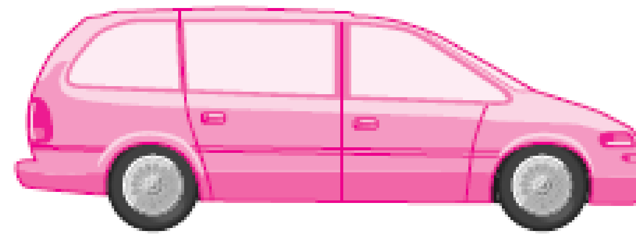
SPC 307
Introduction to Aerodynamics

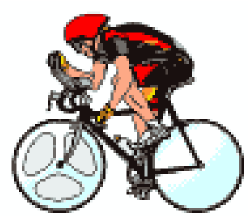
Lecture 5
Flow over Bodies; Drag and Lift

March 12, 2016

External Flow

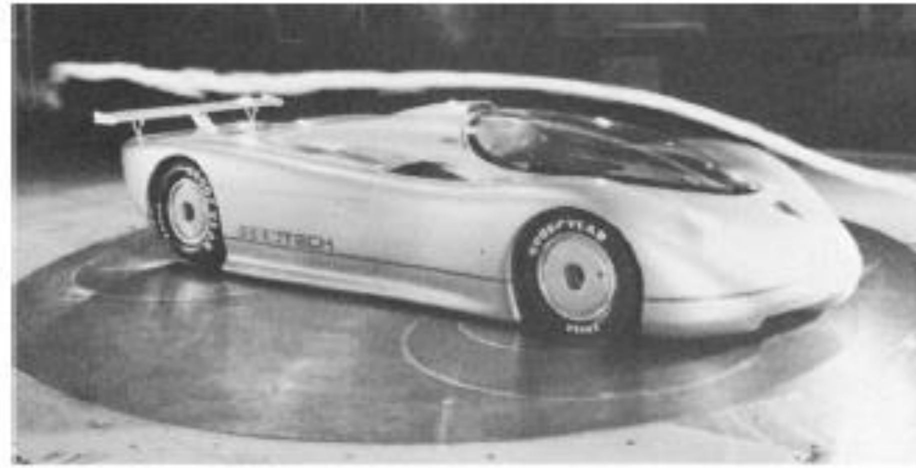
- Bodies and vehicles in motion, or with flow over them, experience fluid-dynamic forces and moments.
- Examples include: aircraft, automobiles, buildings, ships, submarines, turbomachines.
- These problems are often classified as ***External Flows.***
- Fuel economy, speed, acceleration, maneuverability, stability, and control are directly related to the aerodynamic/hydrodynamic forces and moments.

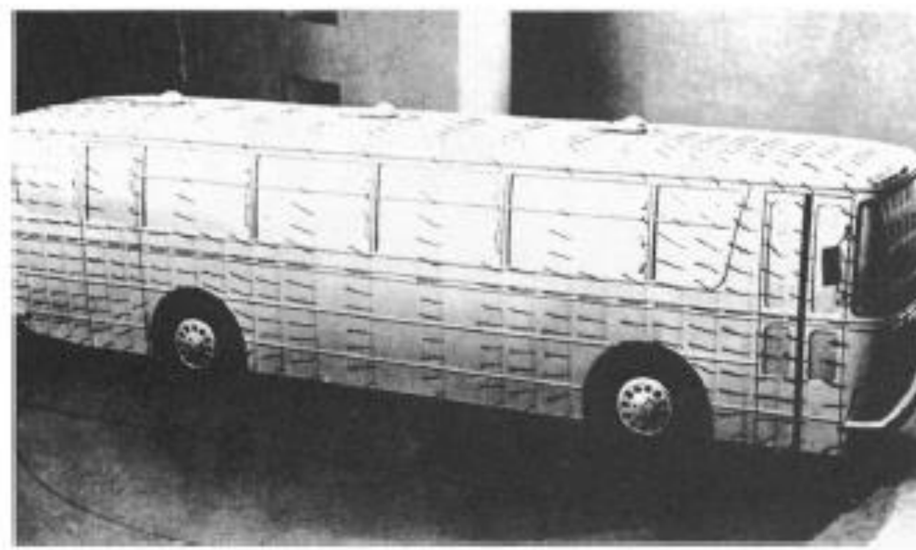
External Flow

(*a*) Flow past a full-sized streamlined vehicle in the GM aerodynamics laboratory wind tunnel, and 18-ft by 34-ft test section facility driven by a 4000-hp, 43-ft-diameter fan.



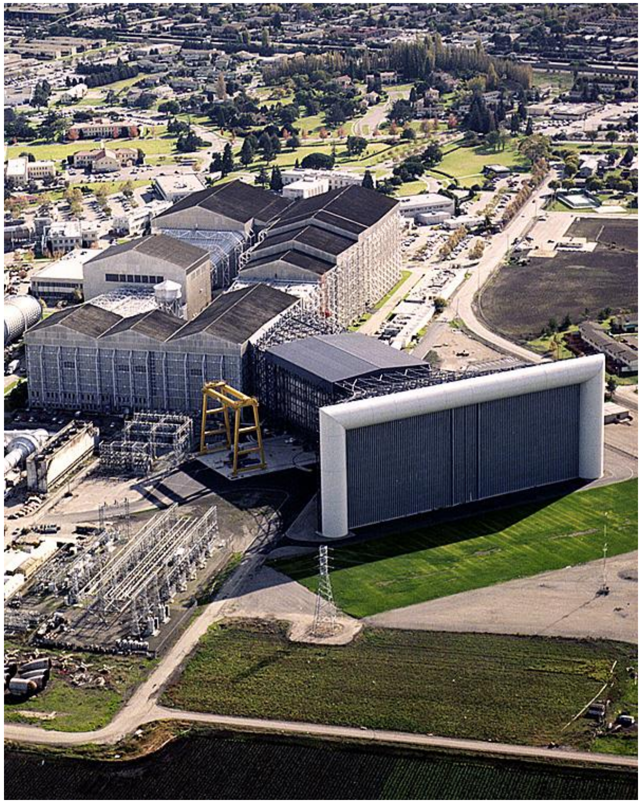
(*a*)

(*b*) Surface flow on a model vehicle as indicated by tufts attached to the surface.



(*b*)

Two of NASA’s Wind Tunnels



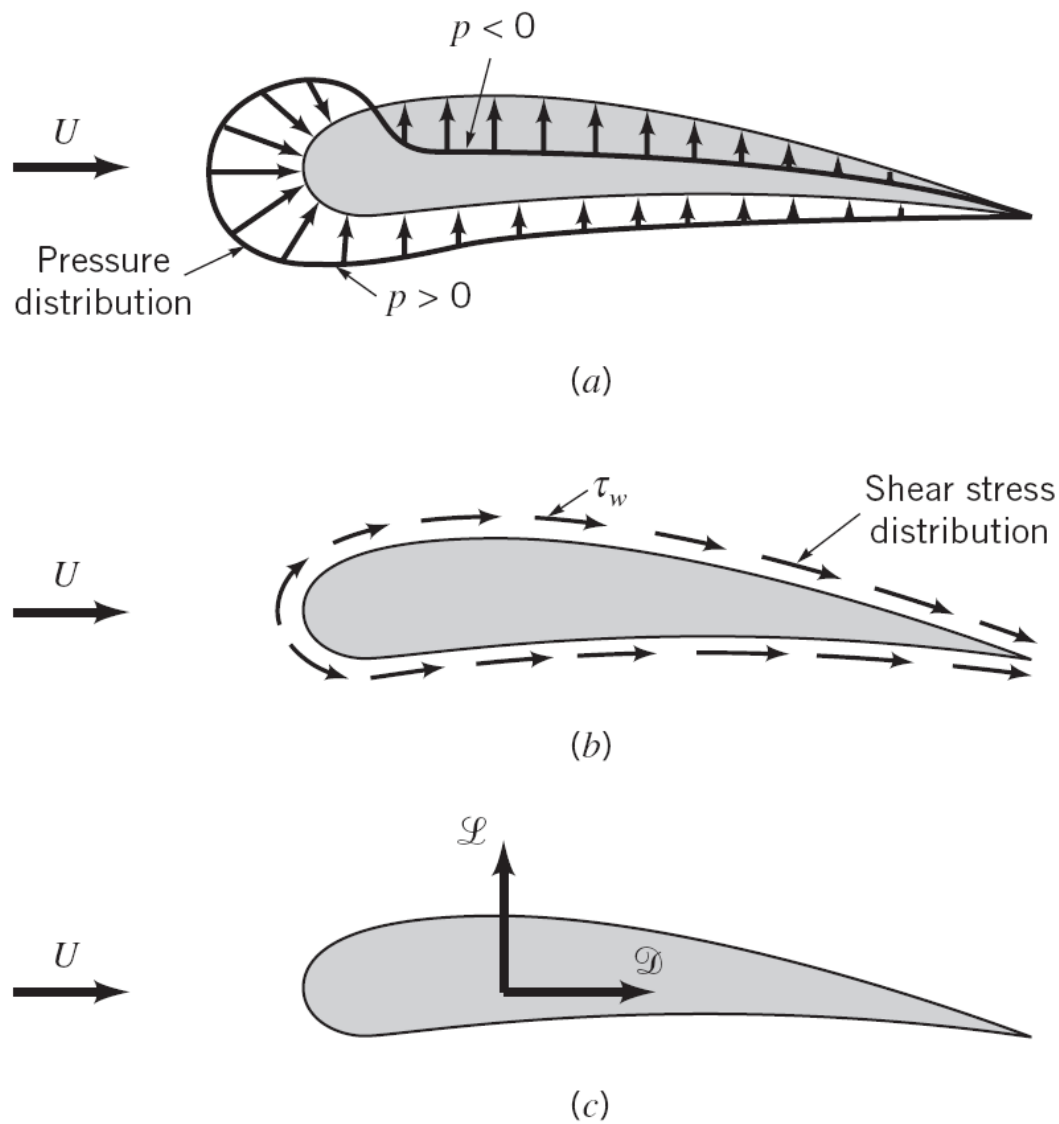
Langley

Ames 80’ x 120’

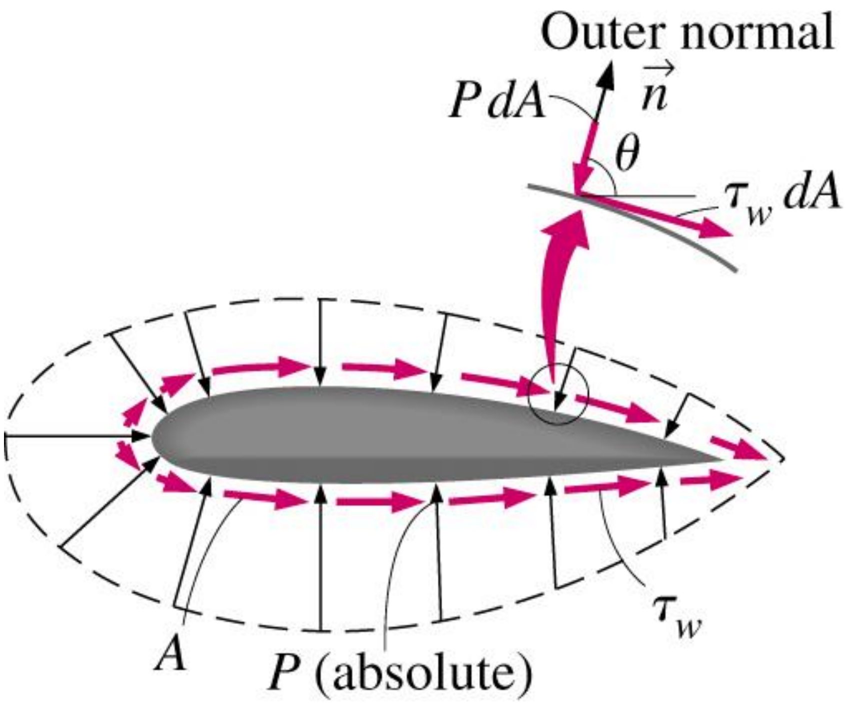
Drag and Lift Concepts

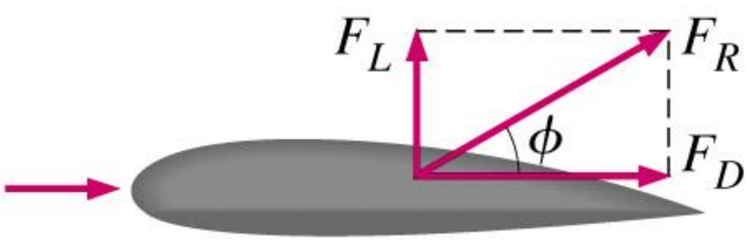
Forces from the surrounding fluid on a two-dimensional object:

(*a*) pressure force,
(*b*) viscous force,
(*c*) resultant force (lift and drag).



Drag and Lift



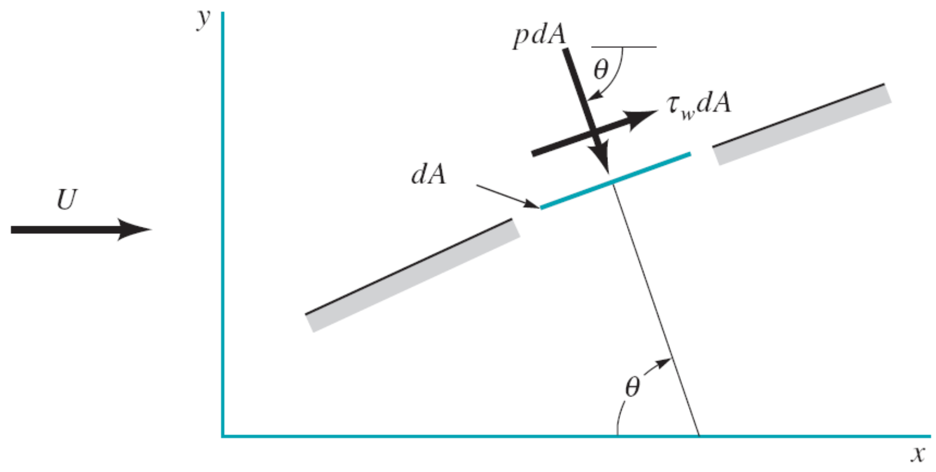


$$F_D = F_R \cos \phi$$
$$F_L = F_R \sin \phi$$

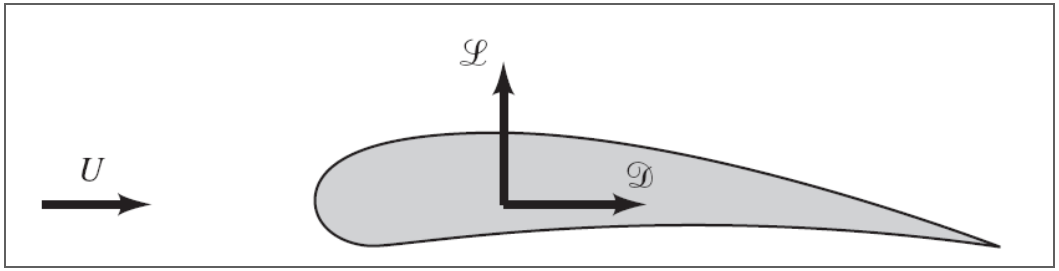
- Fluid dynamic forces are due to pressure (normal) and viscous (shear) forces acting on the body surface.
- Drag: Force component parallel to flow direction.
- Lift: Force component normal to flow direction.

Drag Forces

- Drag forces can be found by integrating pressure and wall-shear stresses.



$$dF_x = (p\,dA)\cos\theta + (\tau_w\,dA)\sin\theta$$



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

$$\mathscr{D} = \int dF_x = \int p\cos\theta\,dA + \int \tau_w \sin\theta\,dA$$

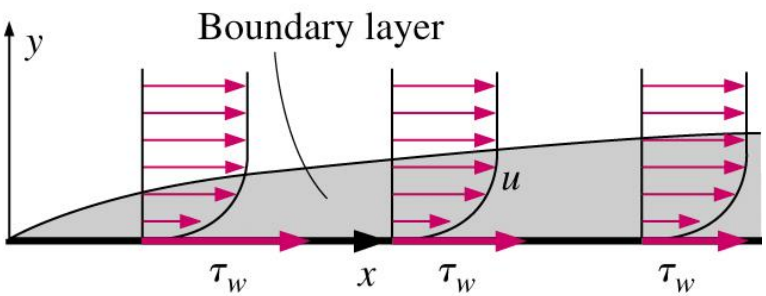
$$\mathscr{L} = \int dF_y = -\int p\sin\theta\,dA + \int \tau_w \cos\theta\,dA$$

θ is the angle between the normal vector and the direction of motion

Drag Forces

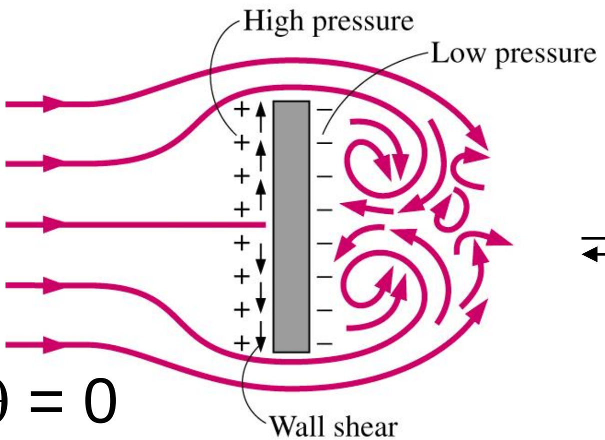
Special Cases

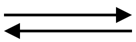
n



$\theta = 90$

Drag due to friction only





n

$\theta = 0$

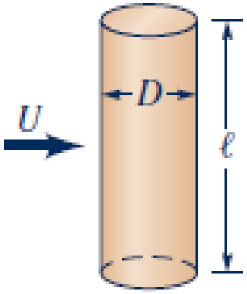
Drag due to pressure only

Lift Coefficient, C_L.

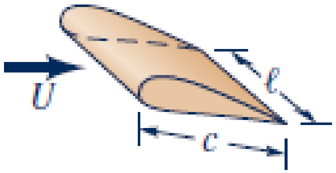
- In addition to geometry, Lift force F_L is a function of density ρ and velocity U.
- drag coefficient, C_L:

$$C_L = \frac{F_L}{\frac{1}{2}\rho U^2 A}$$

- Area A is a reference area: can be frontal area (the area projected on a plane normal to the direction of flow) (drag applications), plan-form area (wing aerodynamics), or wetted-surface area (ship hydrodynamics).



$A = D\ell$



$A = c\ell$

Drag Coefficient, C_D.

- In addition to geometry, drag force F_D is a function of density ρ and velocity V.
- drag coefficient, C_D:

$$\boxed{C_D = \frac{F_D}{\frac{1}{2}\rho V^2 A}}$$

- Area A is a reference area: can be frontal area (the area projected on a plane normal to the direction of flow) (drag applications), plan-form area (wing aerodynamics), or wetted-surface area (ship hydrodynamics).
- For applications such as tapered wings, C_D may be a function of span location. For these applications, a local $C_{D,x}$ is introduced and the total drag is determined by integration over the span L

$$\boxed{C_D = \frac{1}{L}\int_0^L C_{D,x}\,dx}$$

Pressure Coefficient, C_p.

$$\boxed{C_p = \frac{p - p_0}{\frac{1}{2}\rho U^2}}$$

- Where ρ density, p_0 reference pressure and U velocity.

Reynolds and Mach Numbers.

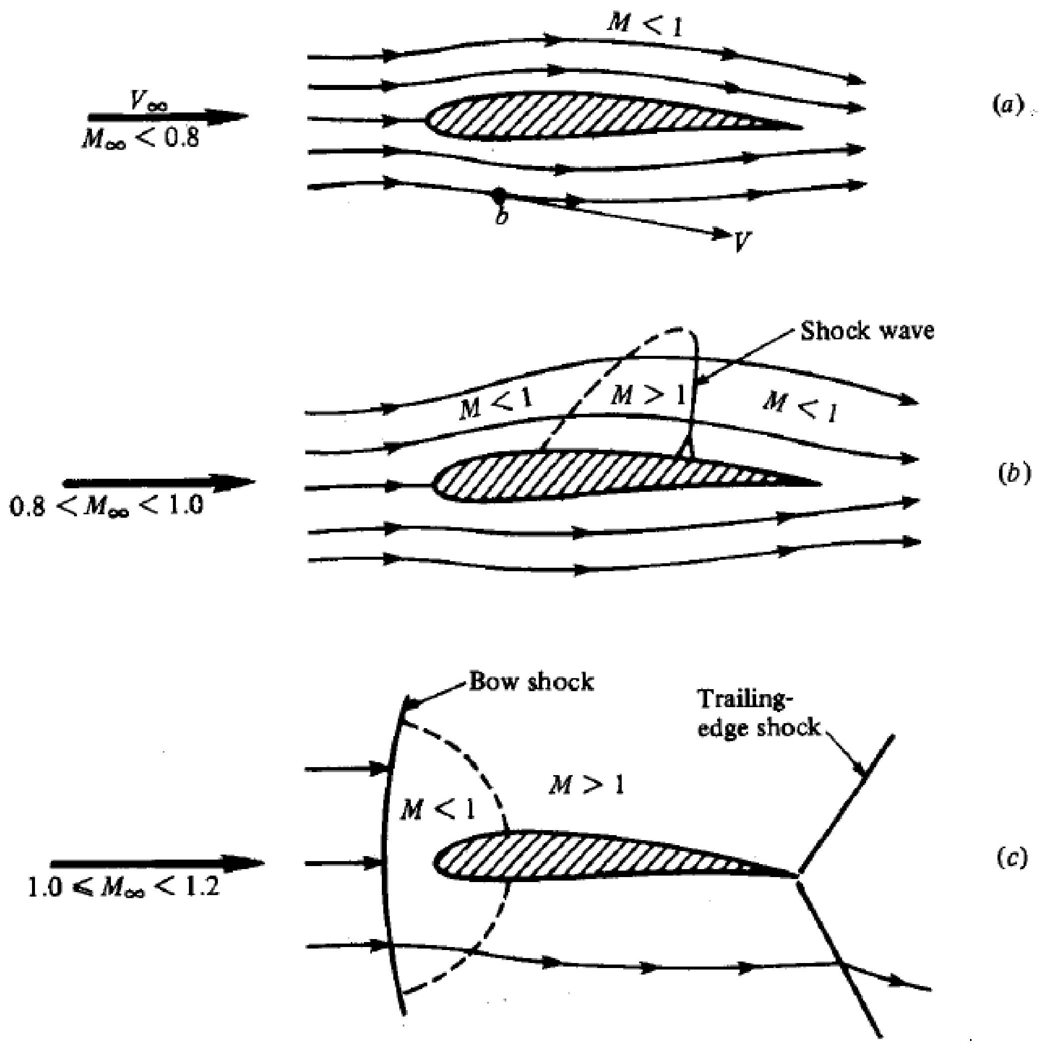
$$\boxed{Re = \frac{\rho V L}{\mu} = \frac{Inertia\ Effect}{VIscosity\ Effect}}$$

- Where ρ density, μ viscosity and V velocity.
- Area L is the characteristic length:
  for a flat plate: Plate Length
  For a circle or a sphere is Diameter

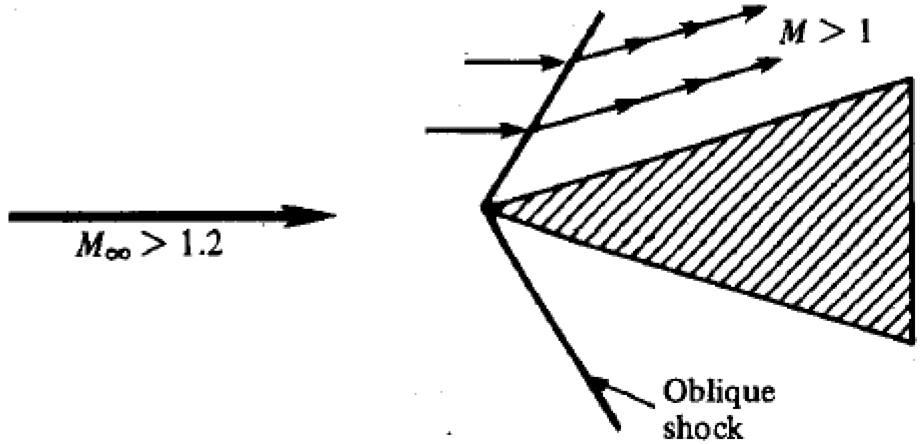
$$\boxed{M = \frac{V}{C}}$$

- Where C =speed of sound and V velocity.

