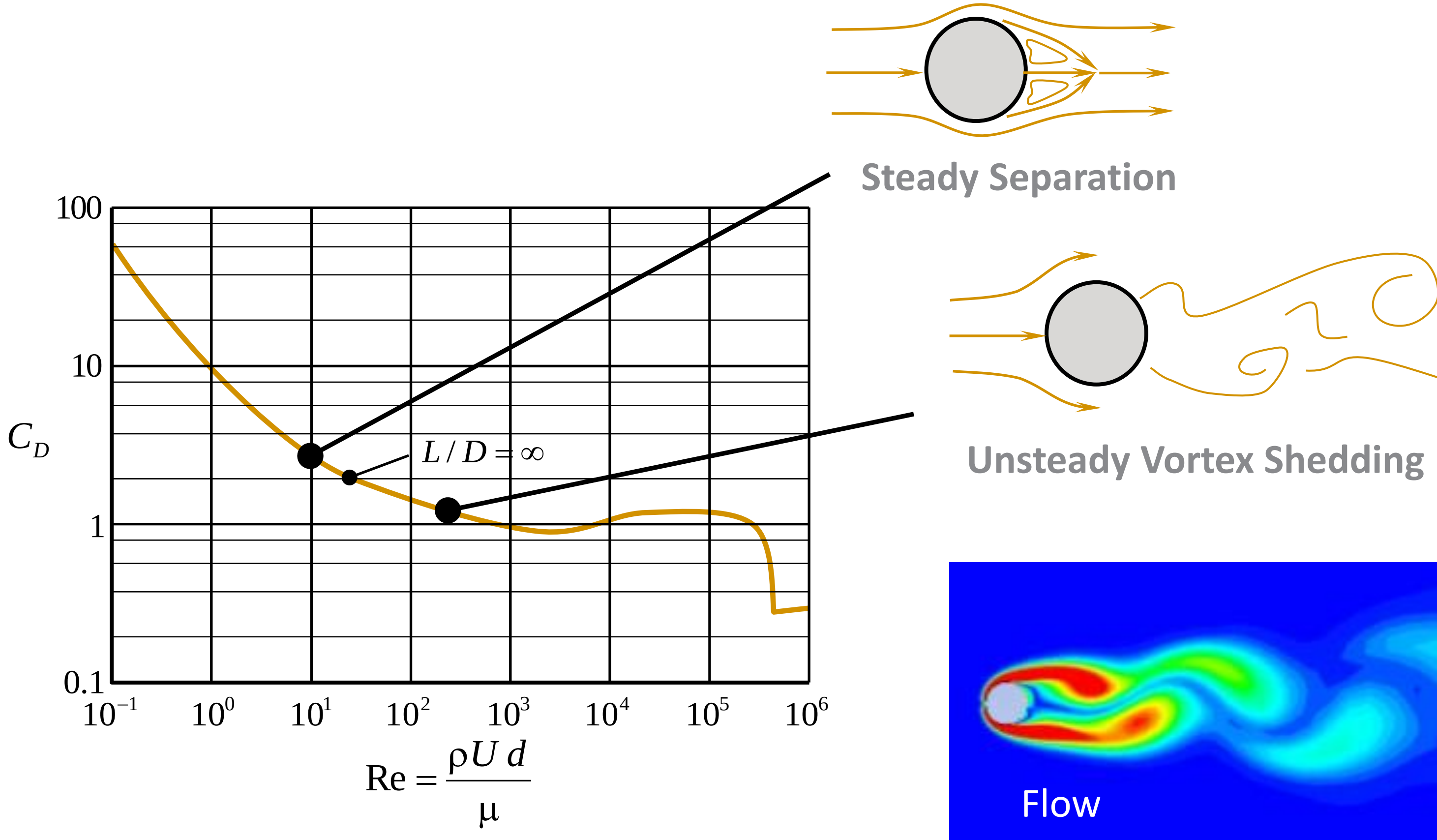




No Separation

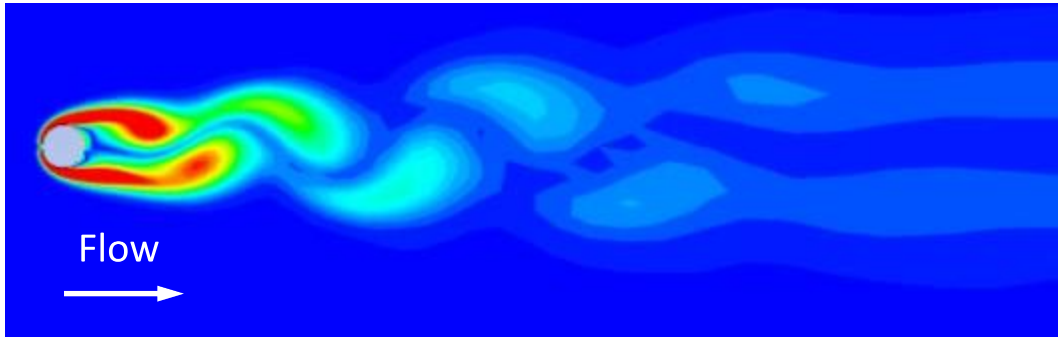
Drag – Effect of Reynolds Number (cont.)

- At moderate Reynolds numbers ($1 < Re < 103$), the flow begins to separate in a periodic fashion in the form of Karman vortices.



