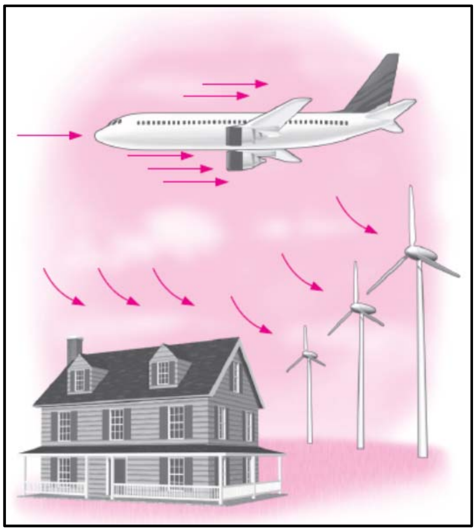
ESO204A, Fluid Mechanics and Rate Processes

Incompressible flows over immersed bodies (External Flow)

Chapter 7 of F M White
Chapter 9 of Fox McDonald

So far, in this course

- **Fluid statics**
- **Fluid Kinematics**
- **Integral Formulation**
- **Differential Formulation**
- **Internal (pipe and duct) Flow**
- **External Flow**

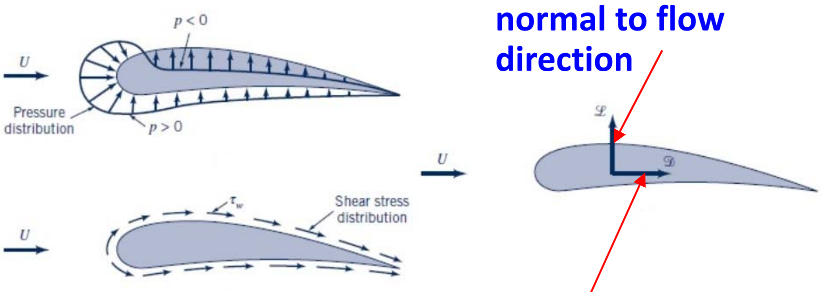


External flows are quite common in practice

Study of external flows led to the concept of **boundary layer,** one of the crucial developments in Fluid Mechanics

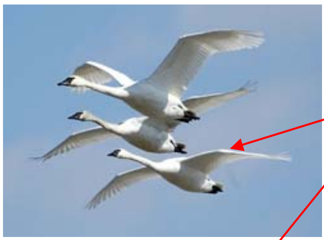
Drag and Lift

Lift: resultant Force normal to flow direction

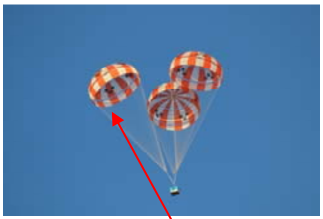


Drag: resultant force in flow direction

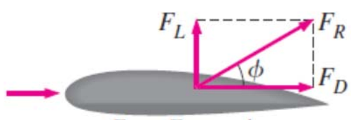
Flow direction: direction of the Free Stream (far away from the body)



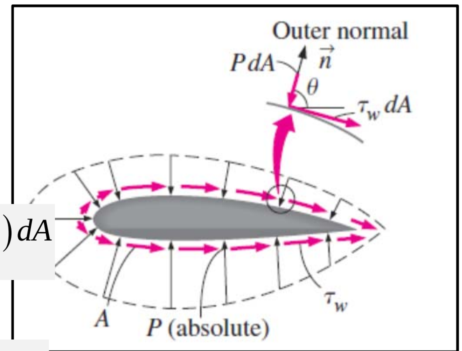
Drug reduction
(streamlined body or airfoil)



Drag enhancement
(bluff body)



$F_D = F_R \cos\phi$
$F_L = F_R \sin\phi$



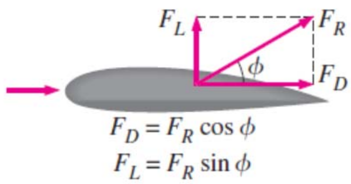
Drag: $F_D = \int_A \left(-p\cos\theta + \tau_w \sin\theta\right) dA$