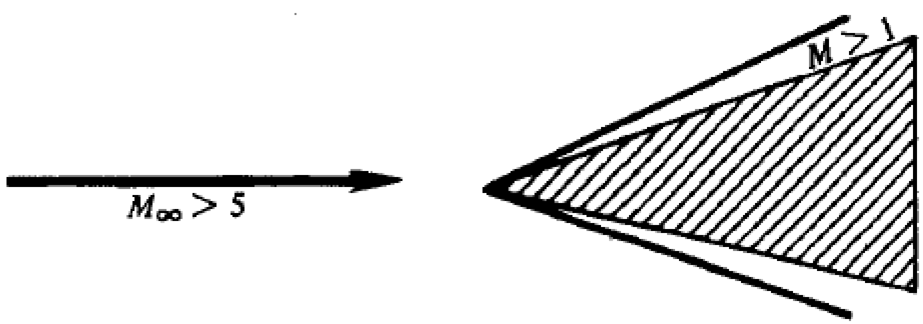
Flow Regimes



Flow Regimes

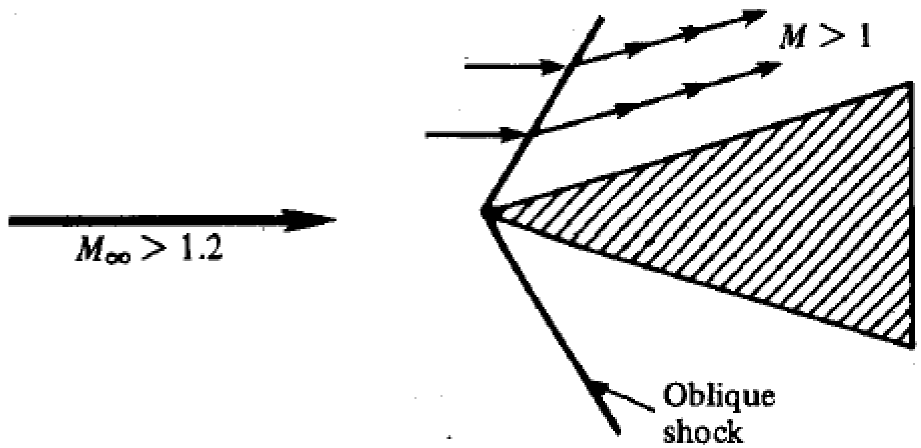


(*d*)

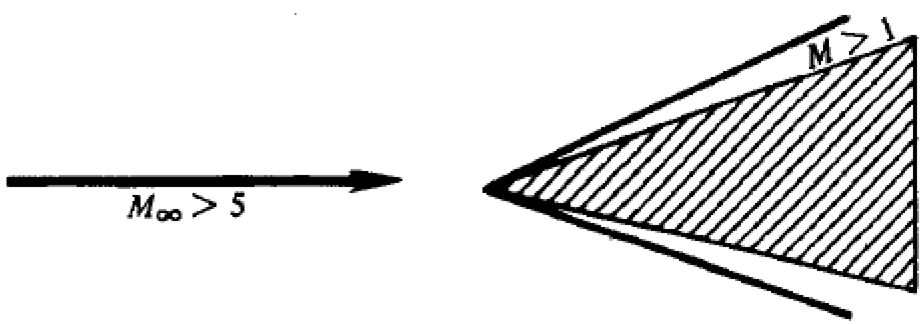


(*e*)

Flow Regimes

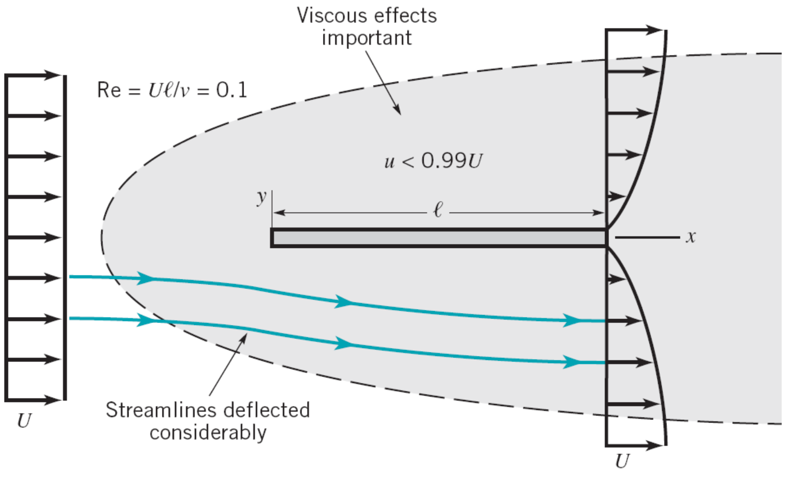


(d)



(e)

Character of the steady, viscous flow past a flat plate parallel to the upstream velocity



(a)

Inertia force = ma = $\rho L^3 * V\, dV/dL = \rho V^2 L^2$

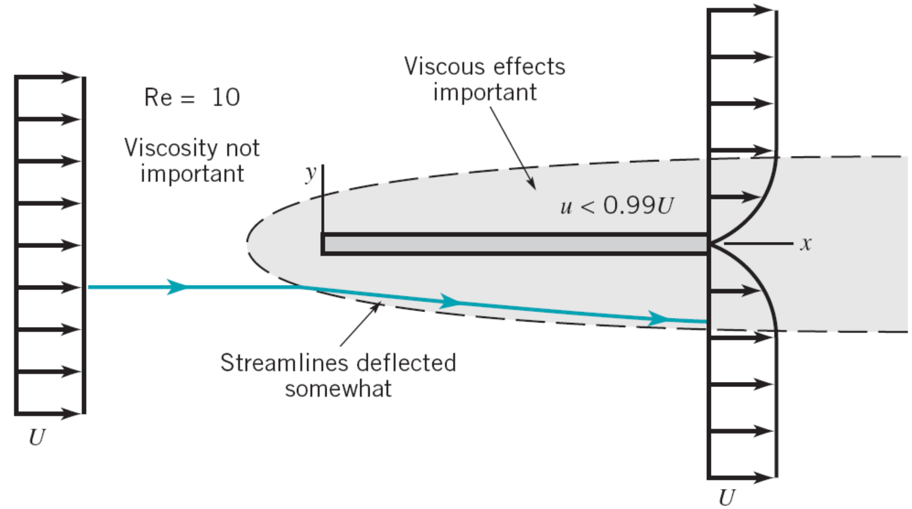
Viscous Force = $\mu\, L^2\, dV/dL = \mu\, V\, L$

$$\boxed{Re = \frac{\rho VL}{\mu} = \frac{Inertia\ Force}{Viscous\ Force}}$$

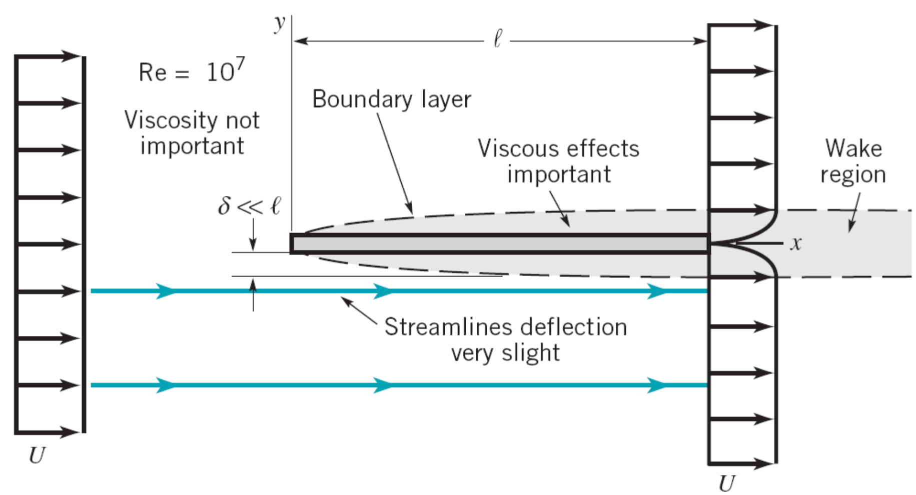
(a) low Reynolds number flow,

(b) moderate Reynolds number flow,

(c) large Reynolds number flow.



(b)



(c)

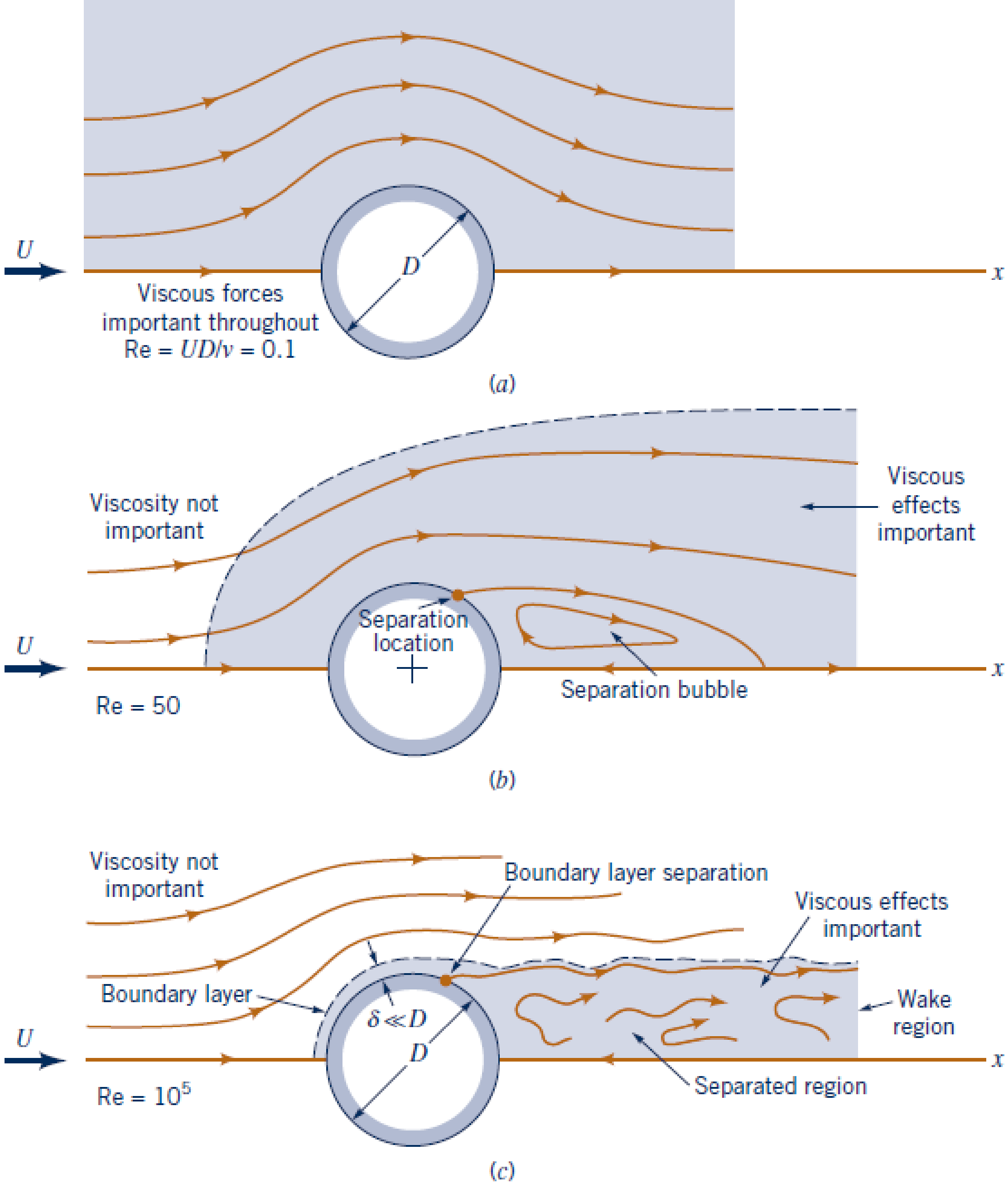
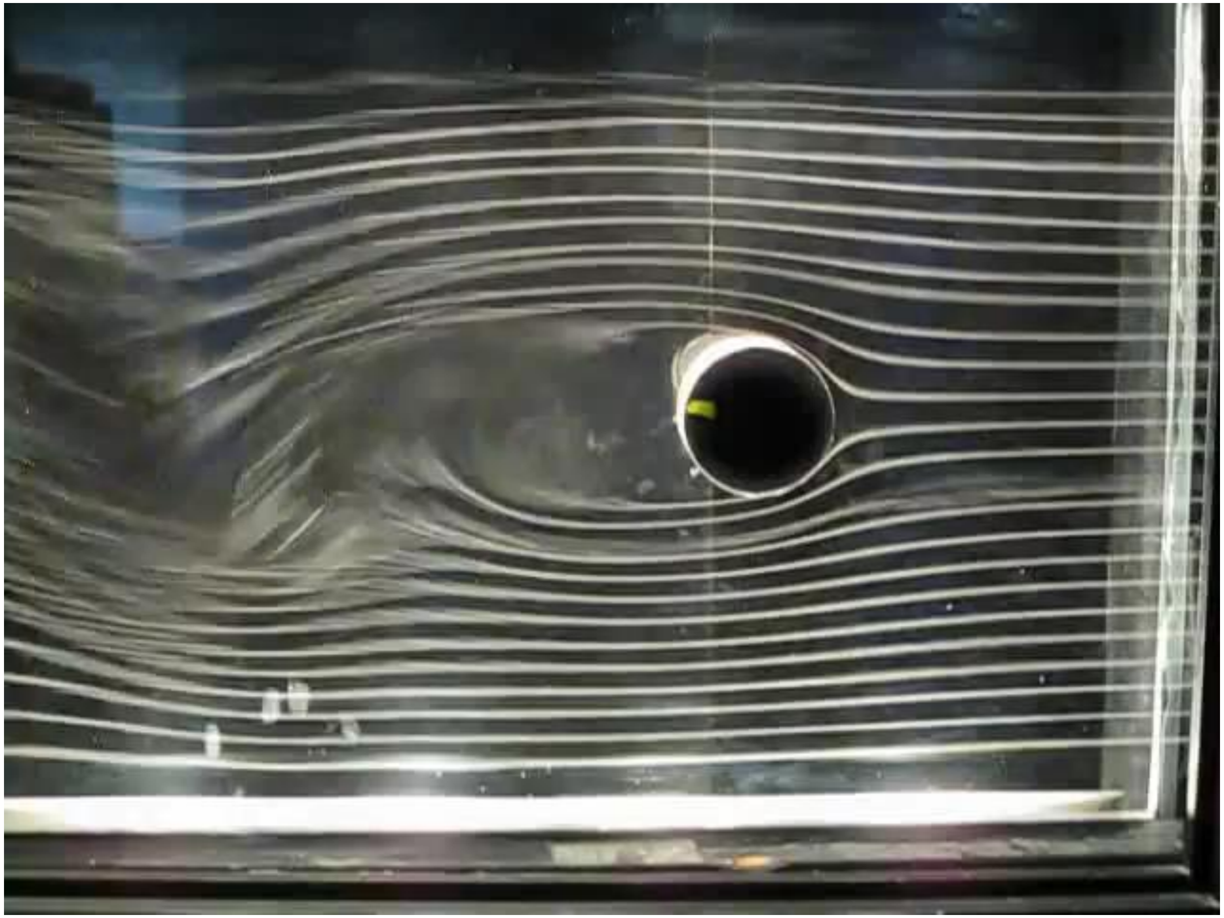
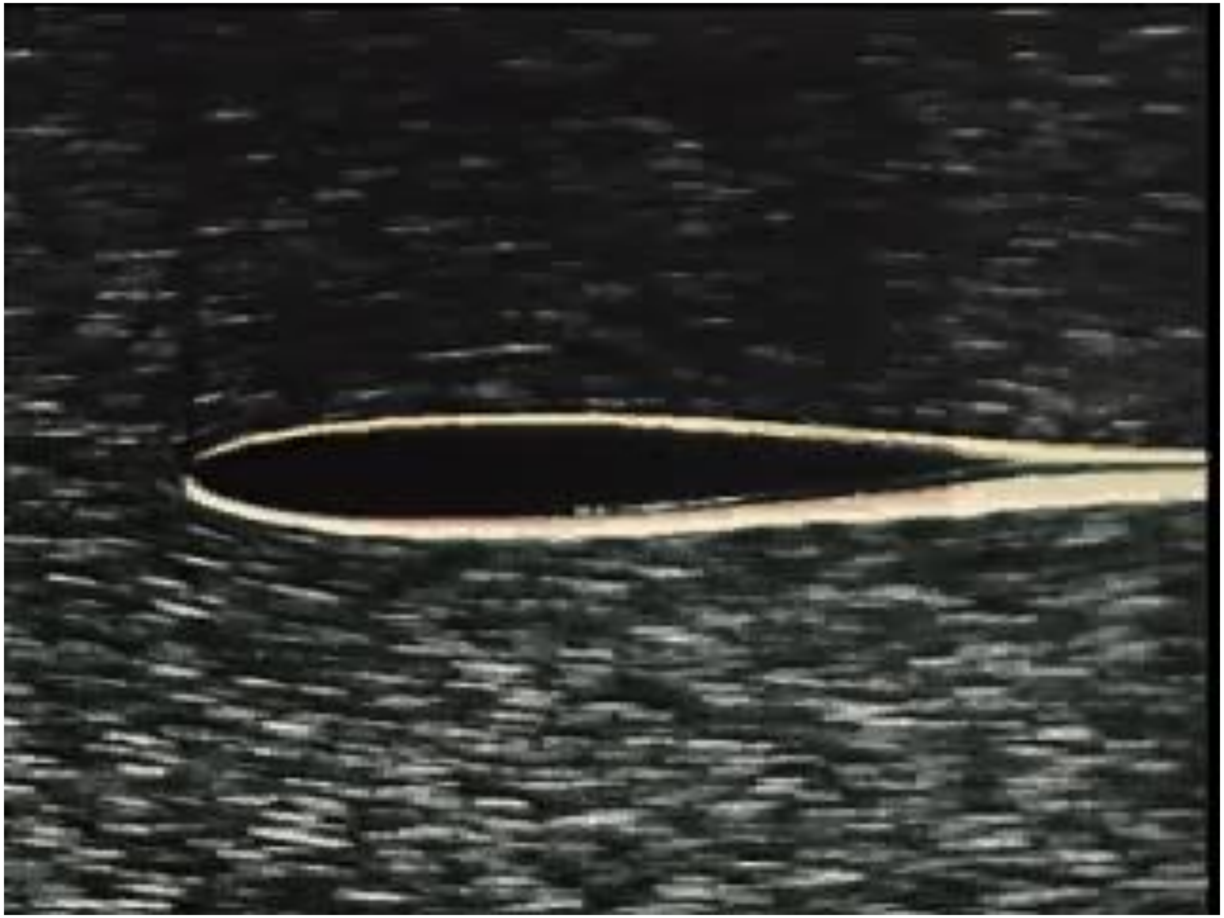


Figure 9.6 Character of the steady, viscous flow past a circular cylinder: (*a*) low Reynolds number flow, (*b*) moderate Reynolds number flow, (*c*) large Reynolds number flow.

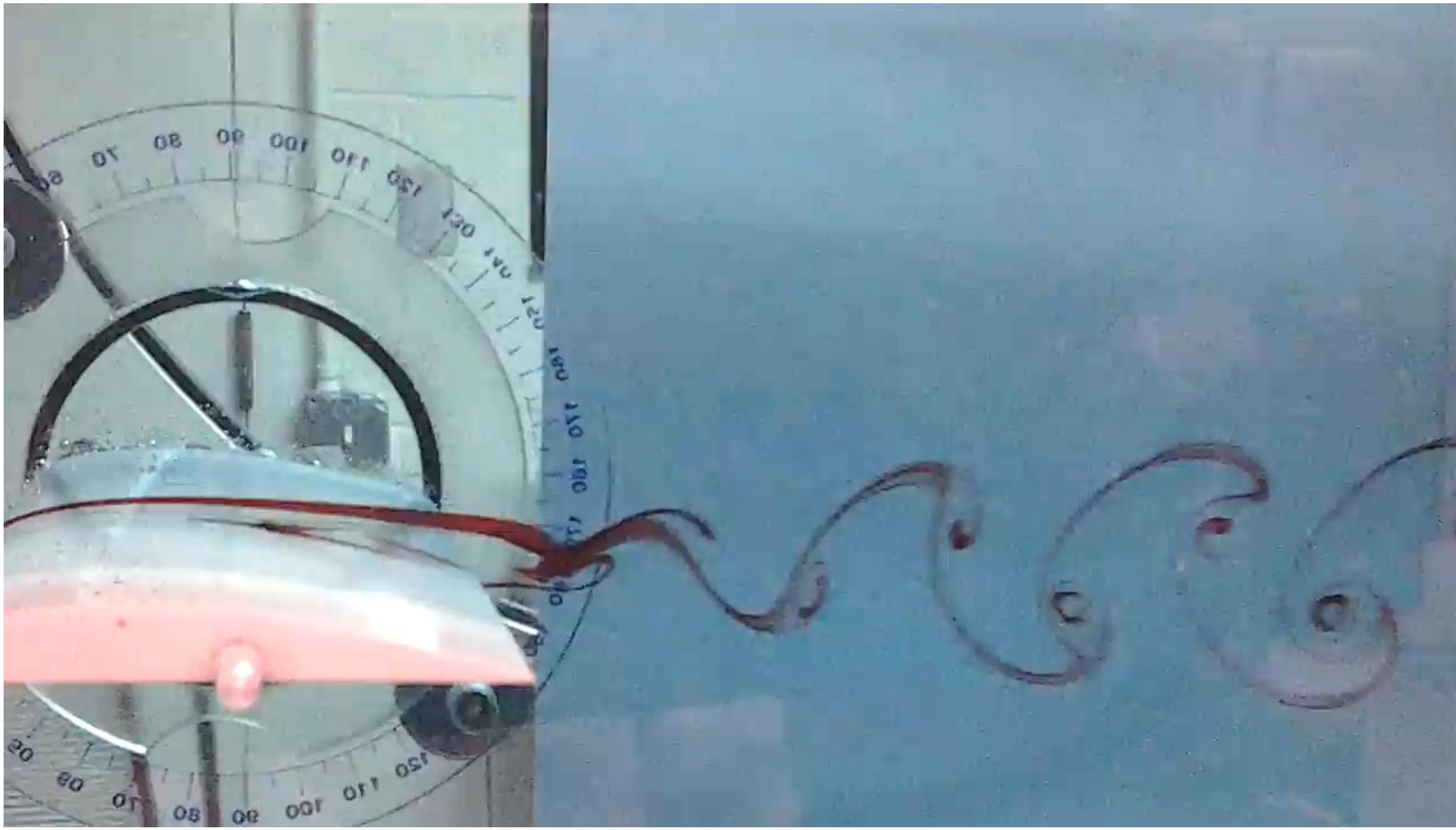
Karman Vortex Wake



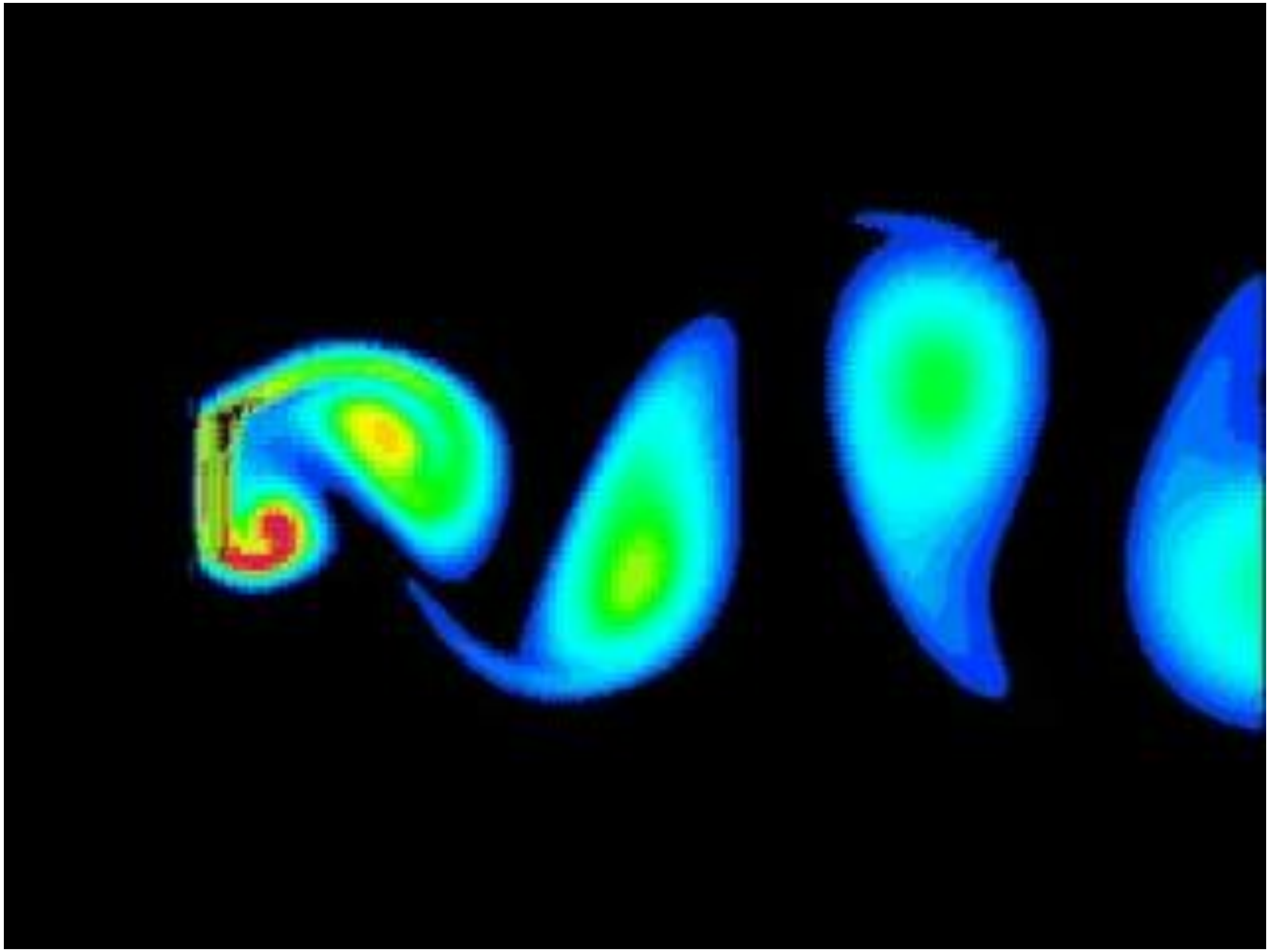
Karman Vortex Wake



Karman Vortex Wake

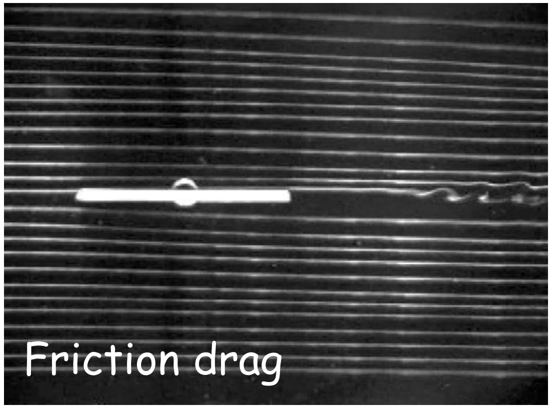


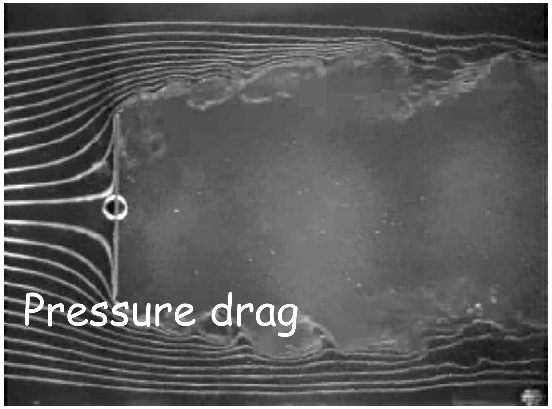
Pressure Drag on a Flat Plate

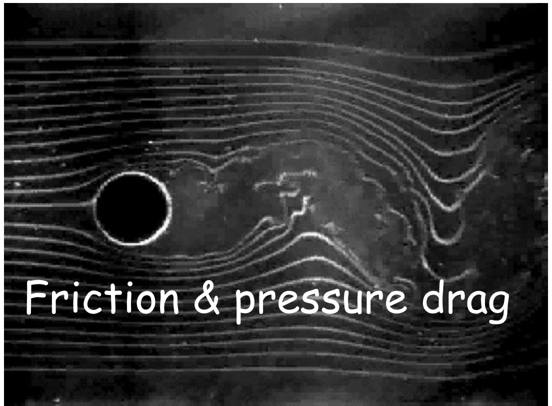


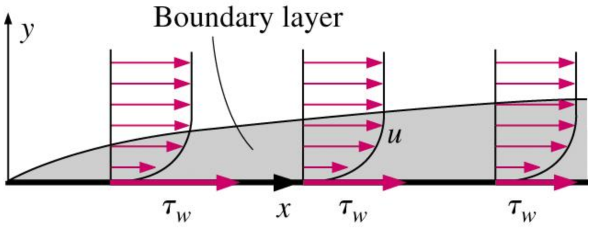
Friction Drag and Pressure Drag

- Fluid dynamic forces are comprised of pressure (form) and friction effects.
- Often useful to decompose,
  - $F_D = F_{D,friction} + F_{D,pressure}$
  - $C_D = C_{D,friction} + C_{D,pressure}$
- This forms the basis of model testing.