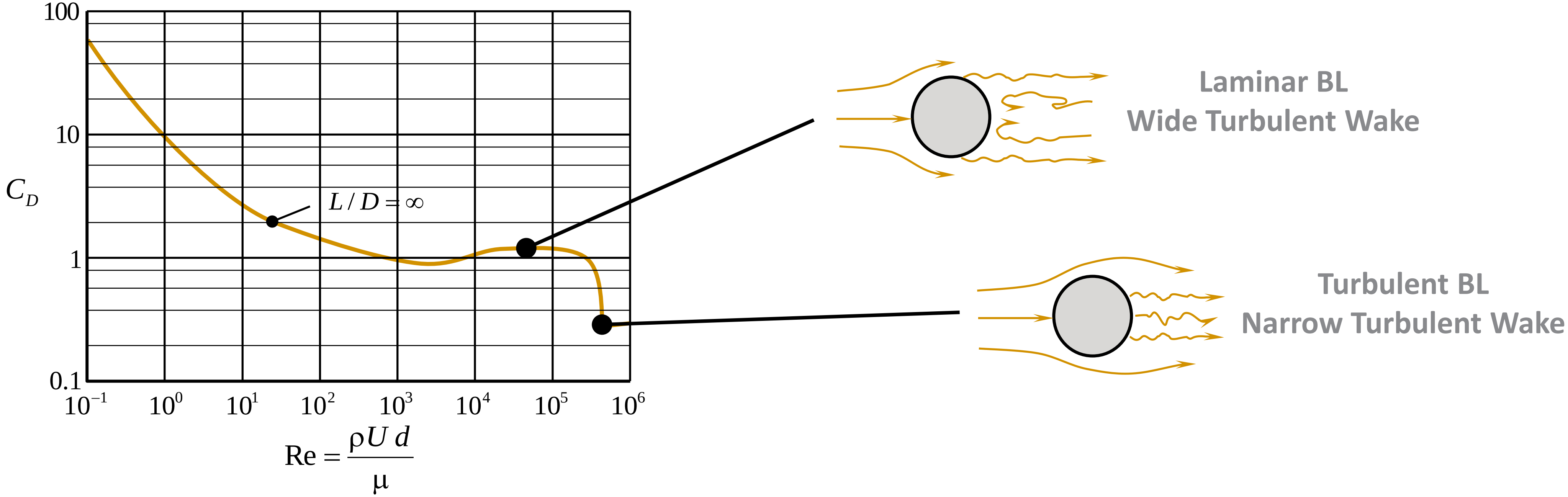
Steady Separation

Unsteady Vortex Shedding



Drag – Effect of Reynolds Number (cont.)

- At higher Reynolds numbers (103 < Re < 10^5), the flow becomes fully separated. An adverse pressure gradient exists over the rear portion of the cylinder, resulting in a rapid growth of the laminar boundary and separation.
- As the Reynolds number increases, the boundary layer becomes turbulent, delaying separation and resulting in a sudden decrease in the drag coefficient. This effect is called drag crisis.



Drag – Other Effects

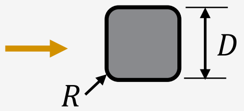
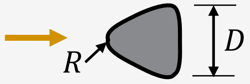
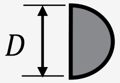
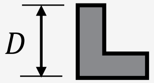
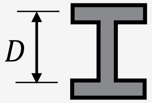
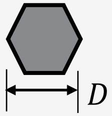
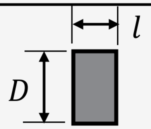
- Streamlining
  - For streamlined objects, the drag coefficient increases with Reynolds number after the boundary layer becomes turbulent due to the increasingly dominant contribution to drag from shear forces on the object.

- Surface Roughness
  - Surface roughness affects the boundary layer by:
    - Increasing the turbulent shear stress
    - Reducing the distance to transition to a turbulent boundary layer
  - This causes an increase in drag in streamlined bodies (e.g., airplane wing) and a decrease in drag in blunt bodies (e.g., golf ball).

Drag Coefficients for Common Shapes

- Drag coefficients for most external flows depend primarily on the Reynolds Number.
- Drag coefficients are derived from experimental data, and therefore we must follow the Reynolds number definition for the data (e. g. definitions of characteristic length, L, and frontal area, A) when comparing analytical estimates or computational data.
- The table on the following slide presents drag coefficients for some common shapes. These can be used to estimate drag forces on the bodies shown.
- For more complex geometries, drag forces can be obtained using experiments or computational fluid dynamics simulations.

Drag Coefficients for Common Shapes (cont.)

Shape	C_D	Re range
 Square rod with rounded corners	R/D: 0.0 | 0.02 | 0.17 | 0.33 C_D: 2.2 | 2.0 | 1.2 | 1.0	$Re = 10^5$
 Rounded equilateral triangle	R/D: 0.0 | 0.02 | 0.08 | 0.25 C_D: 1.4 | 1.2 | 1.3 | 1.1	$Re = 10^5$
 Semicircular cylinder	→ 2.15 ← 1.15	$Re > 10^4$
 Angle	→ 1.98 ← 1.82	$Re > 10^4$
 I-beam	2.05	$Re > 10^4$
 Hexagon	1.0	$Re > 10^4$
 Rectangle	l/D: ≤ 0.1 | 0.5 | 0.65 | 1.0 C_D: 1.9 | 2.5 | 2.9 | 2.2	$Re = 10^5$

Summary

- We have covered the drag component of the fluid flow force acting on an object in an external flow.
- Various factors affecting drag, such as body shape, wake, Reynolds number and surface roughness were discussed.

Ansys