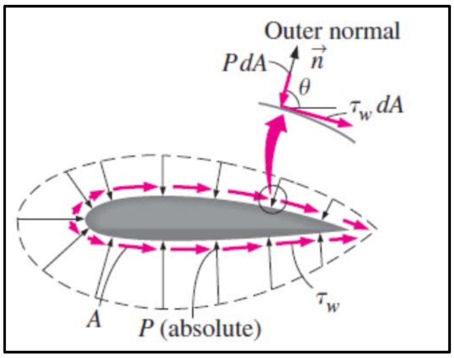
Lift: $F_L = -\int_A \left(p\sin\theta + \tau_w \cos\theta\right) dA$

Drag coefficient: $C_D = F_D \Big/ \left(\frac{1}{2}\rho u^2 A\right)$

Lift coefficient: $C_L = F_L \Big/ \left(\frac{1}{2}\rho u^2 A\right)$

Projected area against the force





Drag:

$$F_D = \int_A (-p\cos\theta + \tau_w \sin\theta)\,dA$$

Form (pressure) drag

Dominates at high Re, Geometry dependent

Viscous (friction) drag

Dominates at low Re

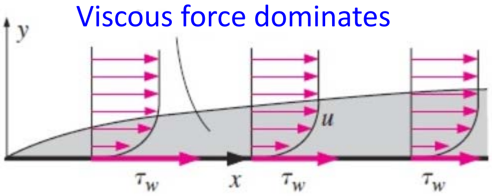
Drag: $$F_D = \int_A (\tau_w \sin\theta)\,dA + \int_A (-p\cos\theta)\,dA$$

Viscous (friction) drag **Form (pressure) drag**

$$\frac{F_D}{\frac{1}{2}\rho u^2 A} = \frac{\int_A (\tau_w \sin\theta)\,dA}{\frac{1}{2}\rho u^2 A} + \frac{\int_A (-p\cos\theta)\,dA}{\frac{1}{2}\rho u^2 A}$$

$$C_D = C_{D,\text{viscous}} + C_{D,\text{pressure}}$$

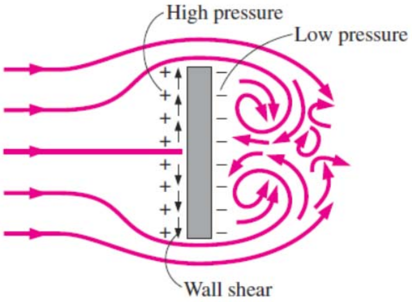
Flow over a flat plate



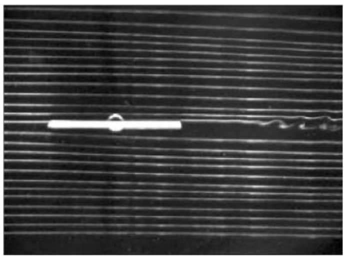
Drag is due to viscous force only

Flow normal to a flat plate

Drag is primarily due to pressure difference across the plate



Flow visualization for flow over a flat plate



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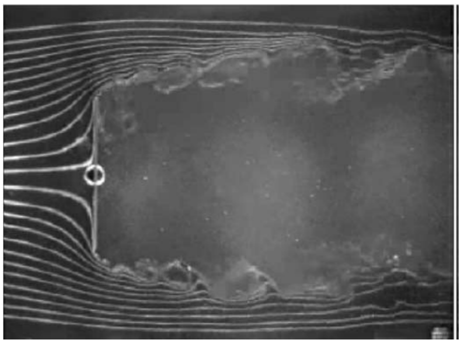

Recall dimensional analysis

Laminar: $C_D = f(\text{Re})$ Turbulent: $C_D = f\left(\text{Re}, \frac{\varepsilon}{d}\right)$

Low Re $C_D = \frac{\text{constant}}{\text{Re}}$, creeping (Stoke's) flow

High Re $C_D = \text{constant (laminar) or } f\left(\frac{\varepsilon}{d}\right) \text{ only (turbulent)}$

In external flow, flows (close to a smooth body) usually remain laminar up to $\text{Re} = \sim 10^5$, unlike internal flows

Recall dimensionless N-S/Continuity Eqns.

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}.\nabla)\mathbf{u} = -\nabla p + \frac{1}{\text{Re}}\nabla^2 \mathbf{u} \qquad \nabla.\mathbf{u} = 0$$

The above Equations may be successfully solved (for many cases) after dropping the viscous term (known as potential flow)

Potential flow solution predicts zero drag/lift for all objects, a phenomenon known as D'Alembert's paradox