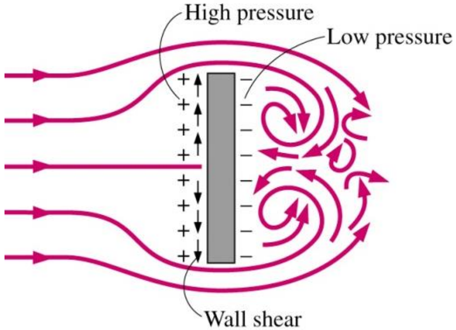








$C_D = C_{D,friction}$

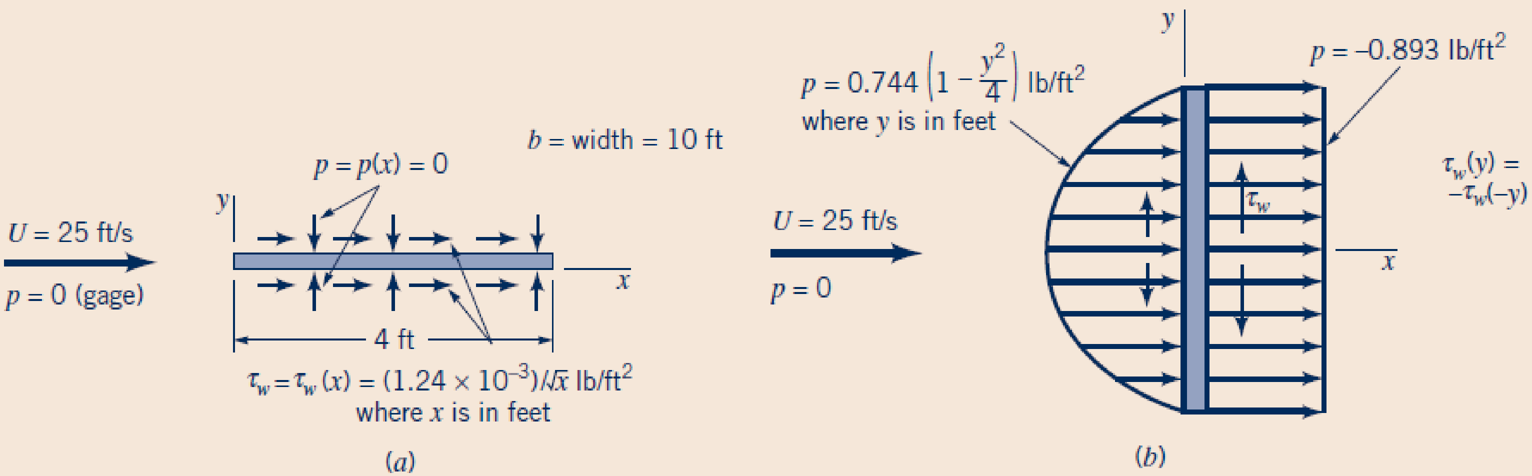


$C_D = C_{D,pressure}$

Example 9.1

GIVEN Air at standard conditions flows past a flat plate as is indicated in Fig. E9.1. In case (a) the plate is parallel to the upstream flow, and in case (b) it is perpendicular to the upstream flow. The pressure and shear stress distributions on the surface are as indicated (obtained either by experiment or theory).

FIND Determine the lift and drag on the plate.



Solution

For either orientation of the plate, the lift and drag are obtained from Eqs. 9.1 and 9.2. With the plate parallel to the upstream flow we have $\theta = 90°$ on the top surface and $\theta = 270°$ on the bottom surface so that the lift and drag are given by

$$\mathscr{L} = -\int_{\text{top}} p\,dA + \int_{\text{bottom}} p\,dA = 0$$

and

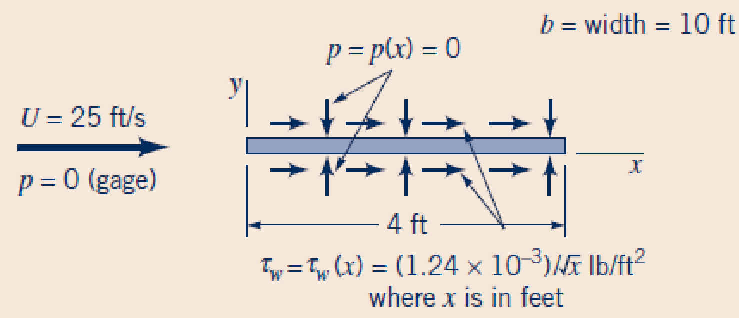
$$\mathscr{D} = \int_{\text{top}} \tau_w\,dA + \int_{\text{bottom}} \tau_w\,dA = 2\int_{\text{top}} \tau_w\,dA \qquad (1)$$

where we have used the fact that because of symmetry the shear stress distribution is the same on the top and the bottom surfaces, as is the pressure also [whether we use gage ($p = 0$) or absolute ($p = p_{\text{atm}}$) pressure]. There is no lift generated—the plate does not know up from down. With the given shear stress distribution, Eq. 1 gives

$$\mathscr{D} = 2\int_{x=0}^{4\text{ ft}} \left(\frac{1.24 \times 10^{-3}}{x^{1/2}}\ \text{lb/ft}^2\right)(10\text{ ft})\,dx$$

or

$$\mathscr{D} = 0.0992\text{ lb} \qquad \textbf{(Ans)}$$



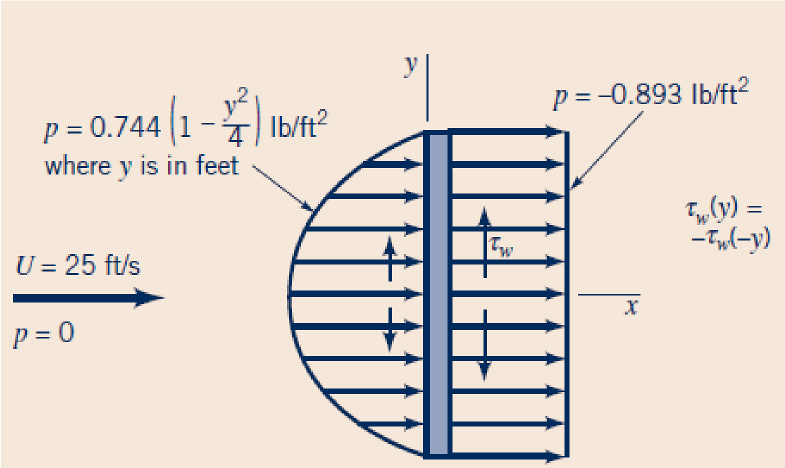
(a)

With the plate perpendicular to the upstream flow, we have $\theta = 0°$ on the front and $\theta = 180°$ on the back. Thus, from Eqs. 9.1 and 9.2

$$\mathscr{L} = \int_{\text{front}} \tau_w \, dA - \int_{\text{back}} \tau_w \, dA = 0$$

and

$$\mathscr{D} = \int_{\text{front}} p \, dA - \int_{\text{back}} p \, dA$$



Again there is no lift because the pressure forces act parallel to the upstream flow (in the direction of $\mathscr{D}$ not $\mathscr{L}$) and the shear stress is symmetrical about the center of the plate. With the given relatively large pressure on the front of the plate (the center of the plate is a stagnation point) and the negative pressure (less than the upstream pressure) on the back of the plate, we obtain the following drag

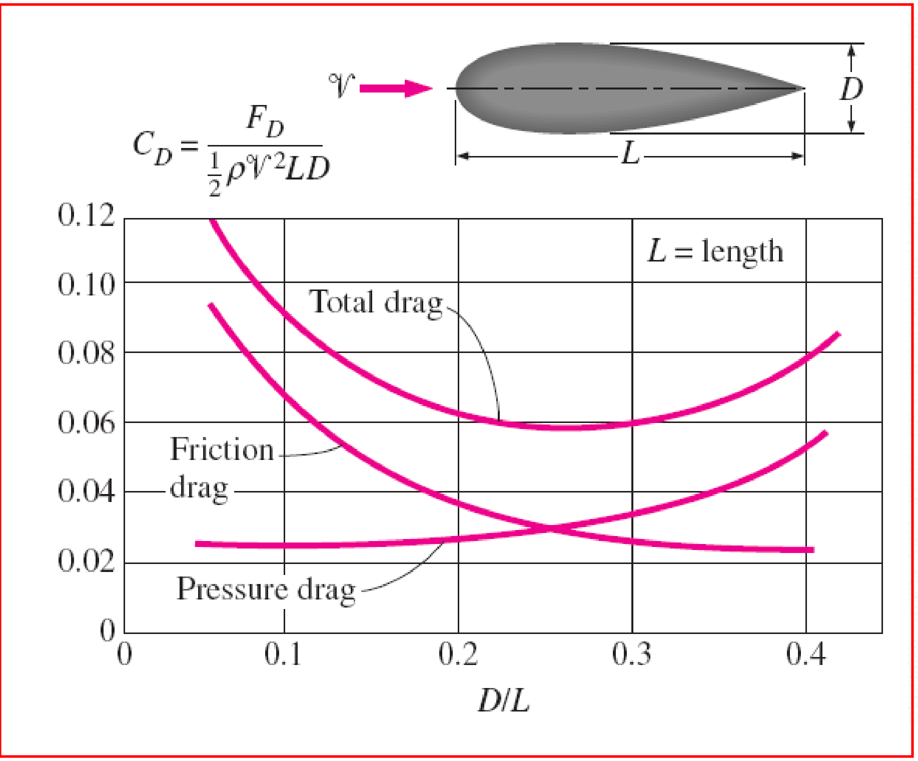
$$\mathscr{D} = \int_{y=-2}^{2\text{ ft}} \left[0.744\left(1 - \frac{y^2}{4}\right) \text{lb/ft}^2 - (-0.893) \text{ lb/ft}^2\right] (10 \text{ ft}) \, dy$$

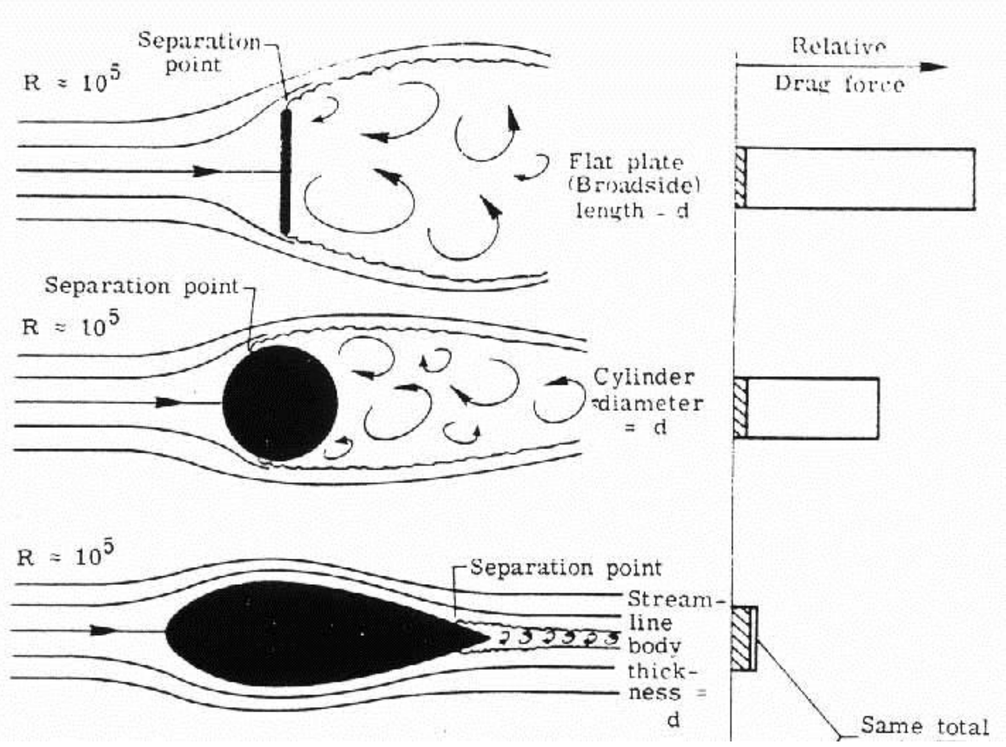
or

$$\mathscr{D} = 55.6 \text{ lb} \qquad \textbf{(Ans)}$$

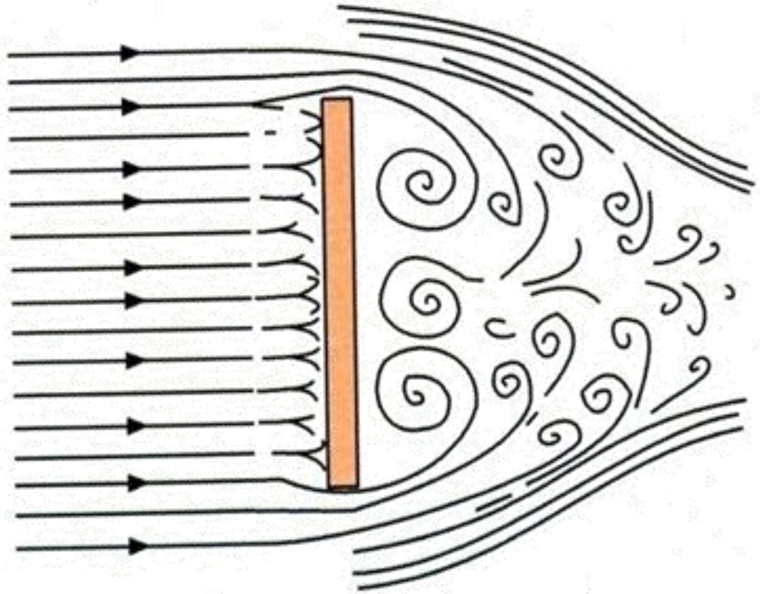
Streamlining

- Streamlining reduces drag by reducing $F_{D,pressure}$, at the cost of increasing wetted surface area and $F_{D,friction}$.
- Goal is to eliminate flow separation and minimize total drag F_D

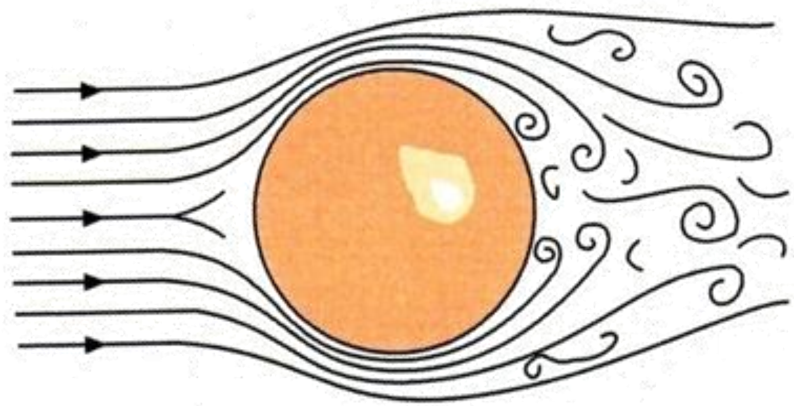




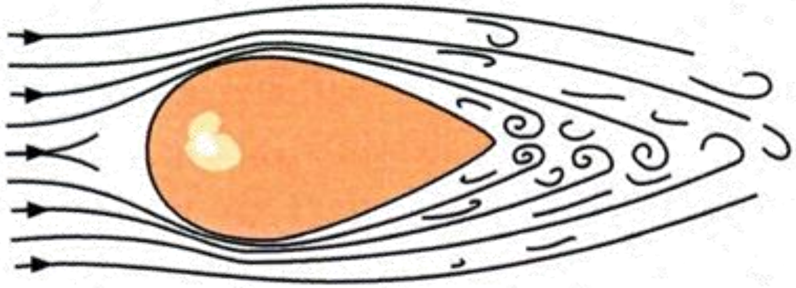
Streamlining to reduce pressure drag



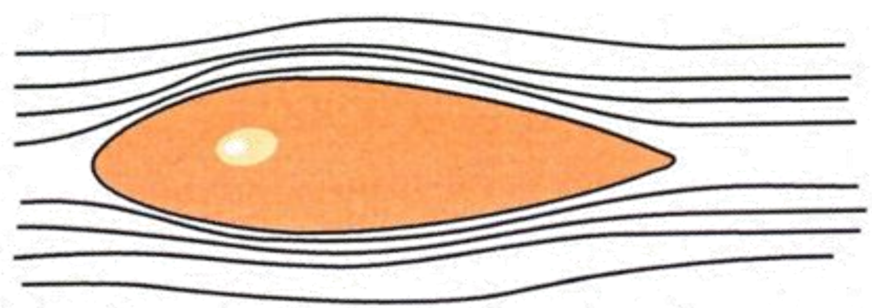
(a) Flat Plate 100% Resistance



(b) Sphere 50% Resistance



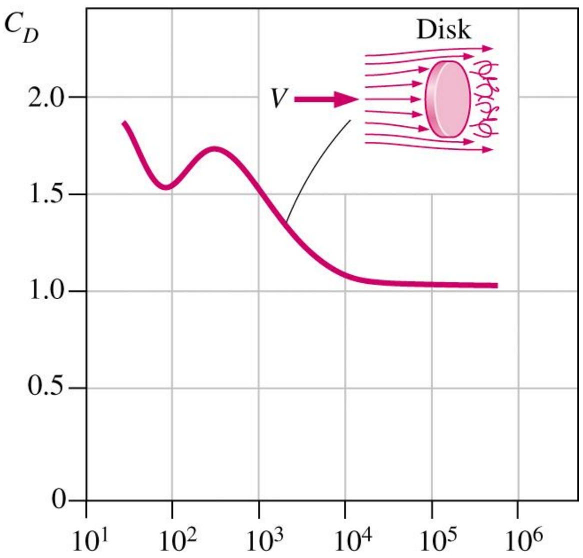
(c) Ovoid 15% Resistance



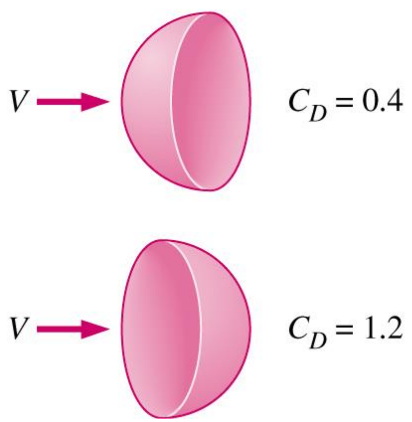
(d) Streamlined 5% Resistance

STREAMLINED

C_D of Common Geometries



A hemisphere at two different orientations for Re > 10^4



- For many geometries, total drag C_D is constant for $Re > 10^4$
- C_D can be very dependent upon orientation of body.
- As a crude approximation, superposition can be used to add C_D from various components of a system to obtain overall drag.

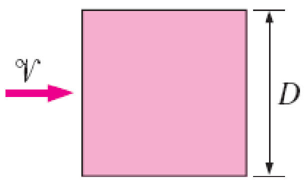
$$\boxed{C_D = \frac{F_D}{\frac{1}{2}\rho V^2 A}}$$

$$\boxed{F_D = C_D \frac{1}{2}\rho V^2 A = C_D \frac{1}{2}\rho V^2 \frac{\pi}{4} D^2}$$

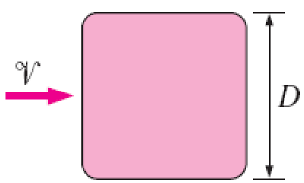
C_D of Common Geometries

Drag coefficients C_D of various two-dimensional bodies for Re $> 10^4$ based on the frontal area $A = bD$, where b is the length in direction normal to paper (for use in the drag force relation $F_D = C_D A \rho \mathcal{V}^2/2$ where $\mathcal{V}$ is the upstream velocity)

Square rod

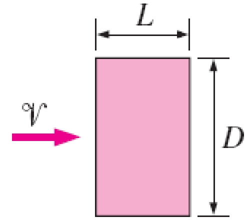


Sharp corners: $C_D = 2.2$



Round corners $(r/D = 0.2)$: $C_D = 1.2$

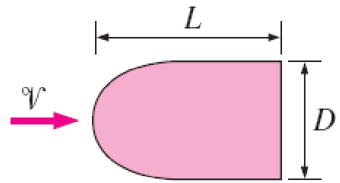
Rectangular rod



Sharp corners:

L/D	C_D
0.0*	1.9
0.1	1.9
0.5	2.5
1.0	2.2
2.0	1.7
3.0	1.3

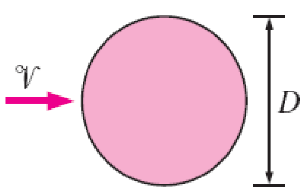
*Corresponds to thin plate



Round front edge:

L/D	C_D
0.5	1.2
1.0	0.9
2.0	0.7
4.0	0.7

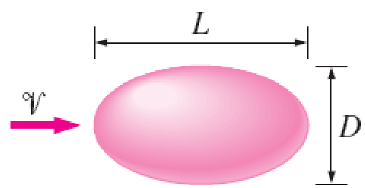
Circular rod (cylinder)



Laminar: $C_D = 1.2$

Turbulent: $C_D = 0.3$

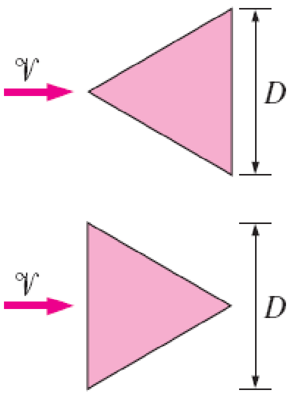
Elliptical rod



	C_D	
L/D	Laminar	Turbulent
2	0.60	0.20
4	0.35	0.15
8	0.25	0.10

Drag coefficients C_D of various two-dimensional bodies for Re > 10^4 based on the frontal area $A = bD$, where b is the length in direction normal to paper (for use in the drag force relation $F_D = C_D A \rho \mathscr{V}^2/2$ where $\mathscr{V}$ is the upstream velocity)

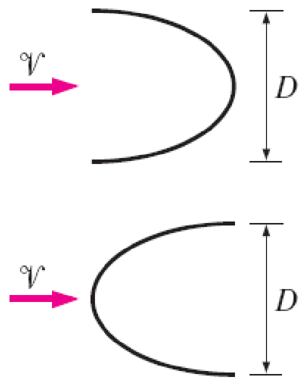
Equilateral triangular rod



$C_D = 1.5$

$C_D = 2.0$

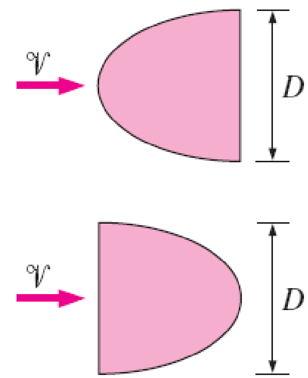
Semicircular shell



$C_D = 2.3$

$C_D = 1.2$

Semicircular rod

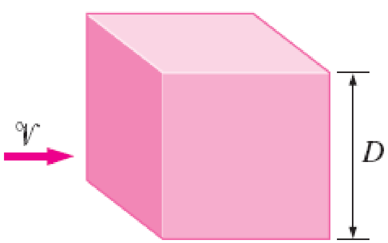


$C_D = 1.2$

$C_D = 1.7$

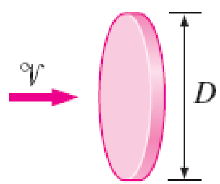
Representative drag coefficients C_D for various three-dimensional bodies for Re > 10^4 based on the frontal area (for use in the drag force relation $F_D = C_D A \rho \mathscr{V}^2/2$ where $\mathscr{V}$ is the upstream velocity)

Cube, $A = D^2$



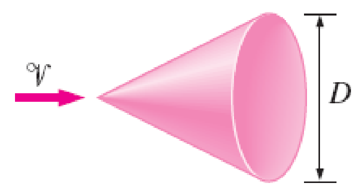
$C_D = 1.05$

Thin circular disk, $A = \pi D^2/4$



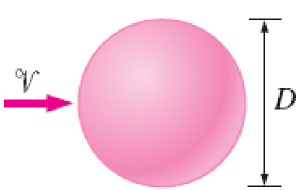
$C_D = 1.1$

Cone (for $\theta = 30°$), $A = \pi D^2/4$



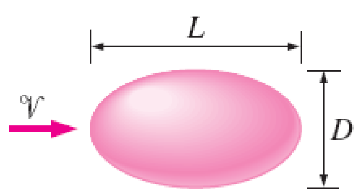
$C_D = 0.5$

Sphere, $A = \pi D^2/4$



Laminar: $C_D = 0.5$
Turbulent: $C_D = 0.2$

Ellipsoid, $A = \pi D^2/4$

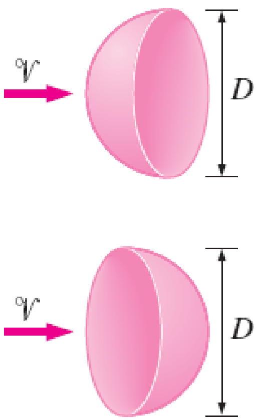


	C_D	
L/D	Laminar	Turbulent
0.75	0.5	0.2
1	0.5	0.2
2	0.3	0.1
4	0.3	0.1
8	0.2	0.1

C_D of Common Geometries

Representative drag coefficients C_D for various three-dimensional bodies for Re > 10^4 based on the frontal area (for use in the drag force relation $F_D = C_D A\rho\mathcal{V}^2/2$ where $\mathcal{V}$ is the upstream velocity)

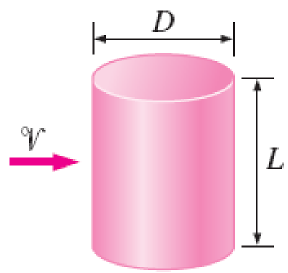
Hemisphere, $A = \pi D^2/4$



$C_D = 0.4$

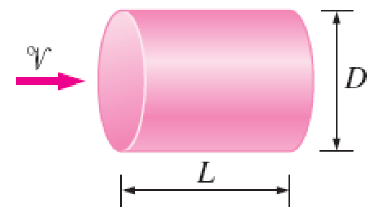
$C_D = 1.2$

Short cylinder, vertical, $A = L\ D$



L/D	C_D
1	0.6
2	0.7
5	0.8
10	0.9

Short cylinder, horizontal, $A = \pi D^2/4$

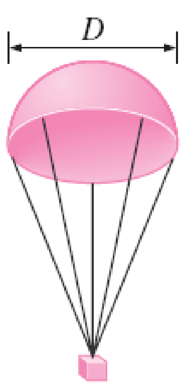


L/D	C_D
0.5	1.1
1	0.9
2	0.9
4	0.9
8	1.0

Streamlined body, $A = \pi D^2/4$

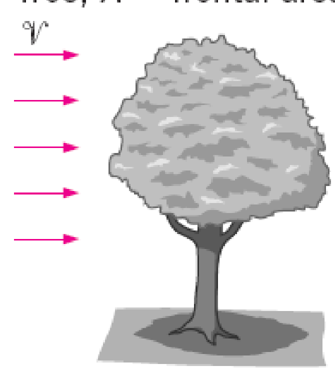
$C_D = 0.04$

Parachute, $A = \pi D^2/4$



$C_D = 1.3$

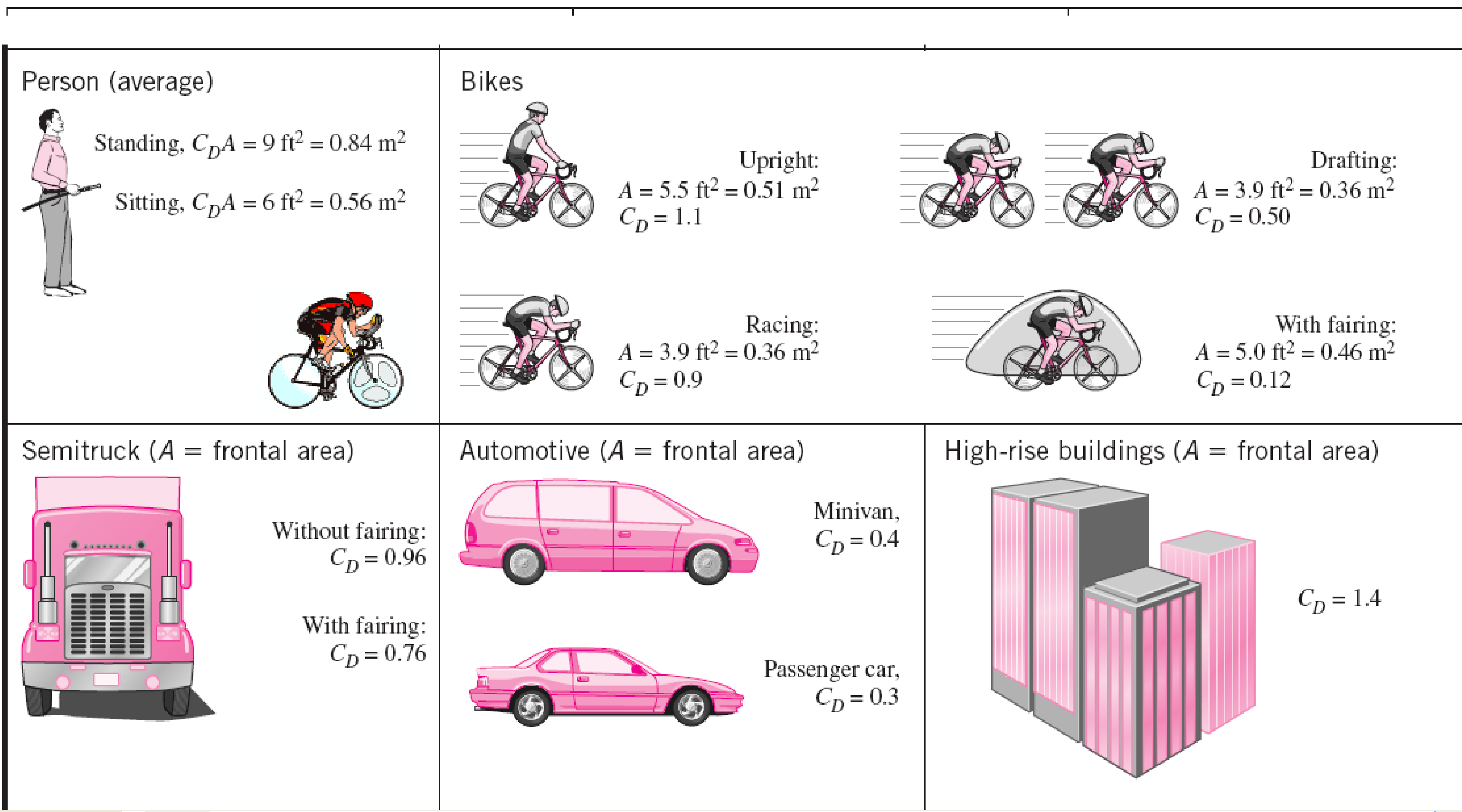
Tree, A = frontal area



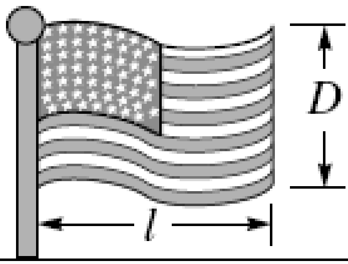
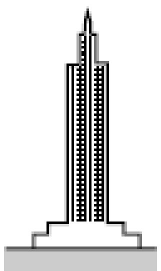
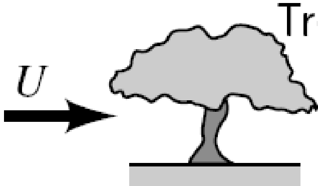
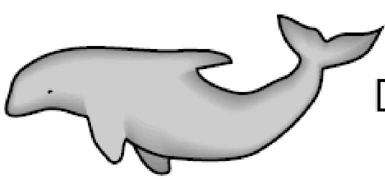
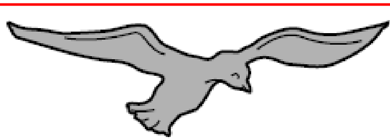
$\mathcal{V}$, m/s	C_D
10	0.4–1.2
20	0.3–1.0
30	0.2–0.7

C_D of Common Geometries

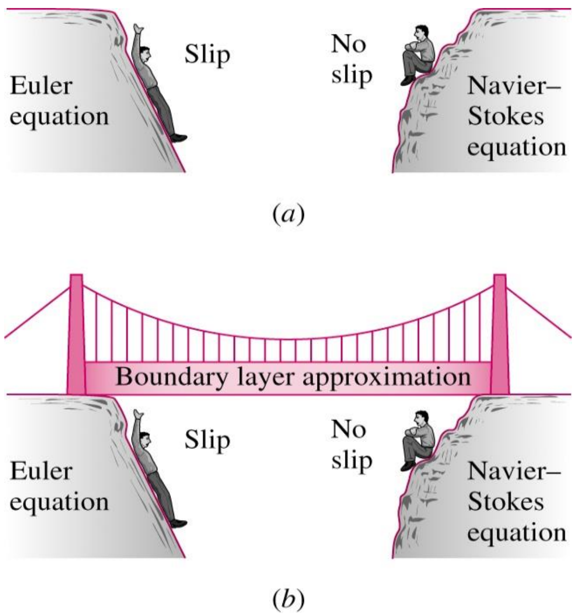
Representative drag coefficients C_D for various three-dimensional bodies for Re > 10^4 based on the frontal area (for use in the drag force relation $F_D = C_D A\rho\mathcal{V}^2/2$ where $\mathcal{V}$ is the upstream velocity)

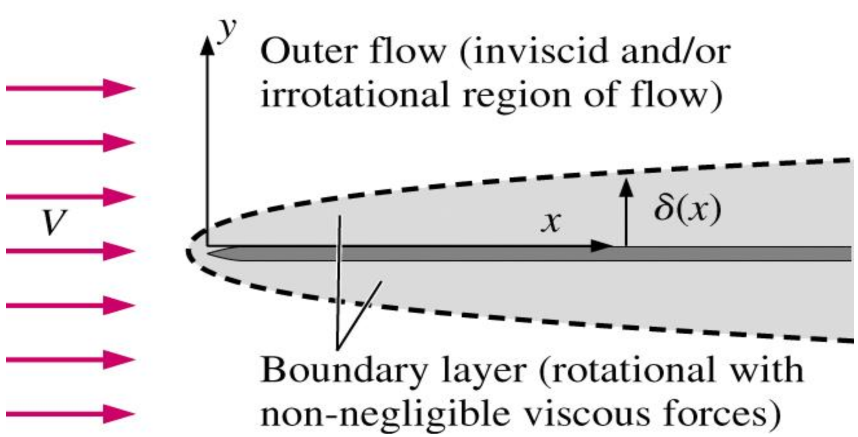


Some more shapes

 Fluttering flag	$A = \ell D$	ℓ/D : C_D 1 : 0.07 2 : 0.12 3 : 0.15
 Empire State Building	Frontal area	1.4
 Tree U = 10 m/s U = 20 m/s U = 30 m/s	Frontal area	0.43 0.26 0.20
 Dolphin	Wetted area	0.0036 at Re = 6×10^6 (flat plate has $C_{Df} = 0.0031$)
 Large birds	Frontal area	0.40

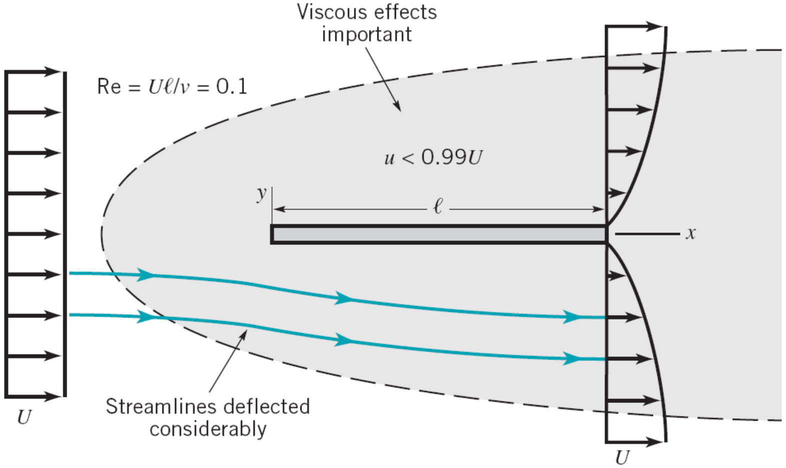
Boundary Layer (BL) Approximation



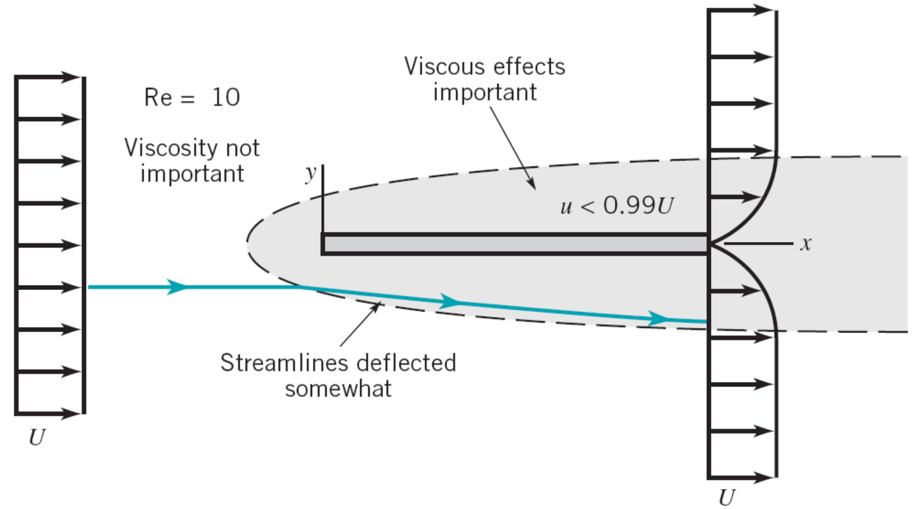


- BL approximation bridges the gap between the Euler (inviscid) and Navier-Stokes (NS) (viscous) equations, and between the slip and no-slip Boundary Conditions (BC) at the wall.
- Prandtl (1904) introduced the BL approximation- BL is **a thin region on the surface of a body in which viscous effects are very important and outside of which the fluid behaves as inviscid.**

Character of the steady, viscous flow past a flat plate parallel to the upstream velocity



(a)

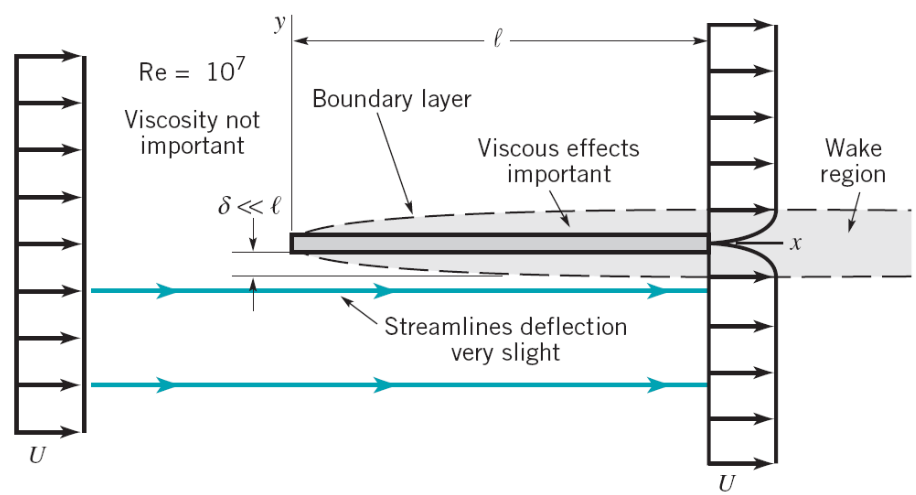


(b)

Inertia force = ma =$\rho L^3 * V\ dV/dL = \rho V^2 L^2$

Viscous Force = $\mu\ L^2\ dV/dL = \mu\ V\ L$

$$\boxed{\mathrm{Re} = \frac{\rho V L}{\mu} = \frac{Inertia\ Force}{Viscous\ Force}}$$



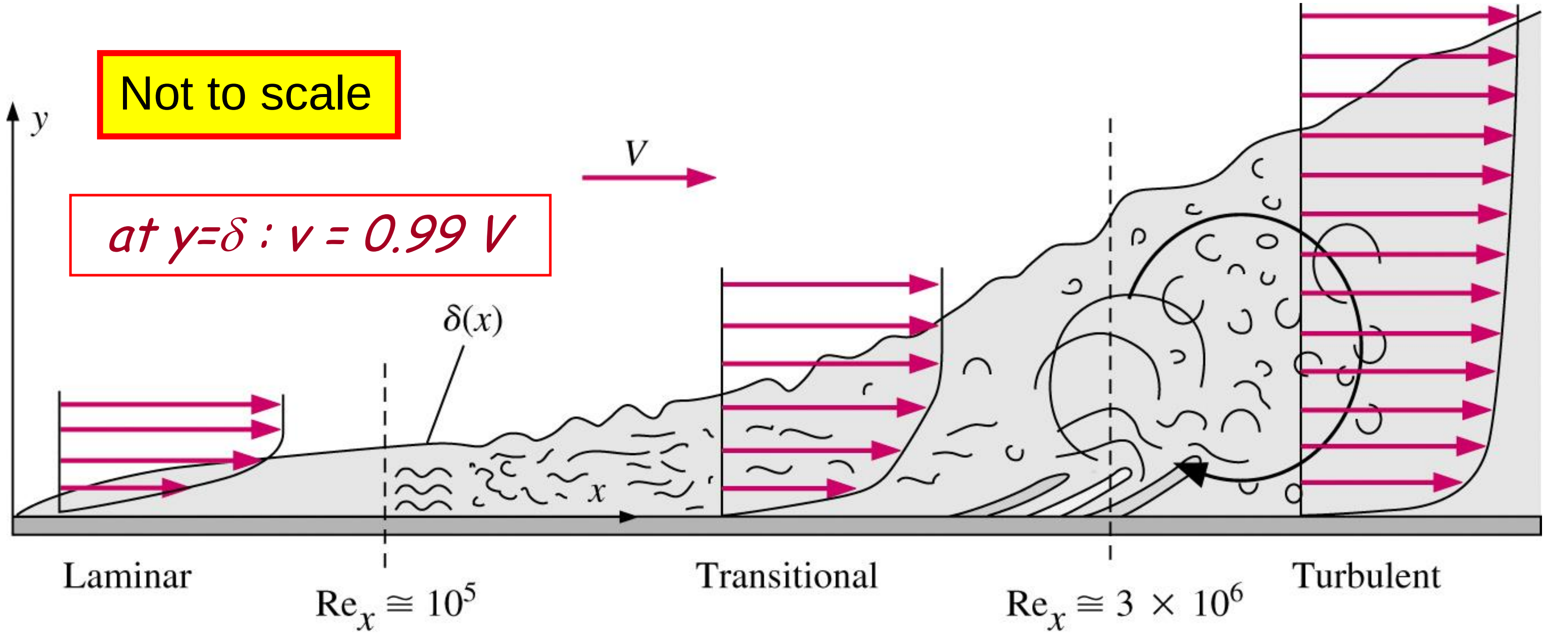
(c)

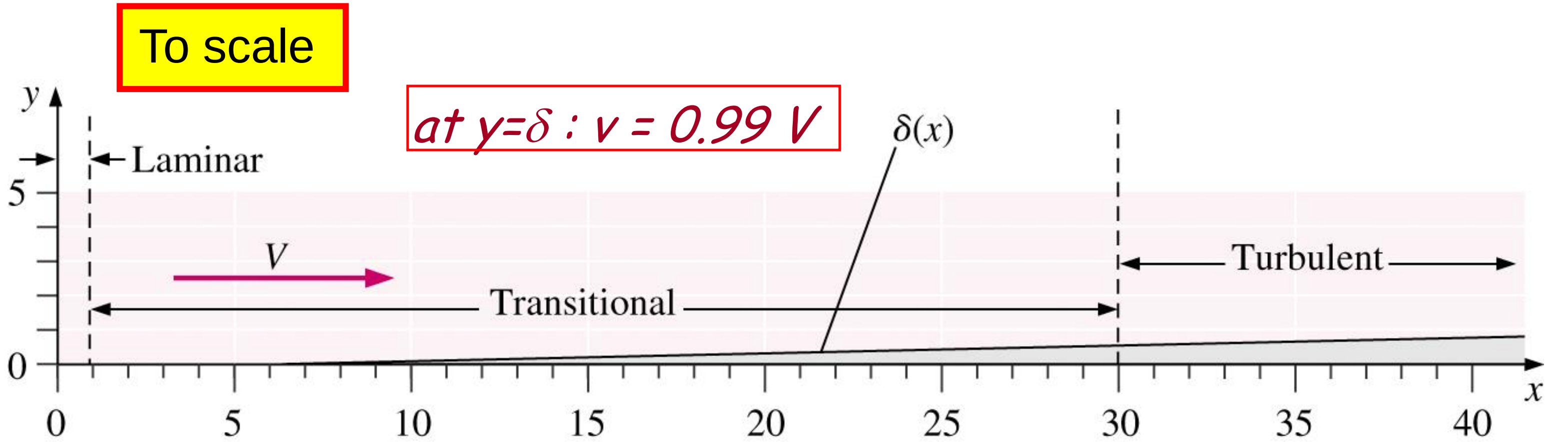
(a) low Reynolds number flow,

(b) moderate Reynolds number flow,

(c) large Reynolds number flow.

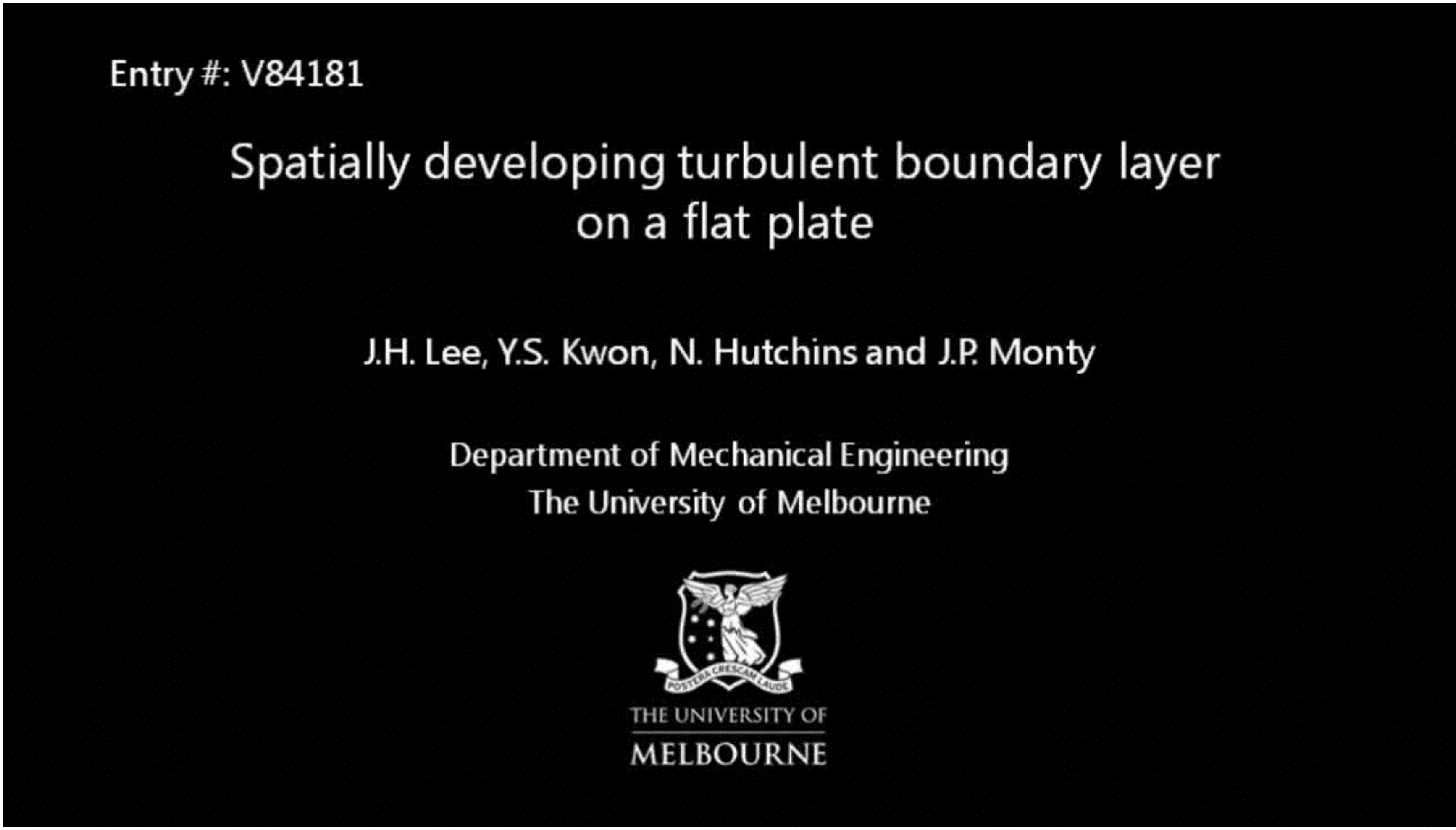
Boundary Layer on a Flat Plate



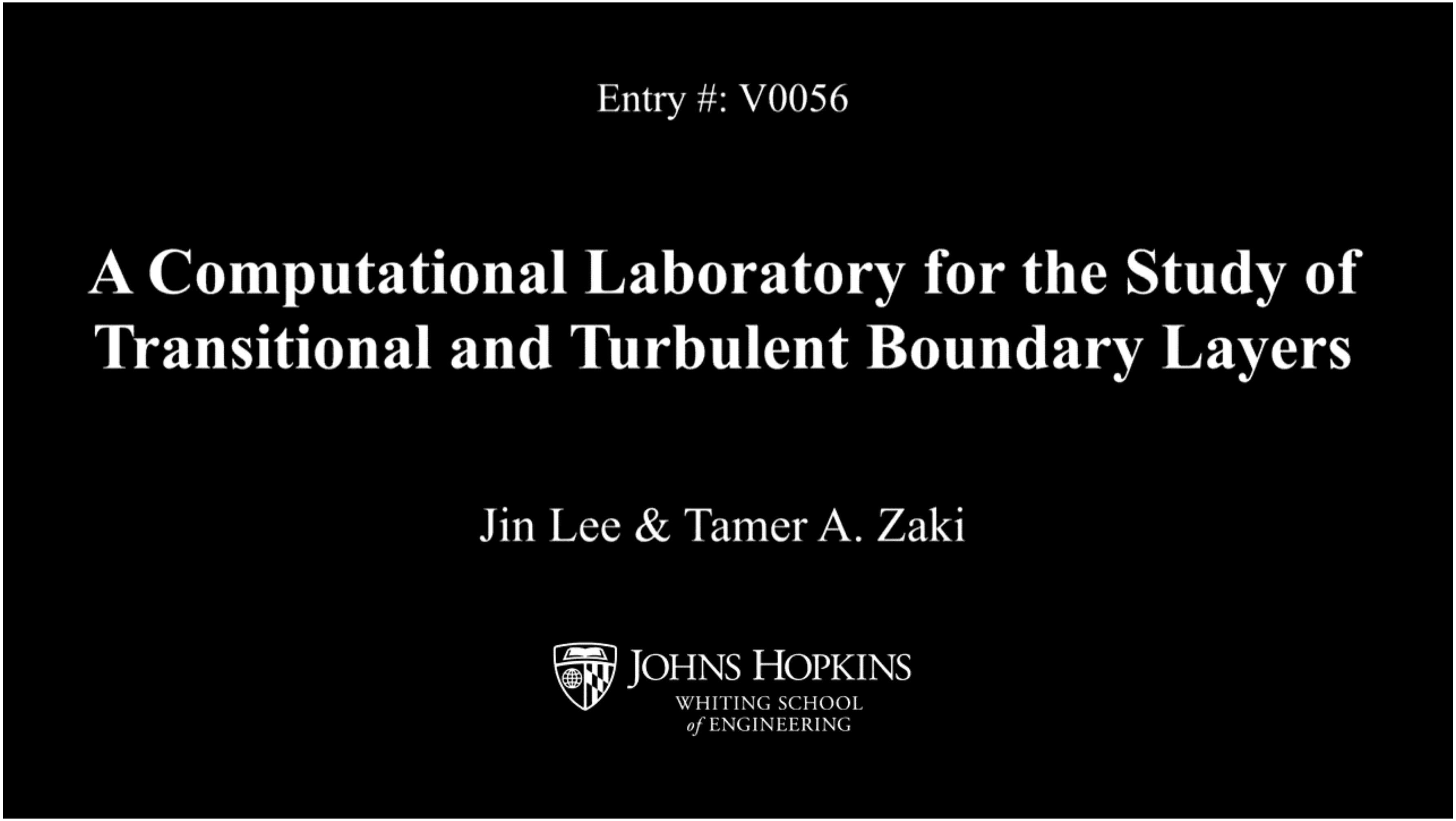


Transition

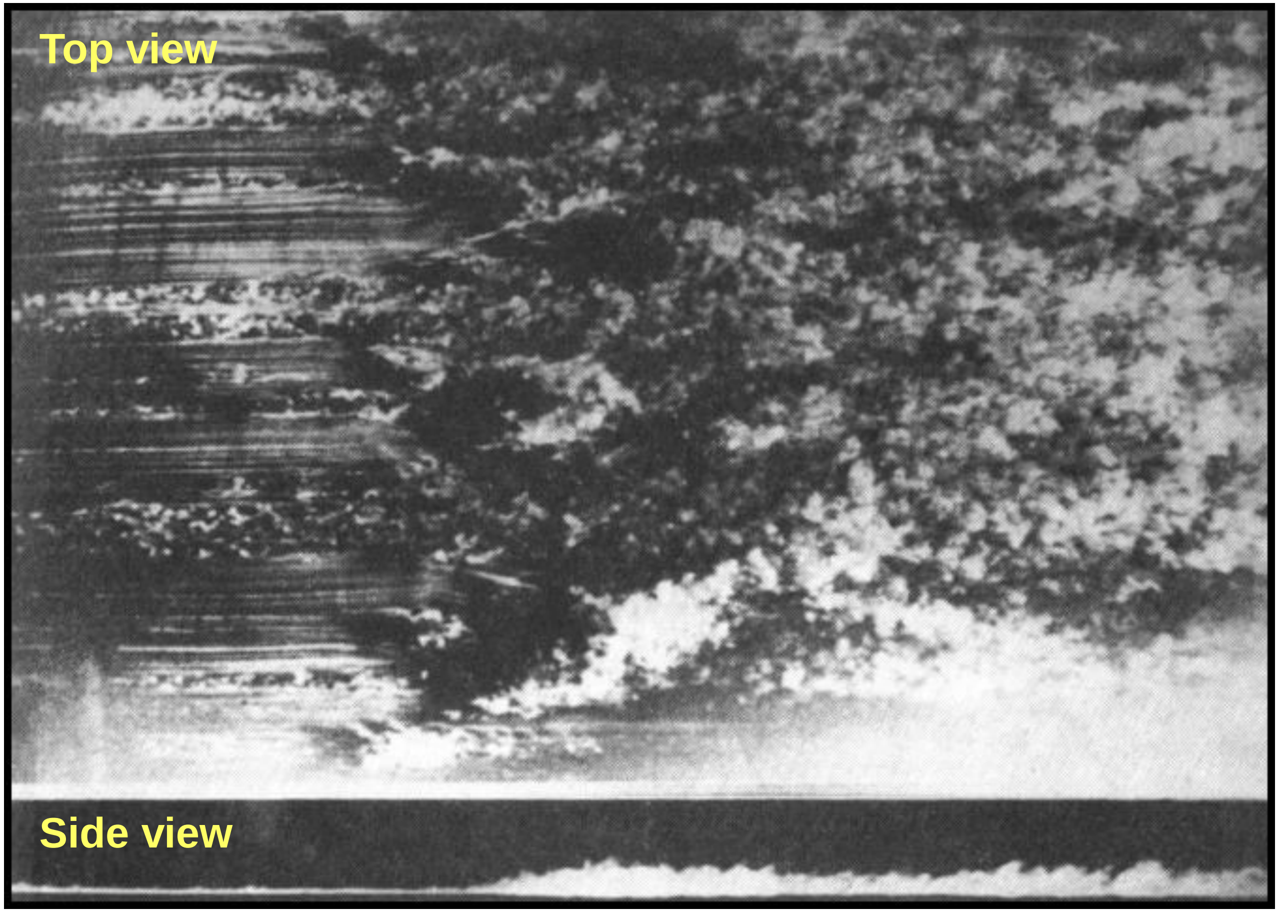
Transition


Entry #: V84181
Spatially developing turbulent boundary layer
on a flat plate
J.H. Lee, Y.S. Kwon, N. Hutchins and J.P. Monty
Department of Mechanical Engineering
The University of Melbourne
THE UNIVERSITY OF
MELBOURNE

Transition

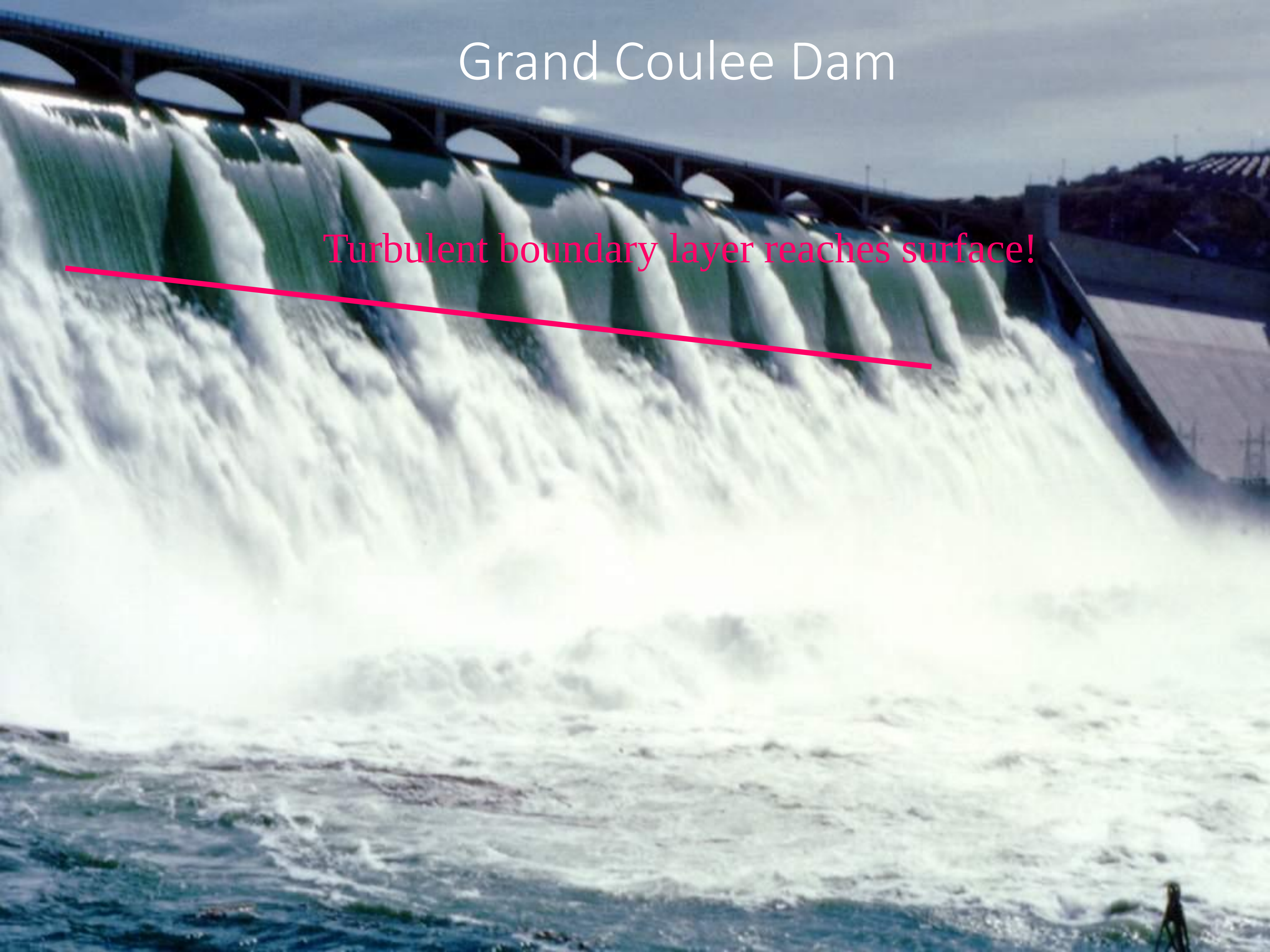

Entry #: V0056
A Computational Laboratory for the Study of Transitional and Turbulent Boundary Layers
Jin Lee & Tamer A. Zaki
JOHNS HOPKINS
WHITING SCHOOL of ENGINEERING

Turbulent boundary layer

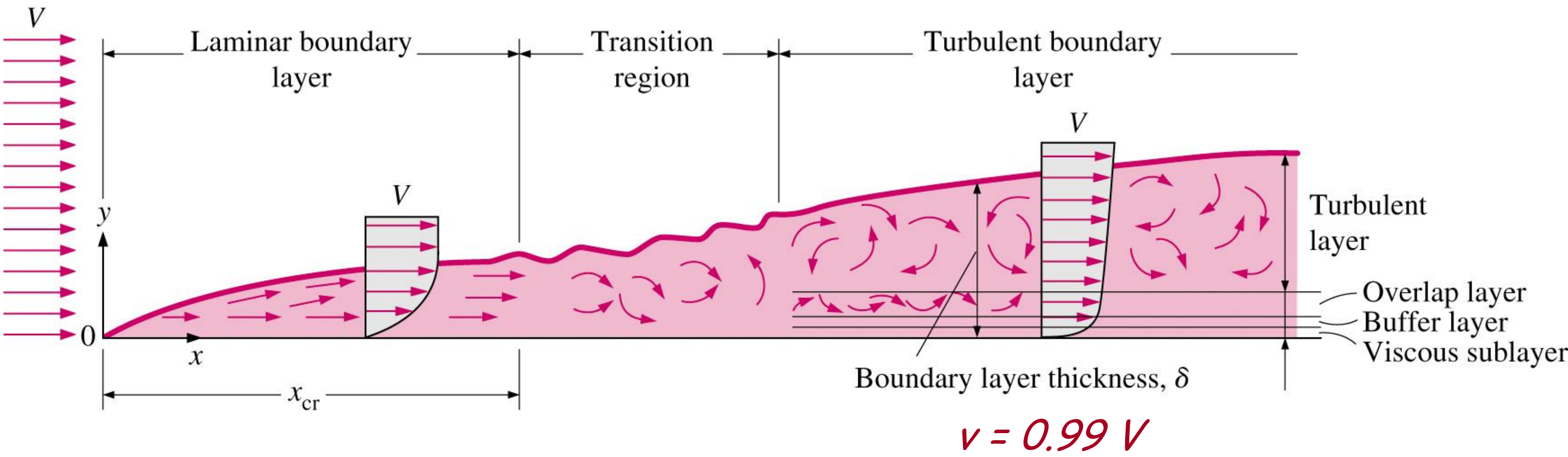


Merging of turbulent spots and transition to turbulence in a natural flat plate boundary layer.

Grand Coulee Dam



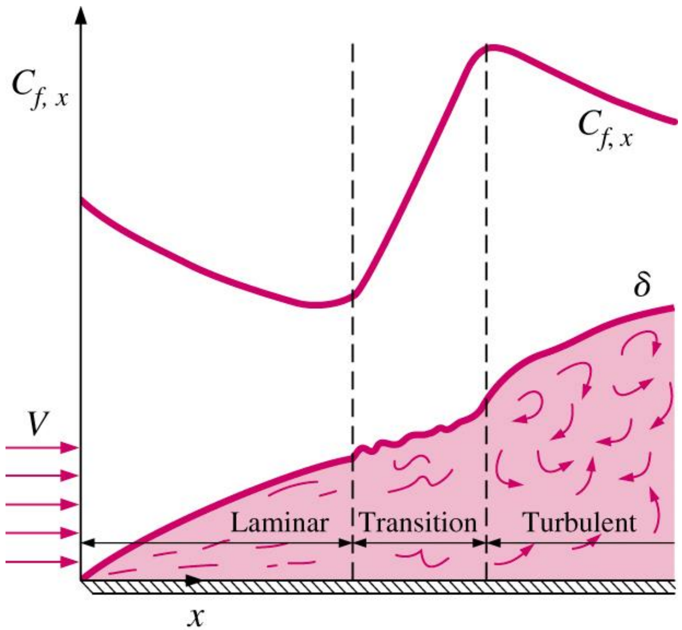
Flat Plate Drag



- Drag on flat plate is solely due to friction ($F_D = F_{Dfriction}$) created by laminar, transitional, and turbulent boundary layers.
- BL thickness, δ, is the distance from the plate at which v = 0.99 V

Flat Plate Drag

$C_{D,\text{ friction}} = C_f$



- Local friction coefficient
  - Laminar: $C_{f,x} = \frac{0.664}{Re_x^{1/2}}$
  - Turbulent: $C_{f,x} = \frac{0.059}{Re_x^{1/5}}$
- Average friction coefficient

$$C_f = \frac{1}{L}\int_0^L C_{f,x}\,dx$$

For some cases, plate is long enough for turbulent flow, but not long enough to neglect laminar portion

$$C_f = \frac{1}{L}\left(\int_0^{x_{cr}} C_{f,x,lam}\,dx + \int_{x_{cr}}^{L} C_{f,x,turb}\,dx\right)$$

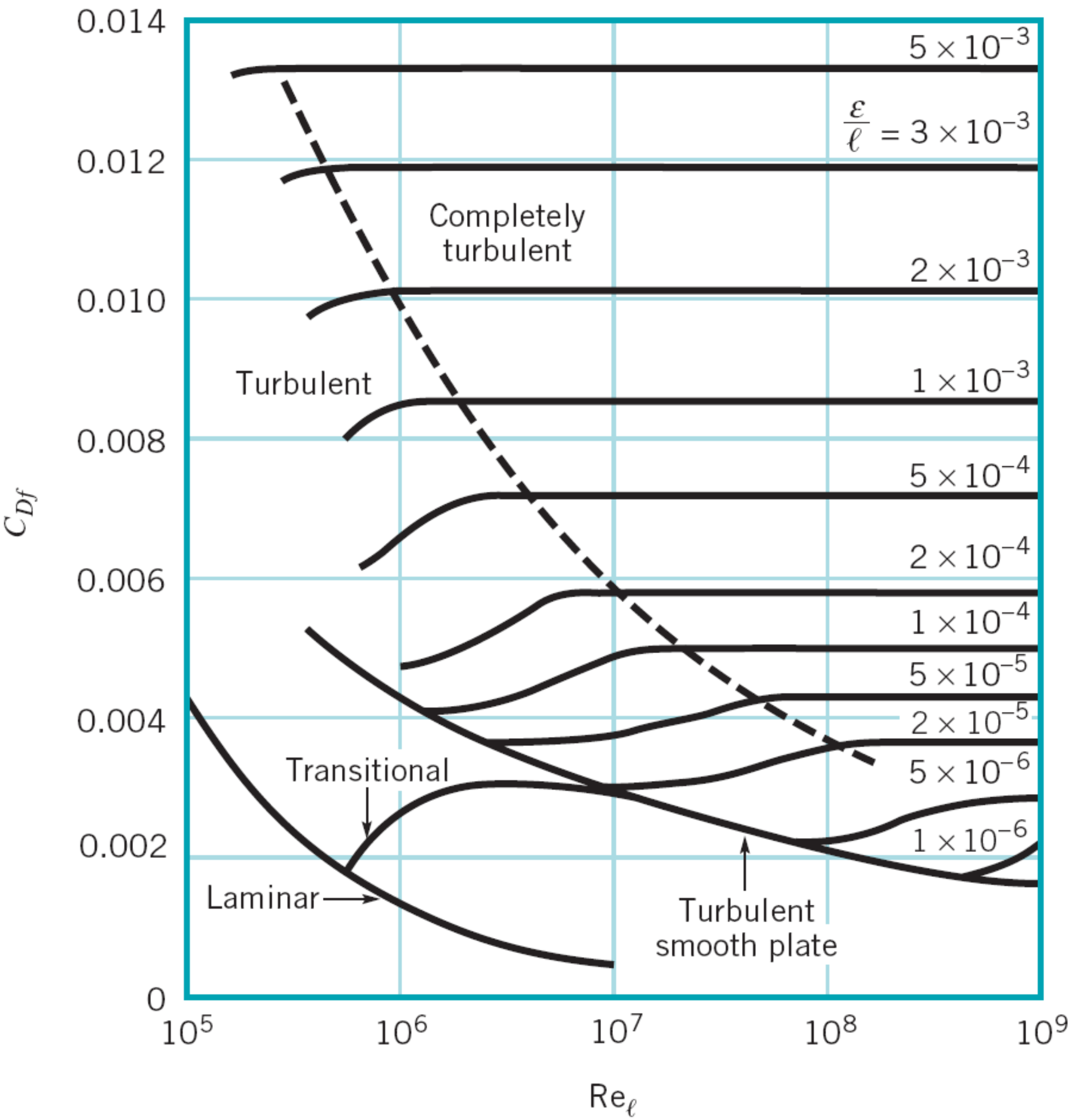
Flat Plate Drag

Empirical Equations for the Flat Plate Drag Coefficient

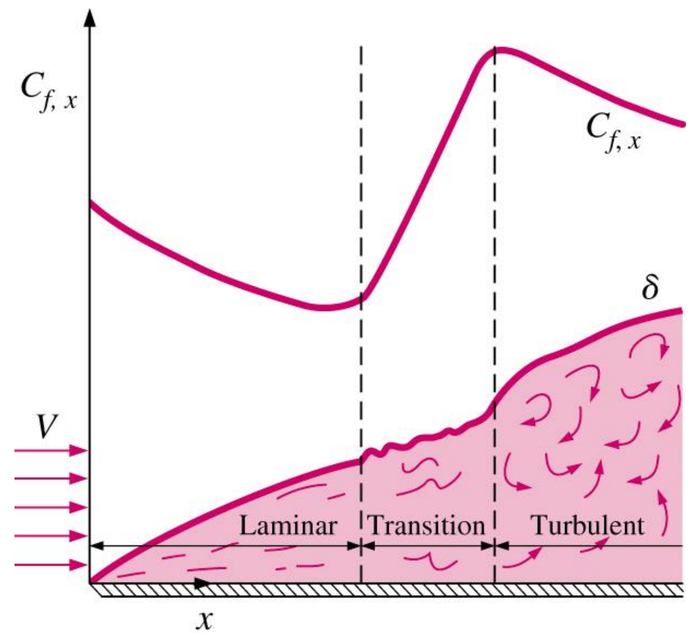
Equation	Flow Conditions
$C_{Df} = 1.328/(\mathrm{Re}_\ell)^{0.5}$	Laminar flow
$C_{Df} = 0.455/(\log \mathrm{Re}_\ell)^{2.58} - 1700/\mathrm{Re}_\ell$	Transitional with $\mathrm{Re}_{xcr} = 5 \times 10^5$
$C_{Df} = 0.455/(\log \mathrm{Re}_\ell)^{2.58}$	Turbulent, smooth plate
$C_{Df} = [1.89 - 1.62 \log(\varepsilon/\ell)]^{-2.5}$	Completely turbulent

Transition takes place at a distance x given by:
$Re_{xcr}=2X10^5$ to $3X10^6$ – $\boxed{\text{We will use } Re_{xcr}= 5X10^5}$

Drag coefficient may also be obtained from charts such as those on the next slides



Friction drag coefficient for a flat plate parallel to the upstream flow.



Laminar: $C_{Df} = f\ (Re)$

Turbulent: $C_{Df} = f\ (Re, \varepsilon/L)$

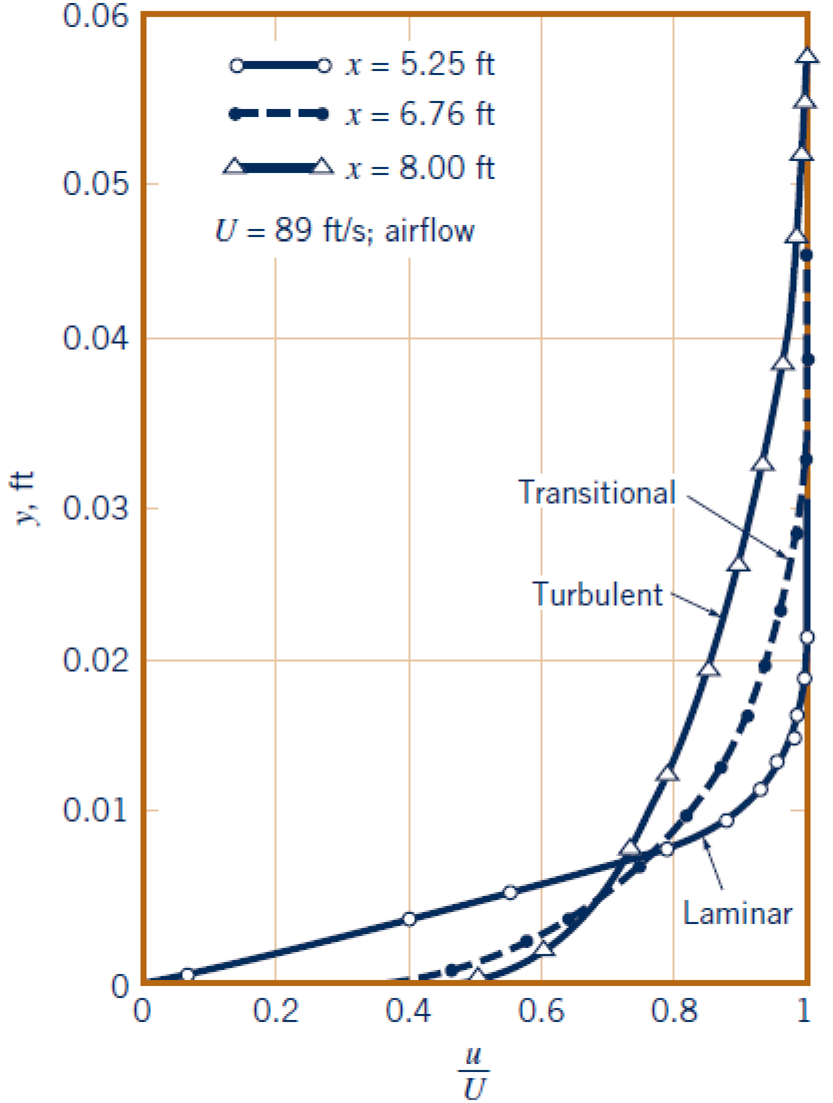


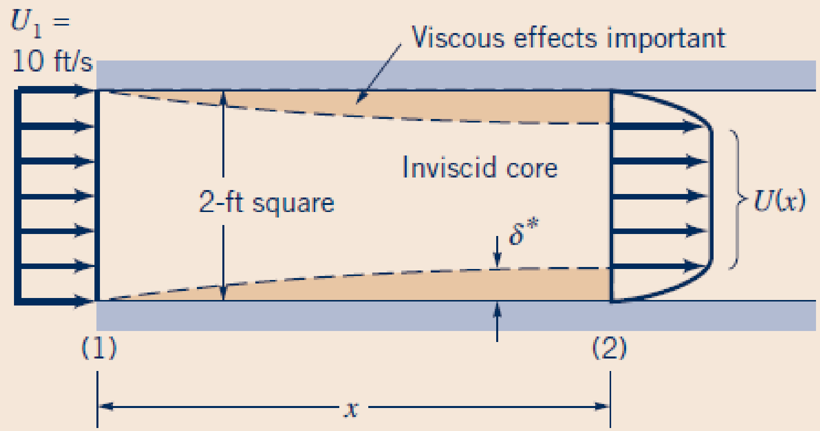
Figure 9.14 Typical boundary layer profiles on a flat plate for laminar, transitional, and turbulent flow (Ref. 1).

Example 9.2

GIVEN Air flowing into a 2-ft-square duct with a uniform velocity of 10 ft/s forms a boundary layer on the walls as shown in Fig. E9.3*a*. The fluid within the core region (outside the boundary layers) flows as if it were inviscid. From advanced calculations it is determined that for this flow the boundary layer displacement thickness is given by

$$\delta^* = 0.0070(x)^{1/2} \qquad (1)$$

where δ^* and x are in feet.



FIND Determine the velocity $U = U(x)$ of the air within the duct but outside of the boundary layer.

Example 9.2 - Solution

If we assume incompressible flow (a reasonable assumption because of the low velocities involved), it follows that the volume flowrate across any section of the duct is equal to that at the entrance (i.e., $Q_1 = Q_2$). That is,

$$U_1 A_1 = 10 \text{ ft/s } (2 \text{ ft})^2 = 40 \text{ ft}^3\text{/s} = \int_{(2)} u \, dA$$

According to the definition of the displacement thickness, δ^*, the flowrate across section (2) is the same as that for a uniform flow with velocity U through a duct whose walls have been moved inward by δ^*. That is,

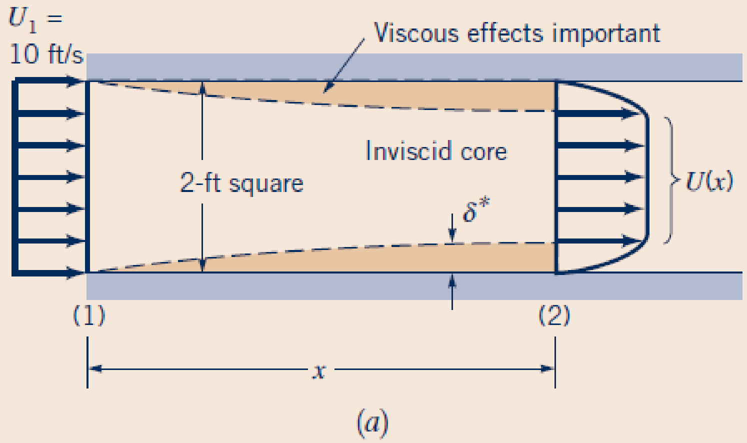
$$40 \text{ ft}^3\text{/s} = \int_{(2)} u \, dA = U(2 \text{ ft} - 2\delta^*)^2 \qquad \textbf{(2)}$$

By combining Eqs. 1 and 2 we obtain

$$40 \text{ ft}^3\text{/s} = 4U(1 - 0.0070x^{1/2})^2$$

or

$$U = \frac{10}{(1 - 0.0070x^{1/2})^2} \text{ ft/s} \qquad \textbf{(Ans)}$$



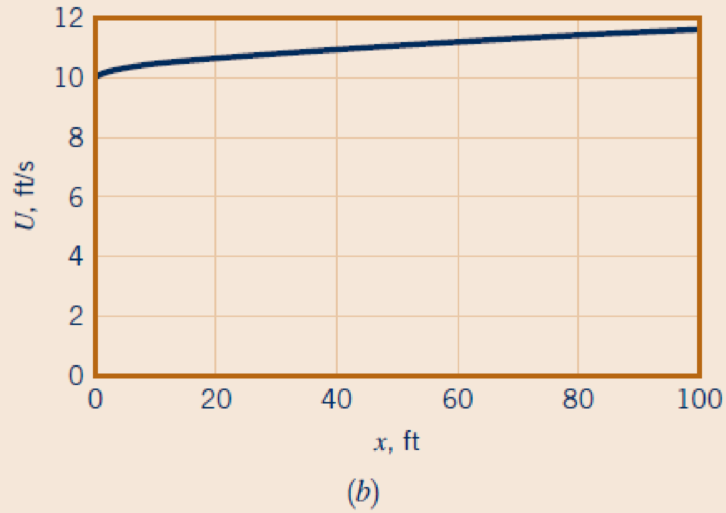
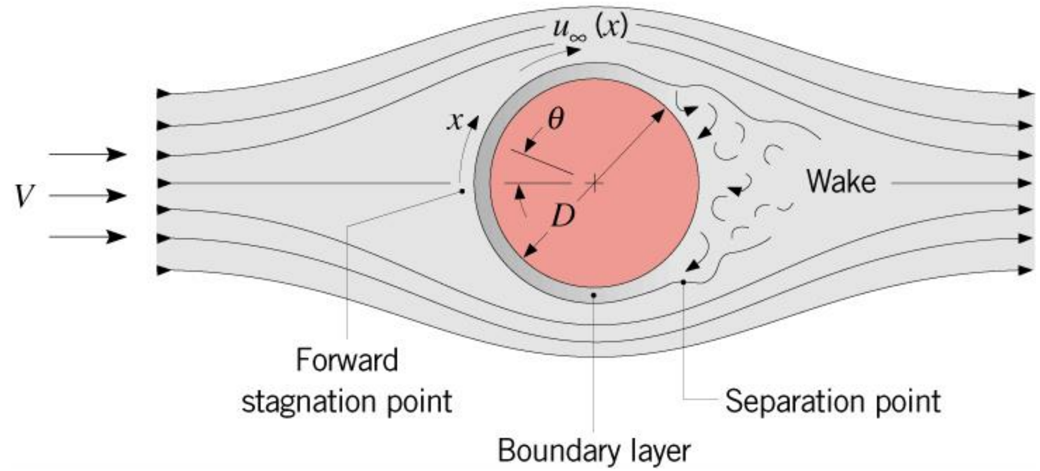


Figure E9.3

Cylinders in Cross Flow

Conditions depend on special features of boundary layer development, including onset at a stagnation point and separation, as well as transition to turbulence.



- Stagnation point: Location of zero velocity and maximum pressure. Followed by boundary layer development under a favorable pressure gradient and hence acceleration of the free stream flow
- As the rear of the cylinder is approached, the pressure must begin to increase.
- Hence, there is a minimum in the pressure distribution, *p(x)*, after which boundary layer development occurs under the influence of an adverse pressure gradient

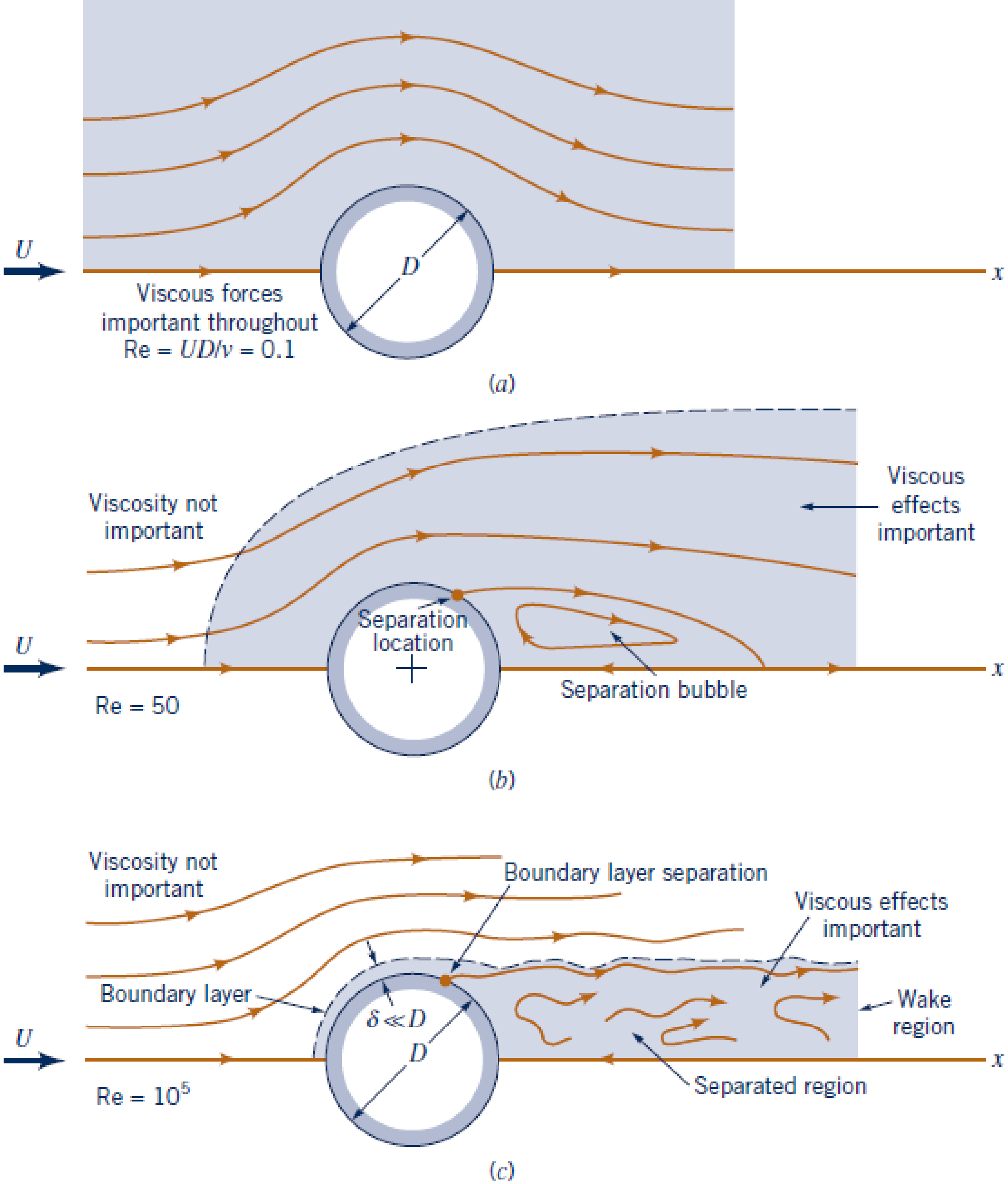


Figure 9.6 Character of the steady, viscous flow past a circular cylinder: (*a*) low Reynolds number flow, (*b*) moderate Reynolds number flow, (*c*) large Reynolds number flow.

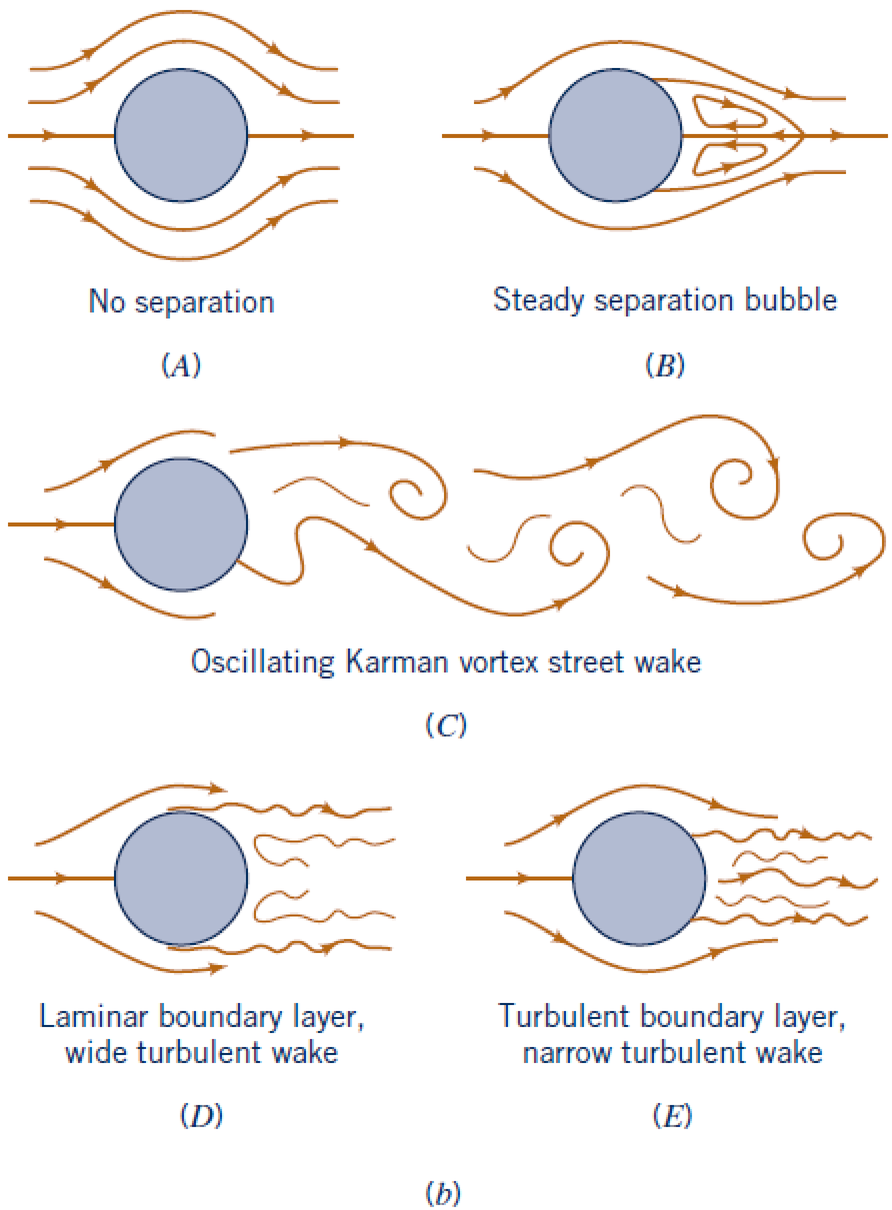
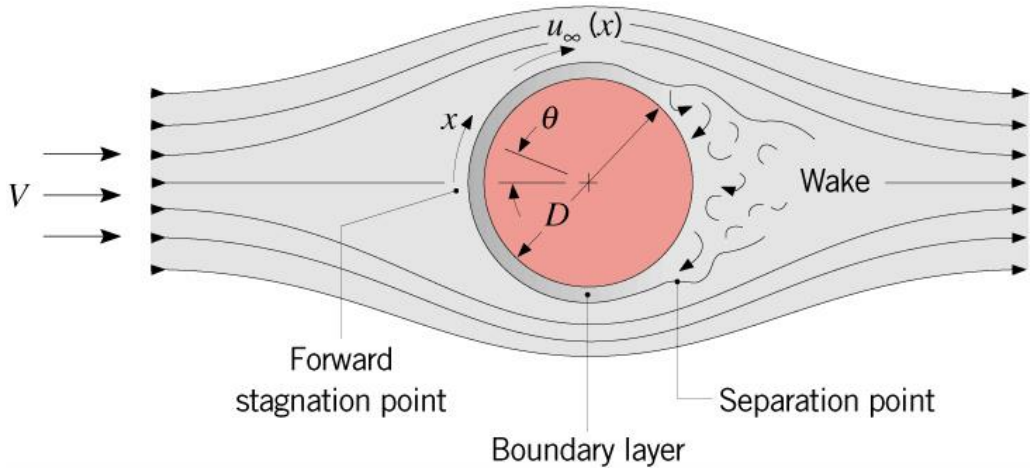
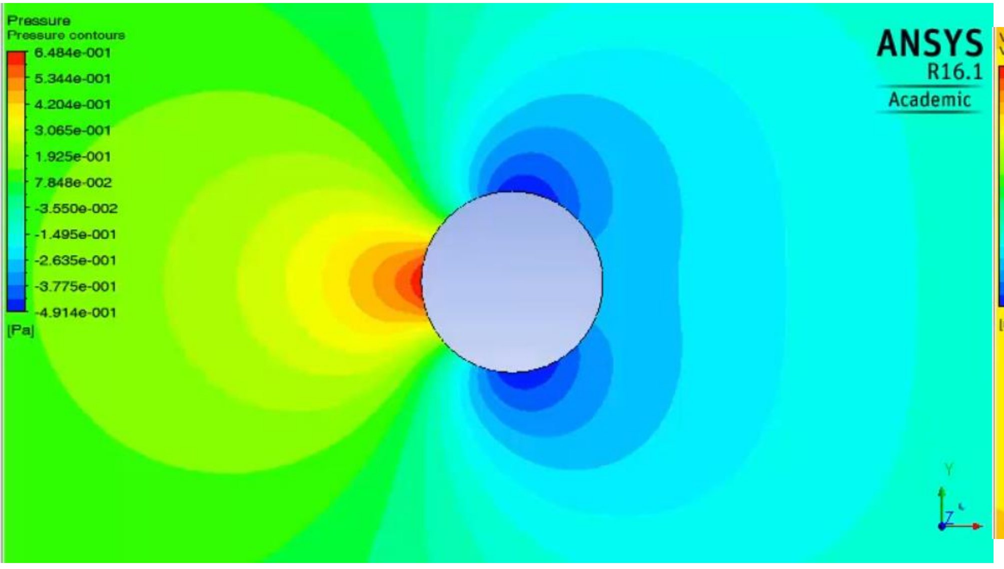
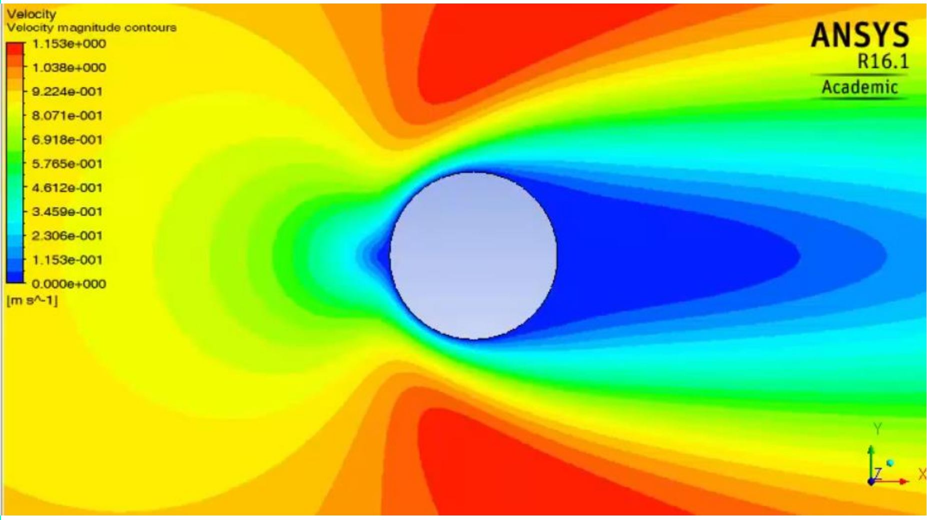


Figure 9.21 (*a*) Drag coefficient as a function of Reynolds number for a smooth circular cylinder and a smooth sphere. (*b*) Typical flow patterns for flow past a circular cylinder at various Reynolds numbers as indicated in (*a*).

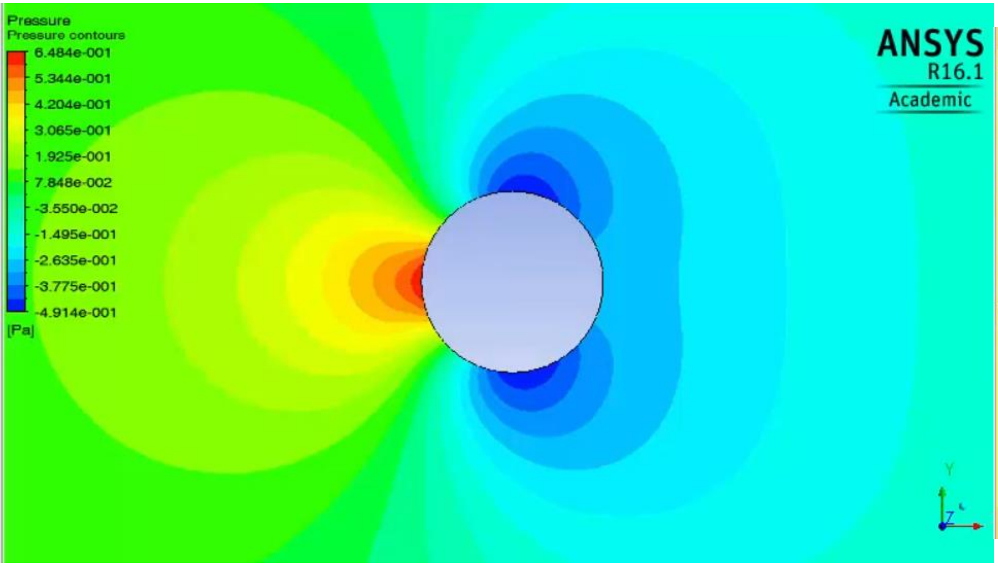
Cylinders in Cross Flow

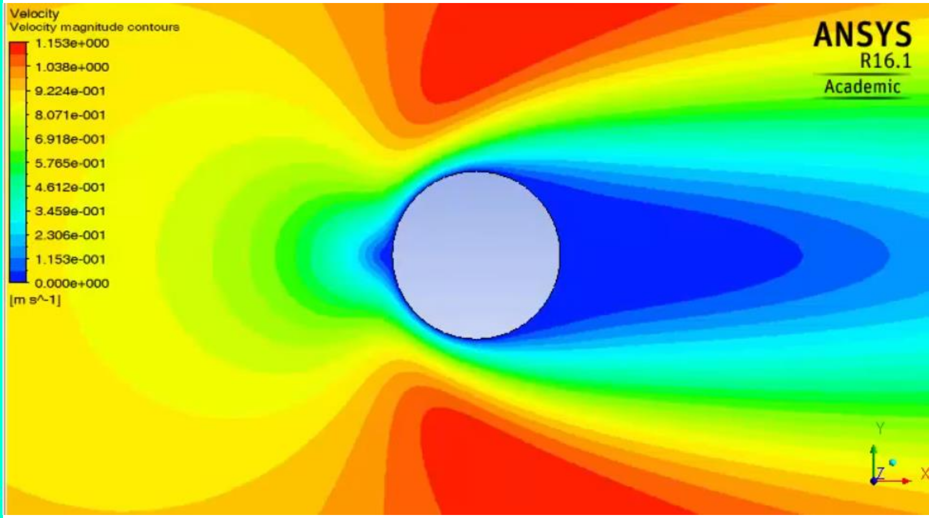


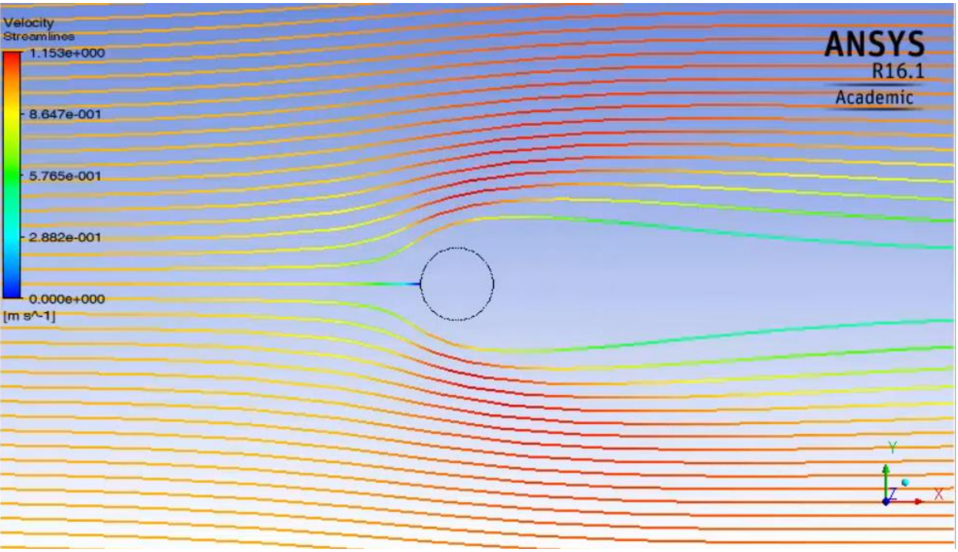


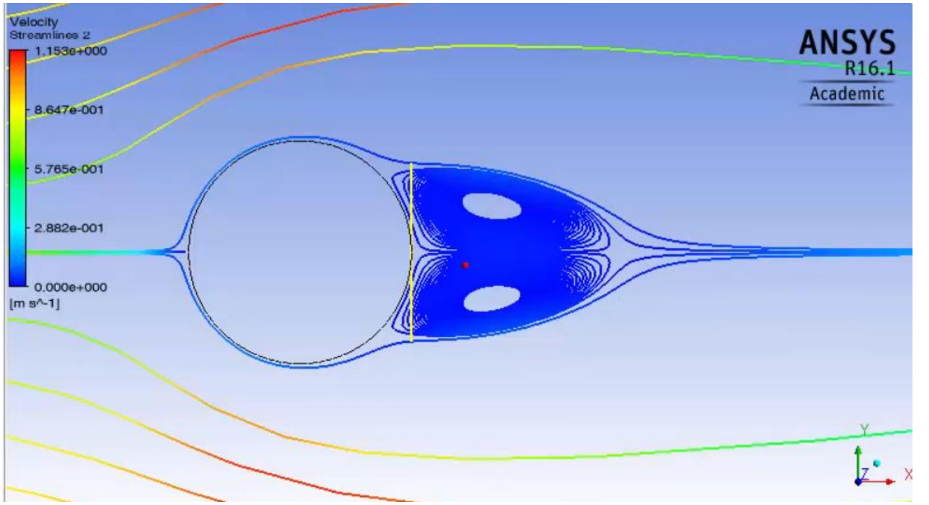


Cylinders in Cross Flow

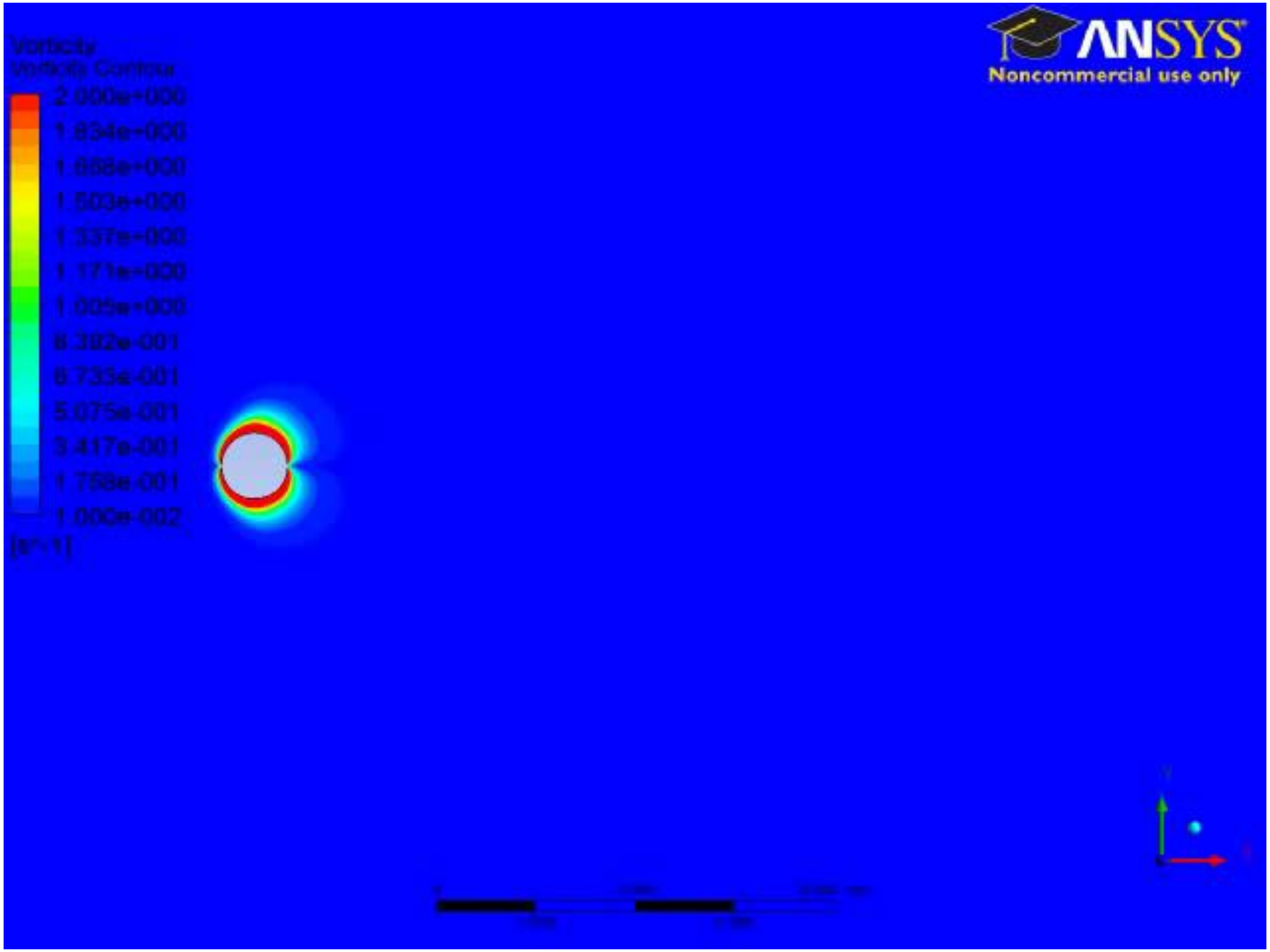




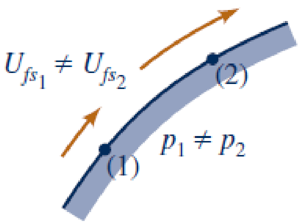




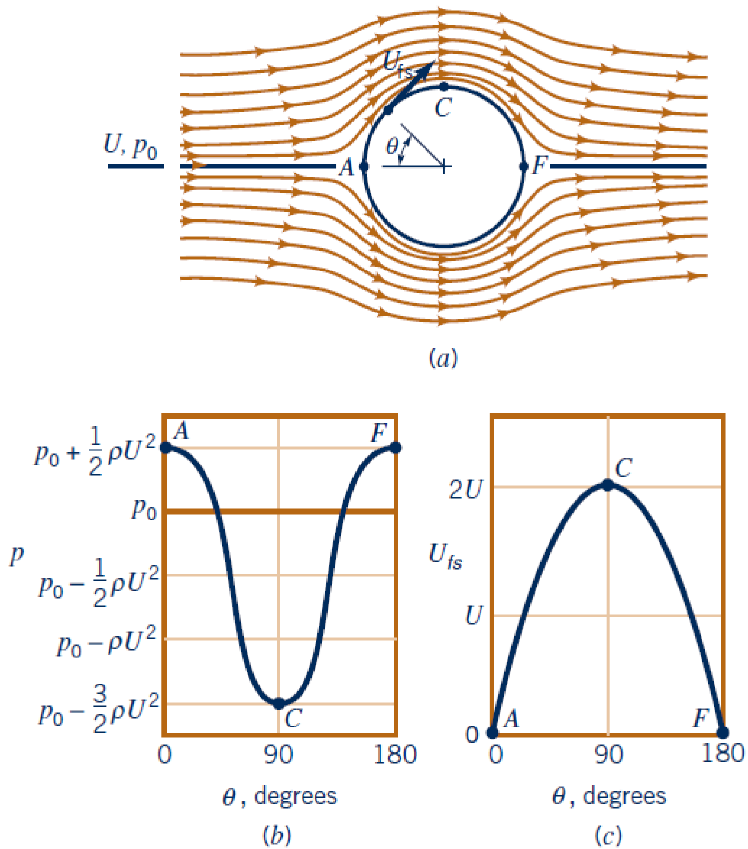
Cylinders in Cross Flow



Cylinders in Cross Flow



The free-stream velocity on a curved surface is not constant.



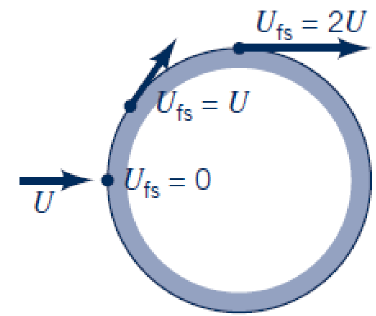


Figure 9.16 **Inviscid flow past a circular cylinder: (*a*) streamlines for the flow if there were no viscous effects, (*b*) pressure distribution on the cylinder's surface, (*c*) free-stream velocity on the cylinder's surface.**

Cylinders in Cross Flow

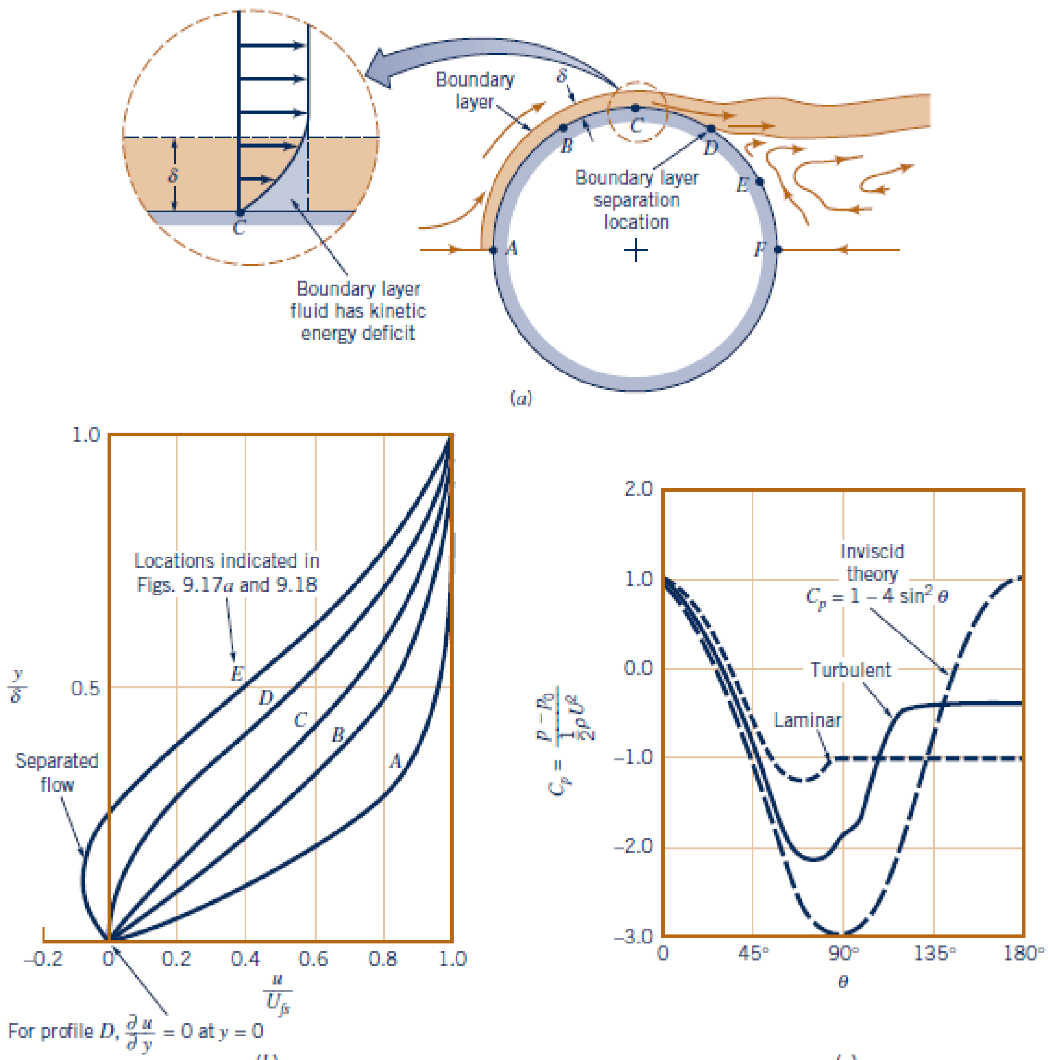
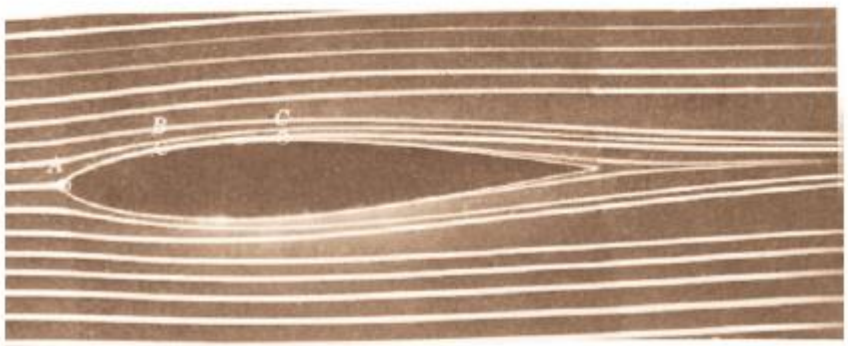
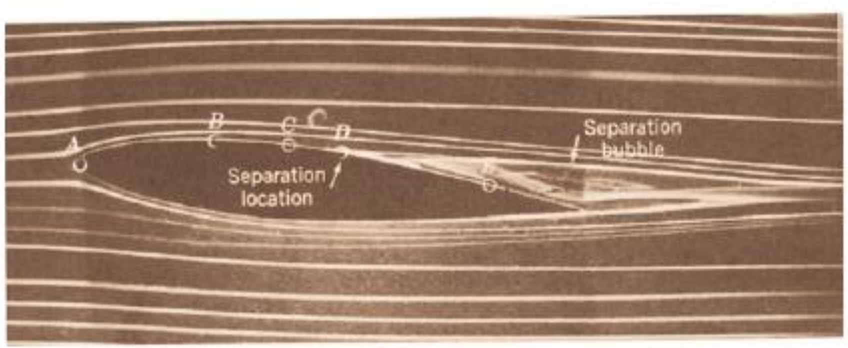


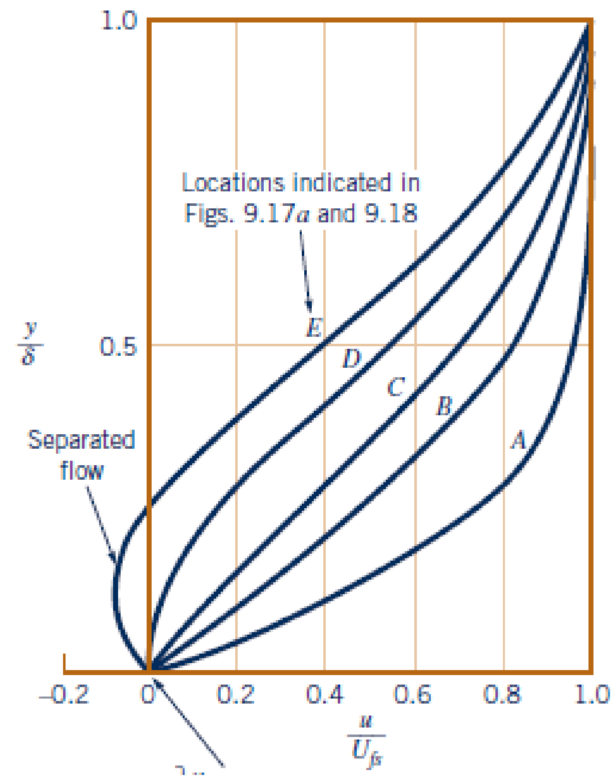
Figure 9.17 Boundary layer characteristics on a circular cylinder: (*a*) boundary layer separation location, (*b*) typical boundary layer velocity profiles at various locations on the cylinder, (*c*) surface pressure distributions for inviscid flow and boundary layer flow.



(*a*)



(*b*)

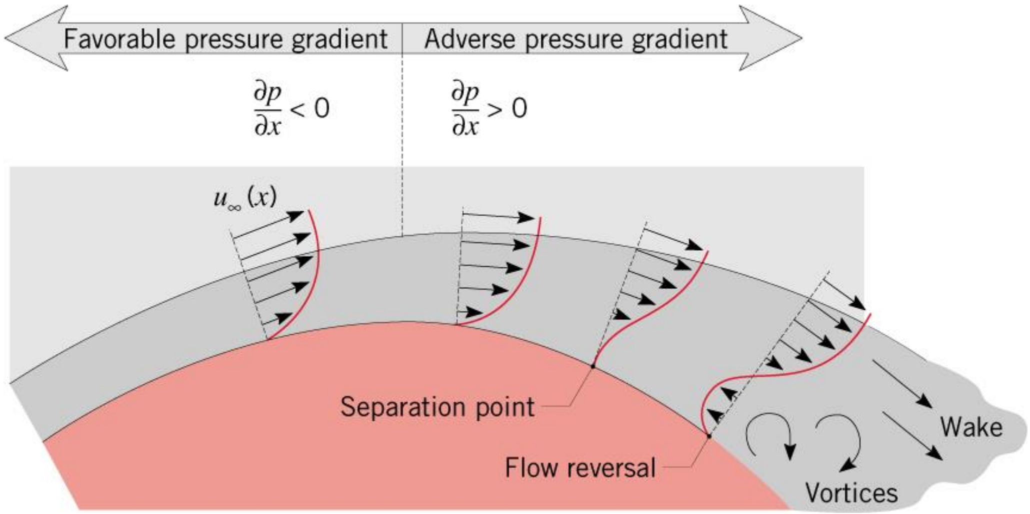


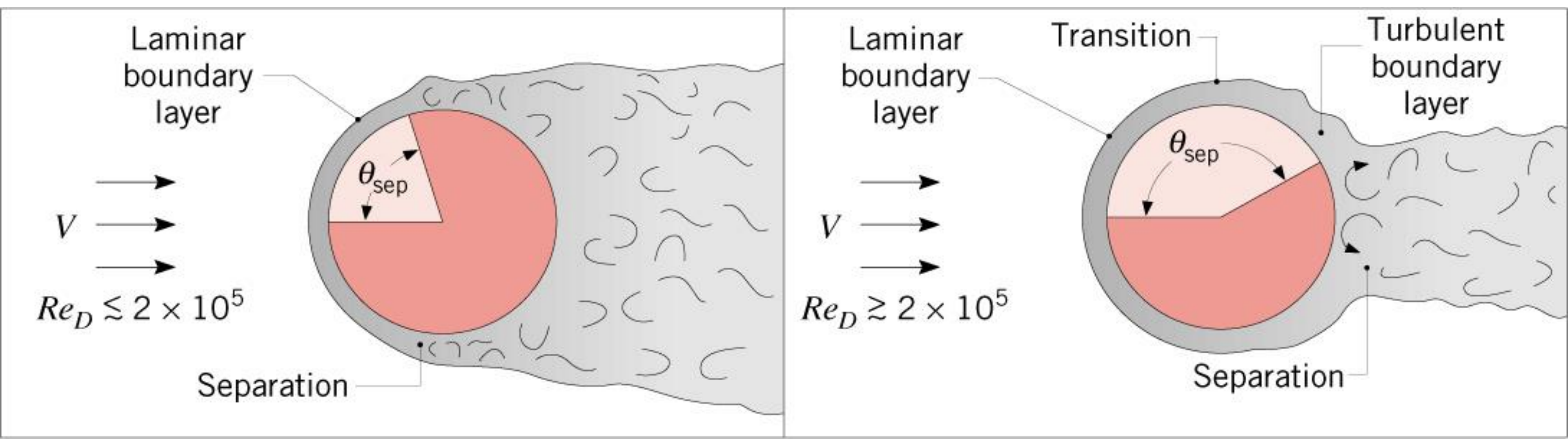
■ **Figure 9.18** **Flow visualization photographs of flow past an airfoil (the boundary layer velocity profiles for the points indicated are similar to those indicated in Fig. 9.17*b*): (*a*) zero angle of attack, no separation, (*b*) 5° angle of attack, flow separation. Dye in water. (Photographs courtesy of ONERA, The French Aerospace Lab.)**

– What features differentiate boundary development for the flat plate in parallel flow from that for flow over a cylinder?

–Separation occurs when the velocity gradient reduces to zero.

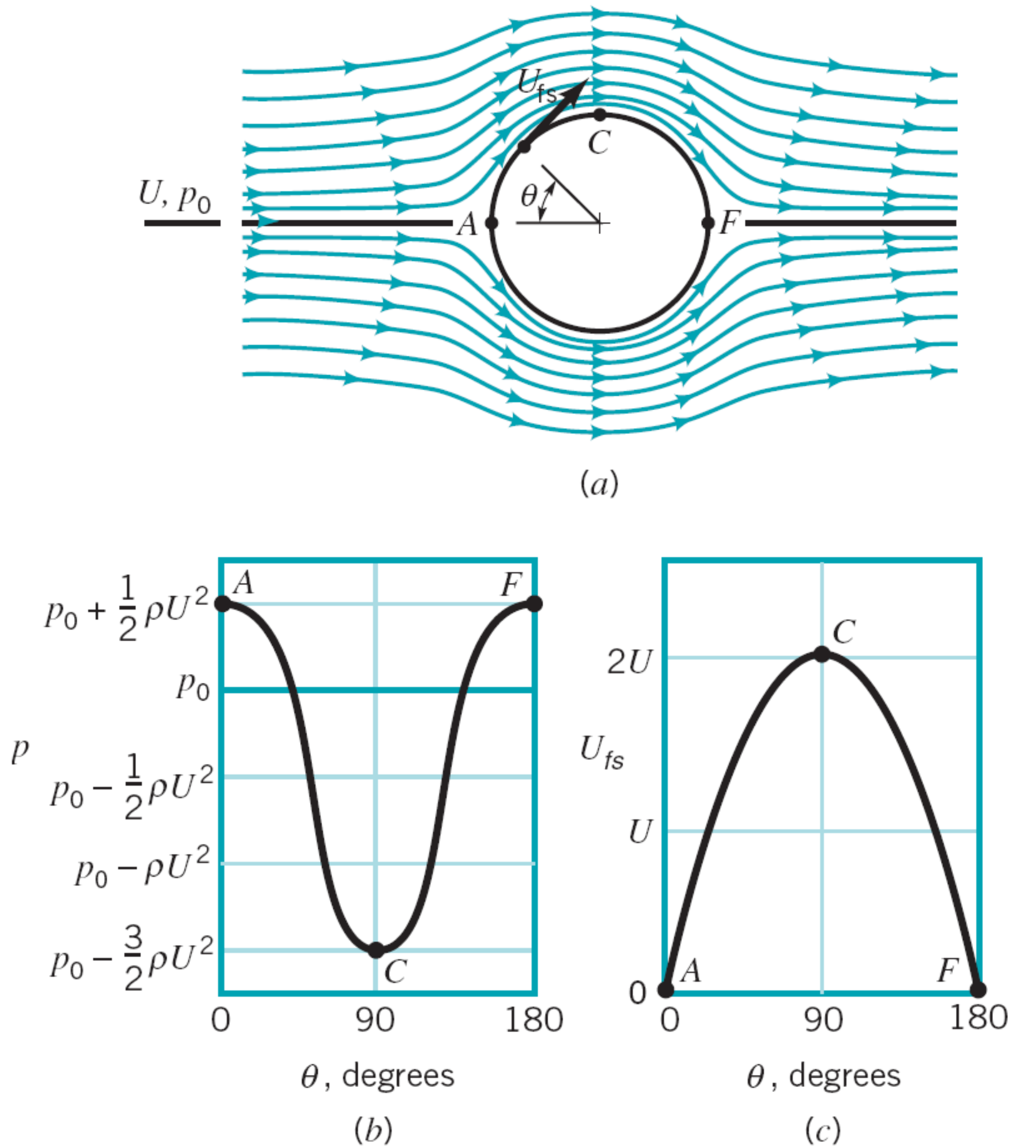
and is accompanied by flow reversal and a downstream wake.
Location of separation depends on boundary layer transition.





Flow around a cylinder

- Inviscid flow past a circular cylinder: (*a*) streamlines for the flow if there were no viscous effects. (*b*) pressure distribution on the cylinder's surface, (*c*) free-stream velocity on the cylinder's surface.

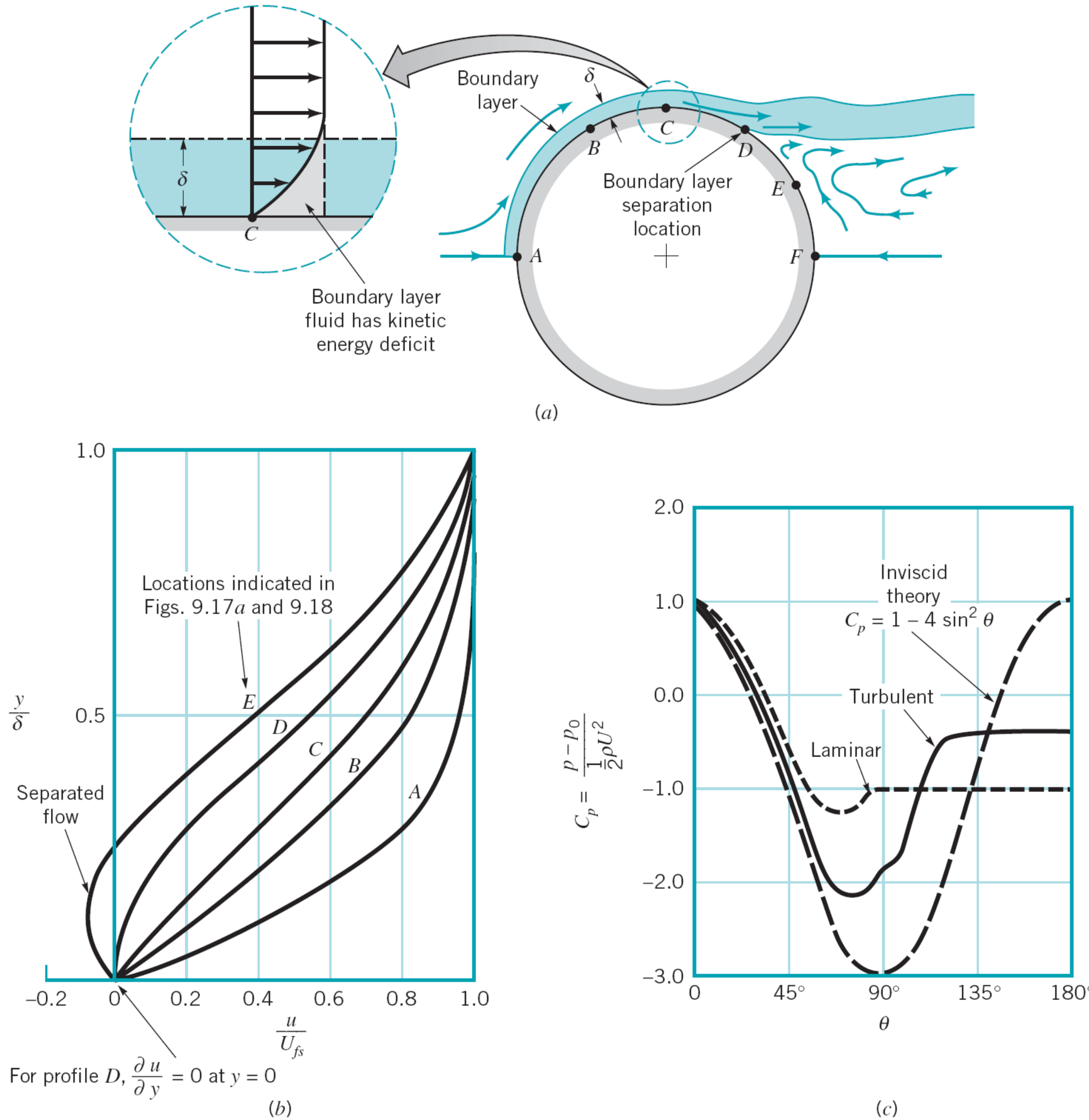


Boundary layer characteristics on a circular cylinder:

(a) boundary layer separation location.

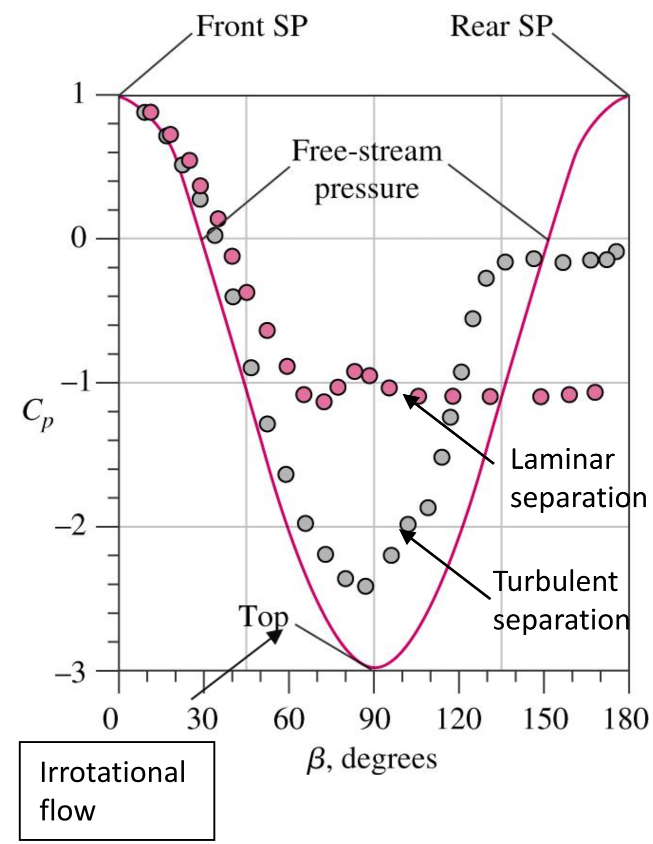
(b) typical boundary layer velocity profiles at various locations on the cylinder,

(c) surface pressure distributions for inviscid flow and boundary layer flow.



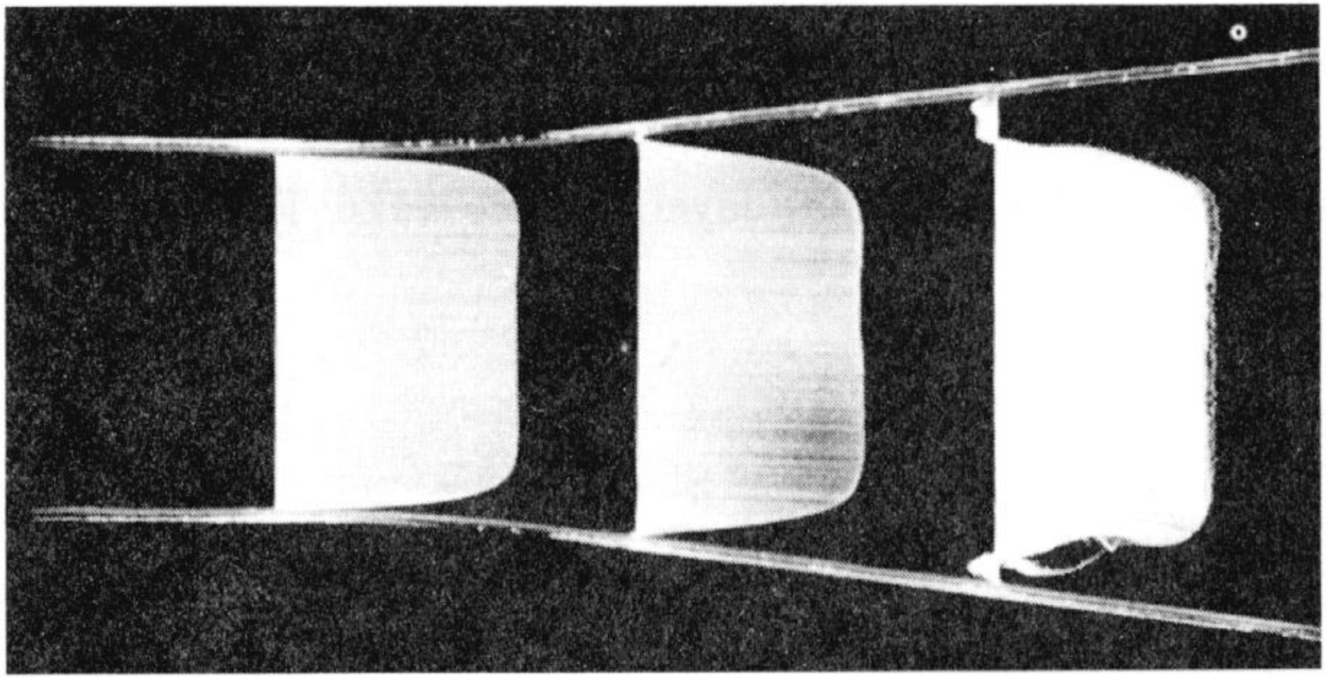
Flow around a Cylinder

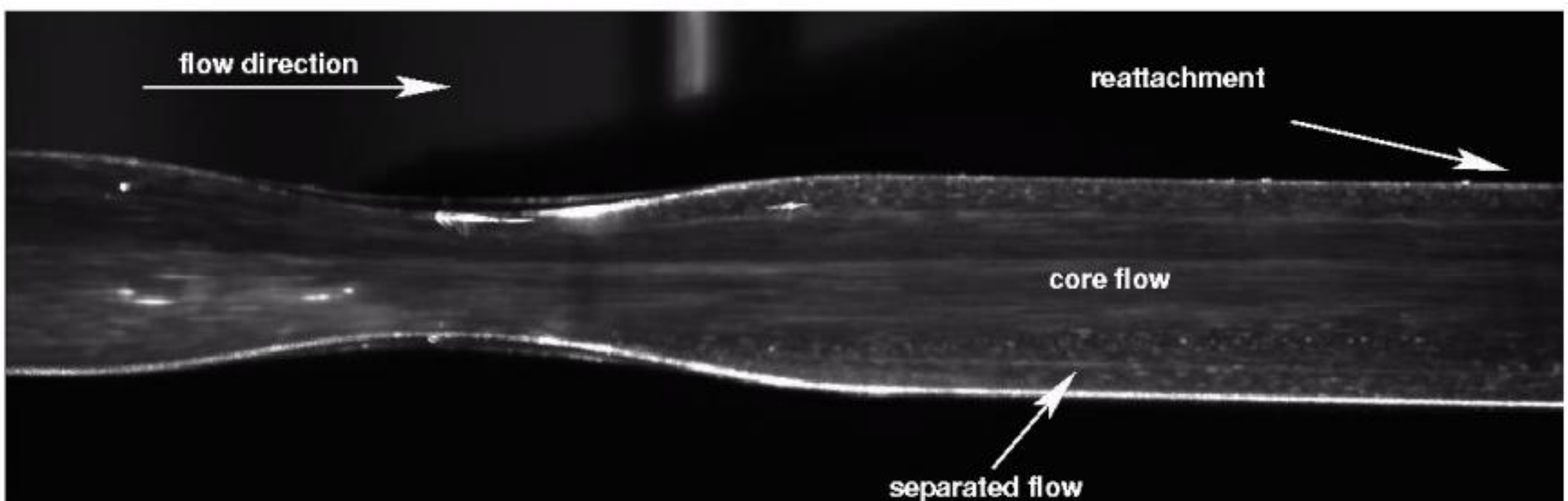
- Integration of surface pressure (which is symmetric in x), reveals that the DRAG is ZERO. This is known as *D'Alembert's Paradox*
  - For the irrotational flow approximation, the drag force on ***any*** non-lifting body of ***any*** shape immersed in a uniform stream is **ZERO**
  - Why?
  - Viscous effects have been neglected. Viscosity and the no-slip condition are responsible for
  - ➢Flow separation (which contributes to pressure drag)
  - ➢Wall-shear stress (which contributes to friction drag)



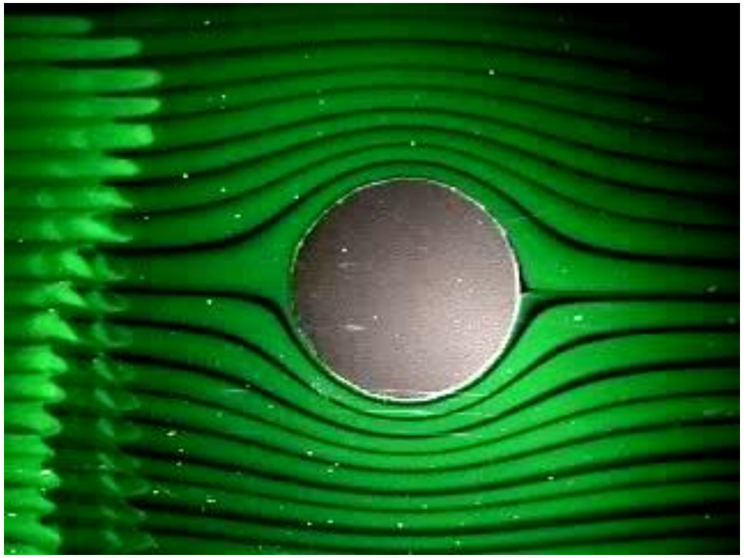
$$C_P = \frac{P - P_\infty}{\rho V^2} = 1 - \frac{V^2}{V_\infty^2}$$

Flow separation in a diffuser with a large angle

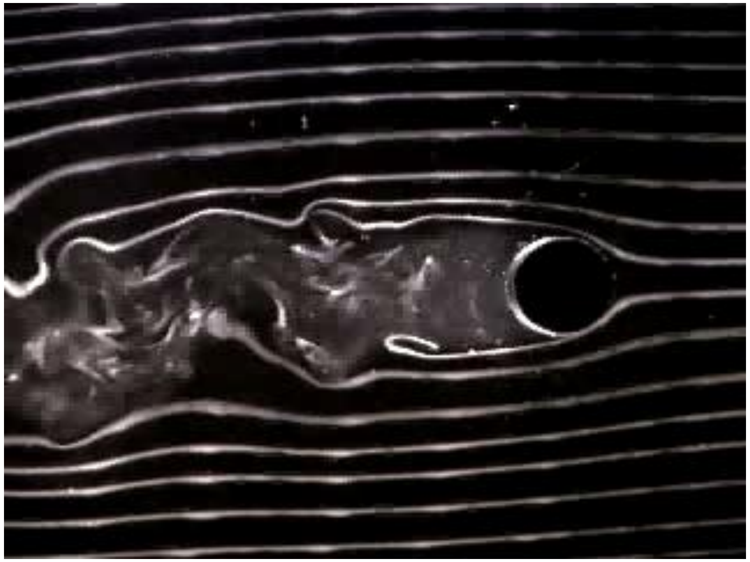




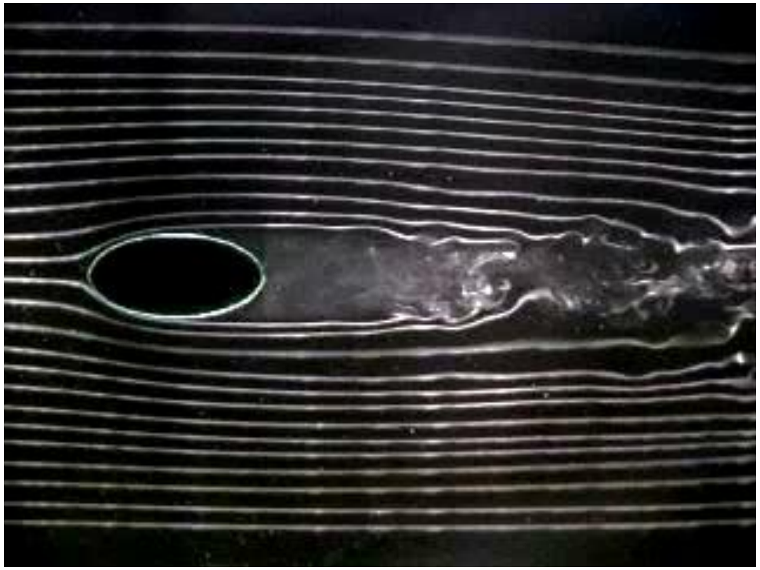
Flow around Cylinders & Ellipsoids



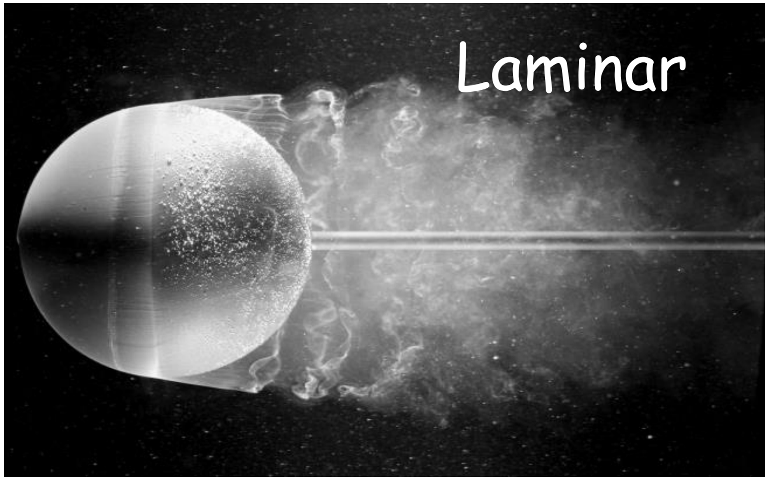
Potential (Ideal) Flow

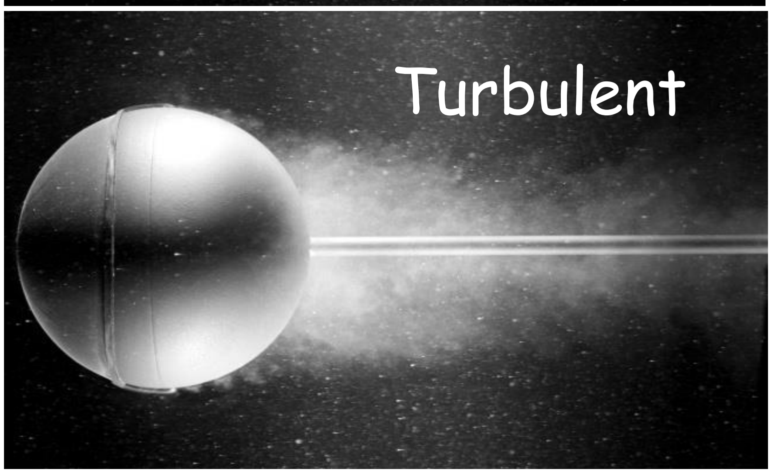


Real Flow

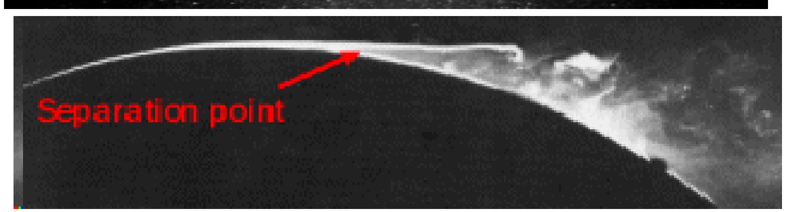


Cylinder and Sphere Drag

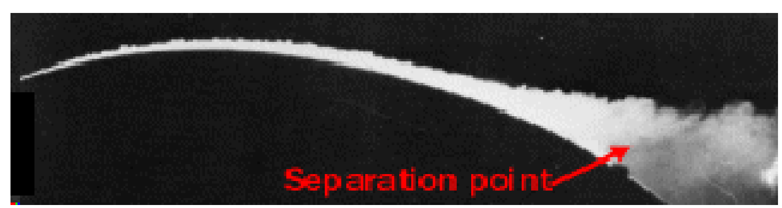




- Flow is strong function of Re.
- Wake narrows for turbulent flow since TBL (turbulent boundary layer) is more resistant to separation due to adverse pressure gradient.
- $\theta_{sep,lam} \approx 80^{\circ}$
- $\theta_{sep,turb} \approx 140^{\circ}$



Laminar Separation



Turbulent Separation

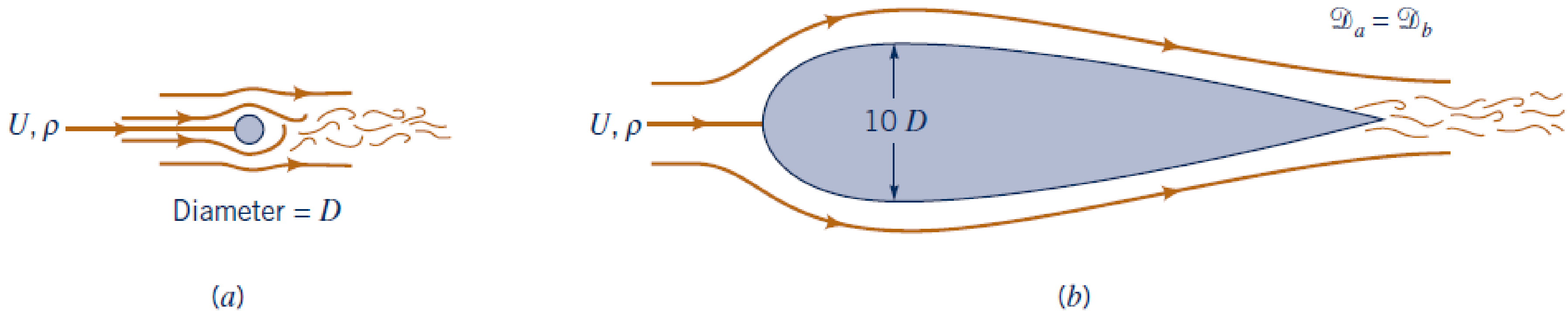
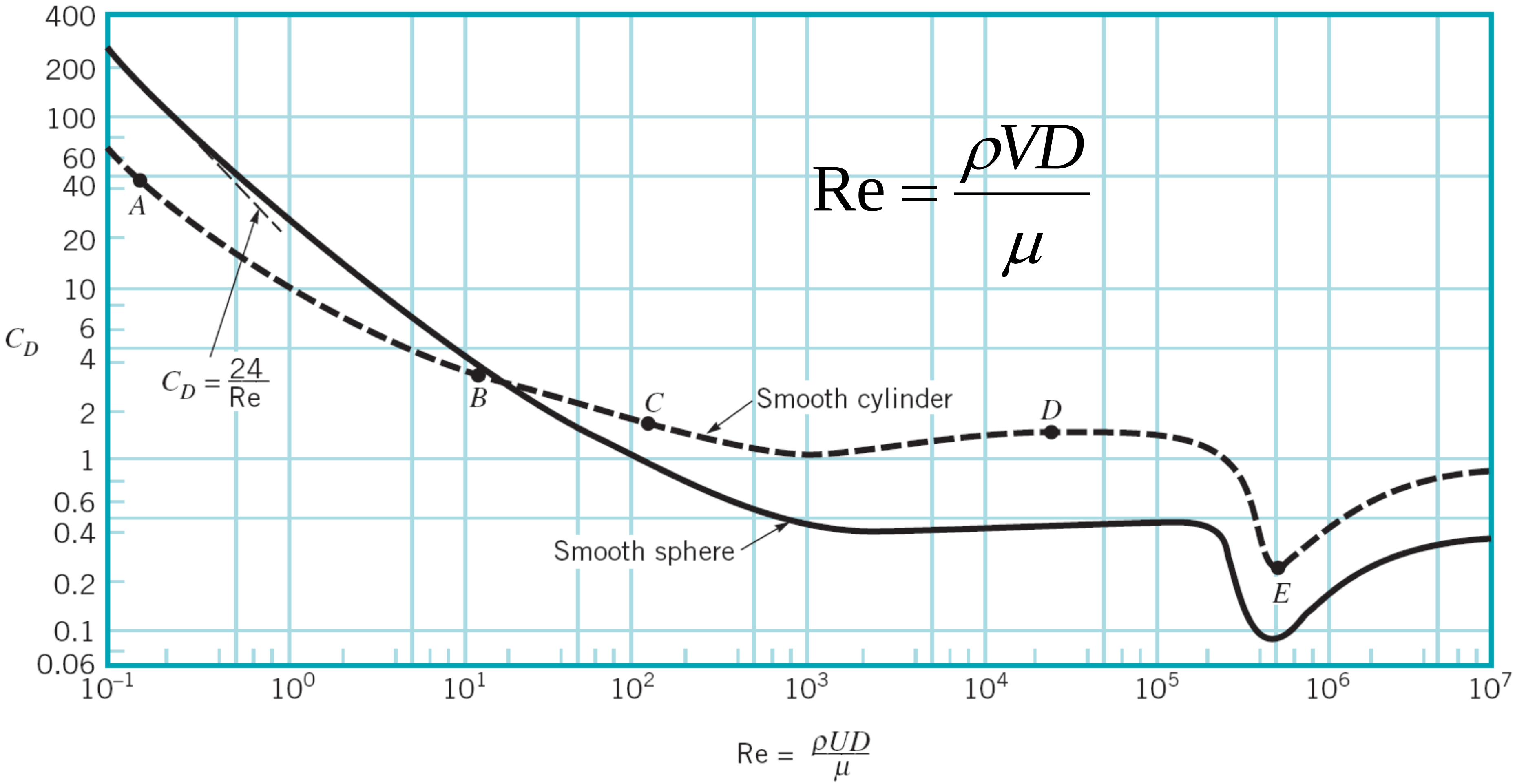


Figure 9.20 Two objects of considerably different size that have the same drag force: (*a*) circular cylinder $C_D = 1.2$; (*b*) streamlined strut $C_D = 0.12$.

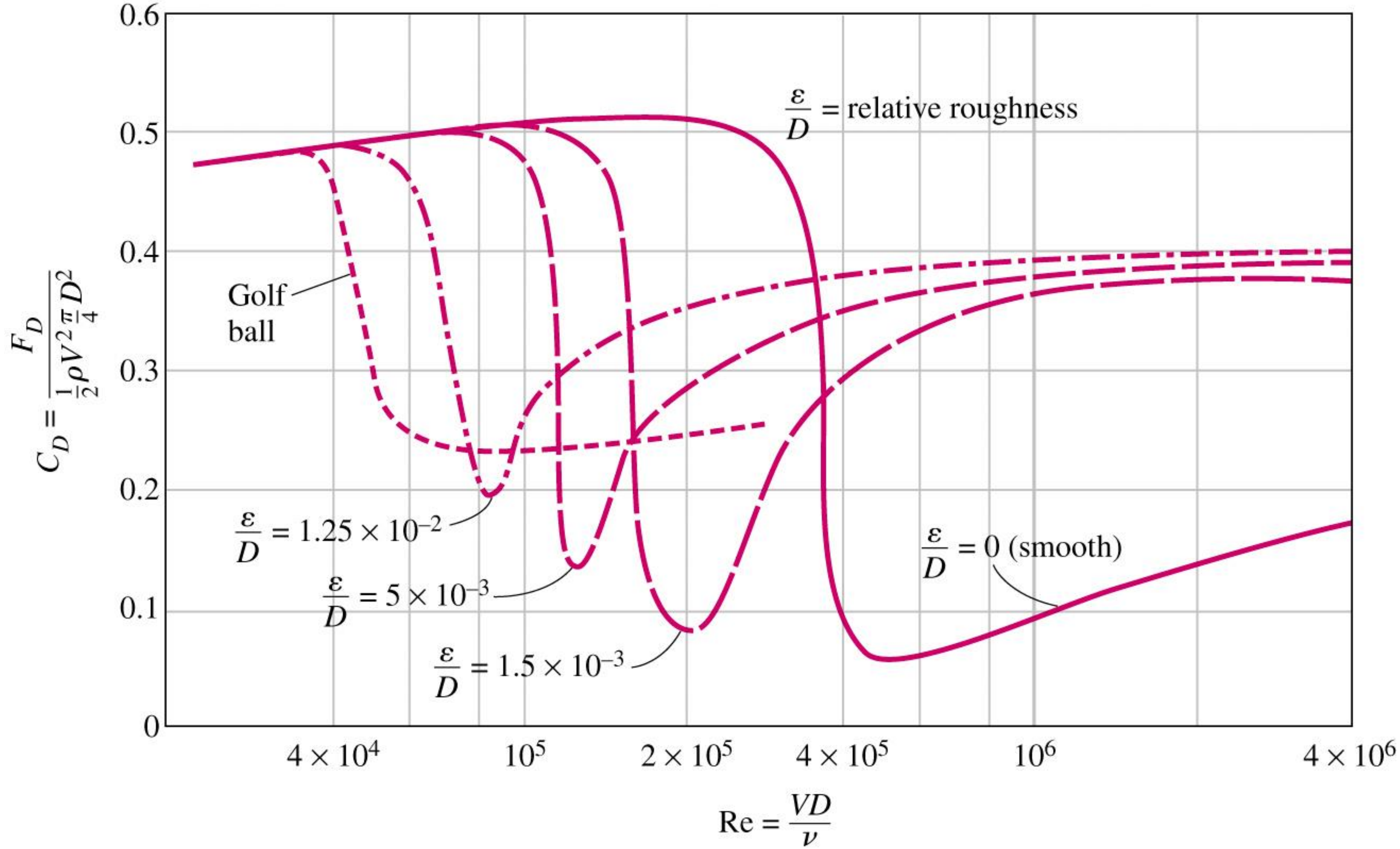
Smooth Cylinder and Sphere Drag



$$Re = \frac{\rho V D}{\mu}$$

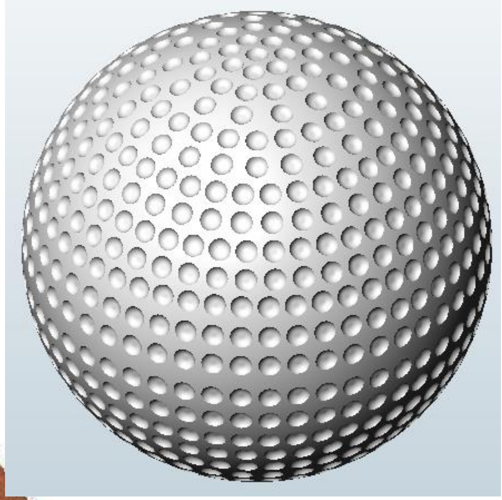
Drag coefficient as a function of Reynolds number for a smooth circular cylinder and a smooth sphere.

Effect of Surface Roughness



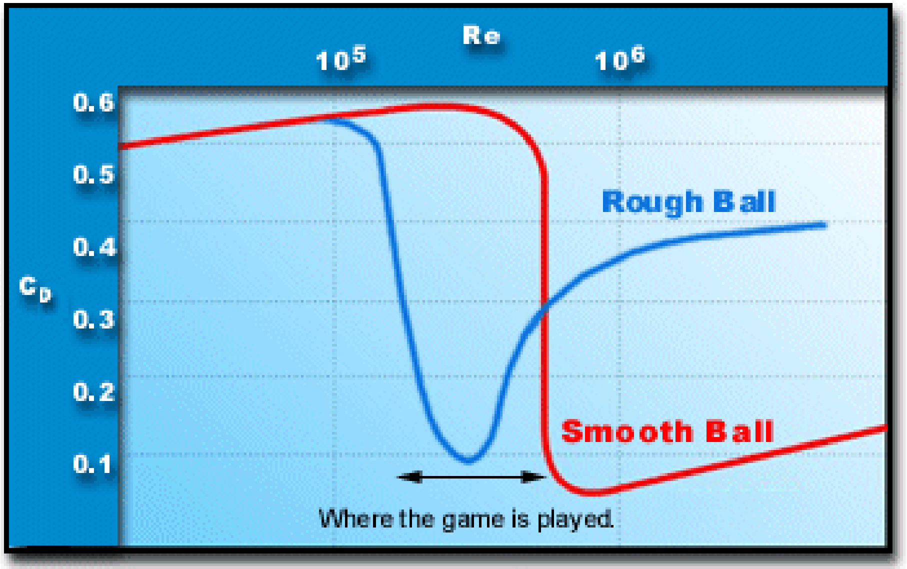
For blunt bodies an increase in ε may decrease C_D by tripping the flow into turbulent at lower Re

Sports Balls



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.

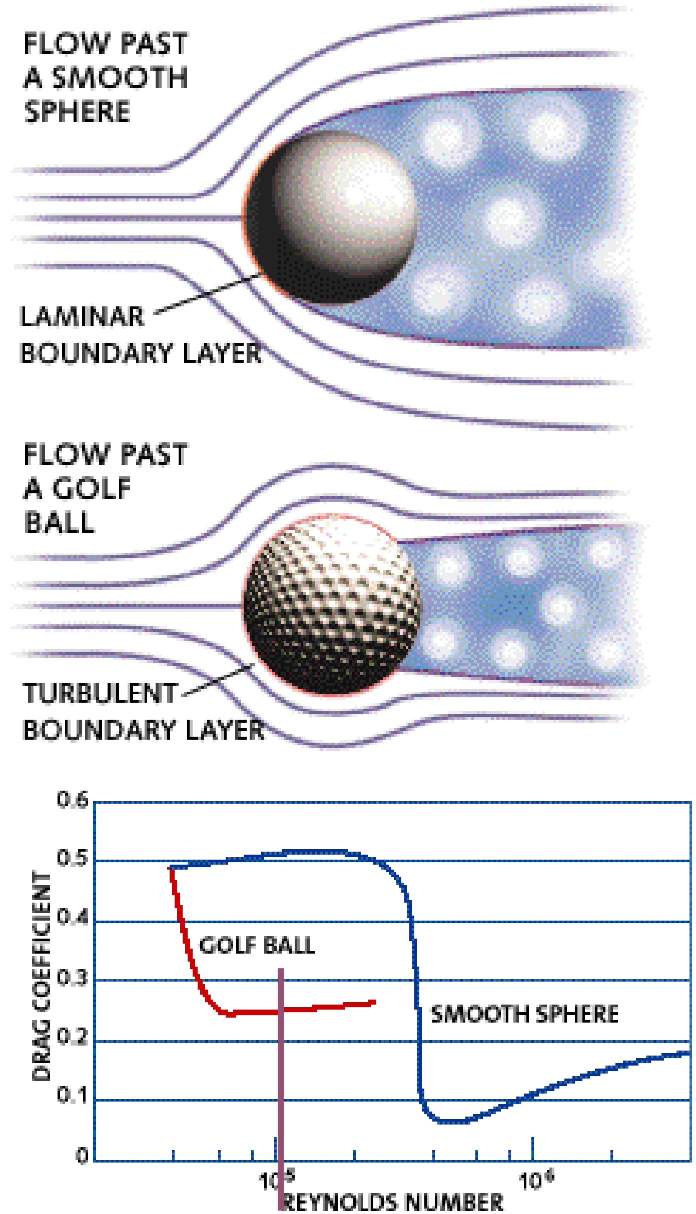


- It is the Reynolds number (not the speed) that determines whether the boundary layer is laminar or turbulent.
- Thus, the larger the ball, the lower the speed at which a rough surface can be of help in reducing the drag.

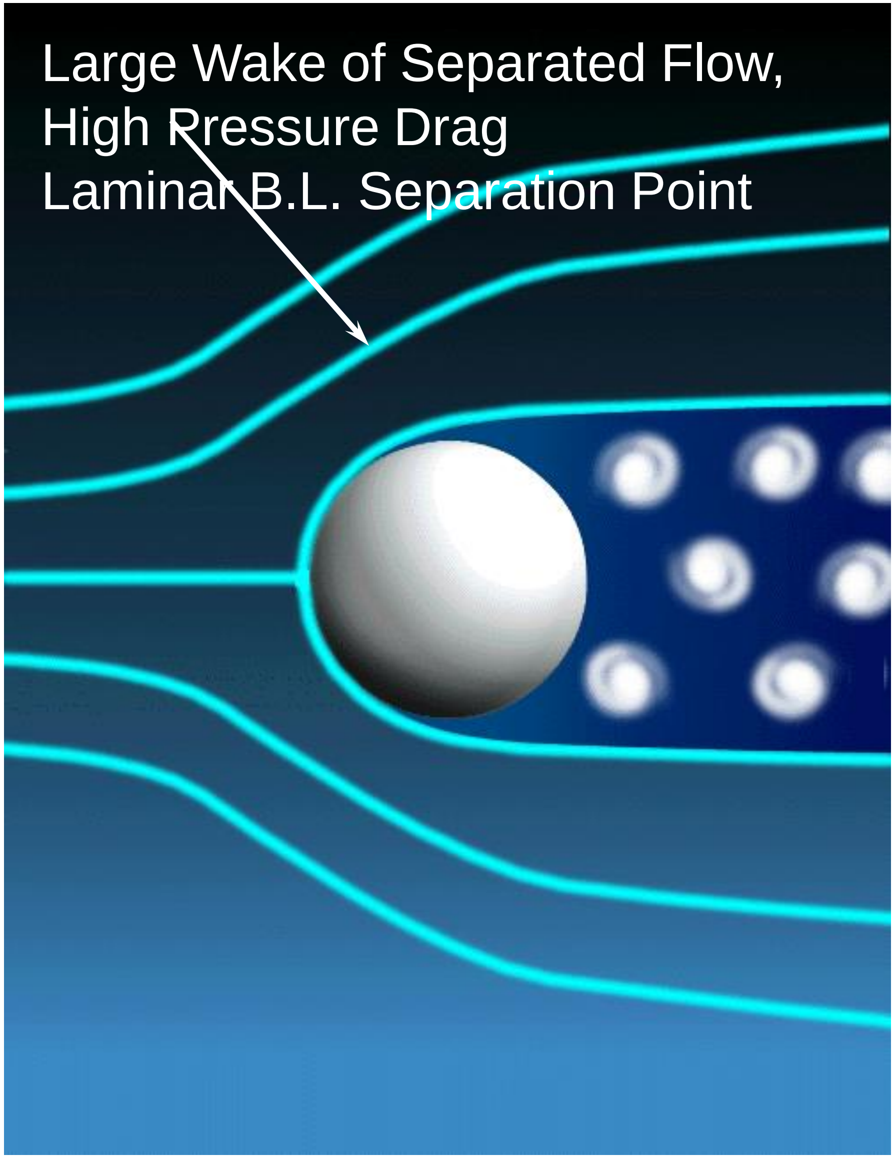
$$\mathrm{Re} = \frac{\rho V D}{\mu}$$

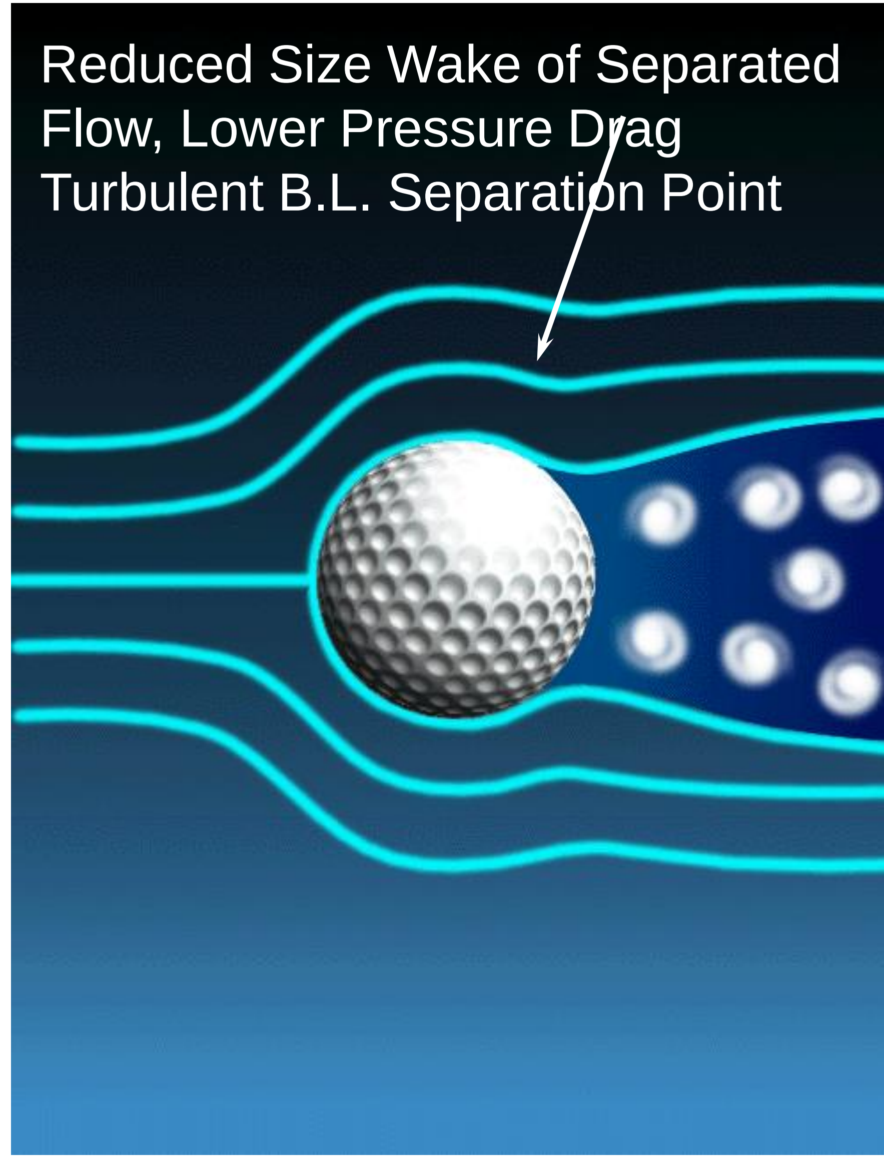
Drag on a Golf Ball

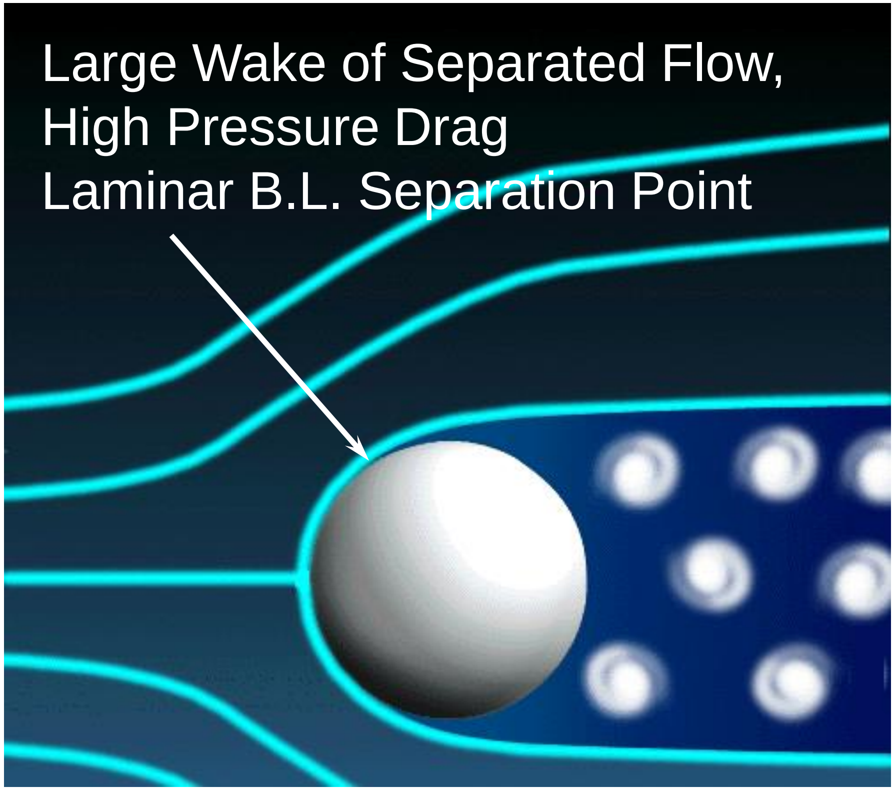
- Drag on a golf ball comes mainly from pressure drag.
- The only practical way of reducing pressure drag is to design the ball so that the point of separation moves back further on the ball.
- The golf ball's dimples increase the turbulence in the boundary layer, increase the inertia of the boundary layer, and delay the onset of separation.
- The Reynolds number where the boundary layer begins to become turbulent with a golf ball is 40,000
- A non-dimpled golf ball would really hamper Tiger Woods’ long game
- Why not use this for aircraft or cars?

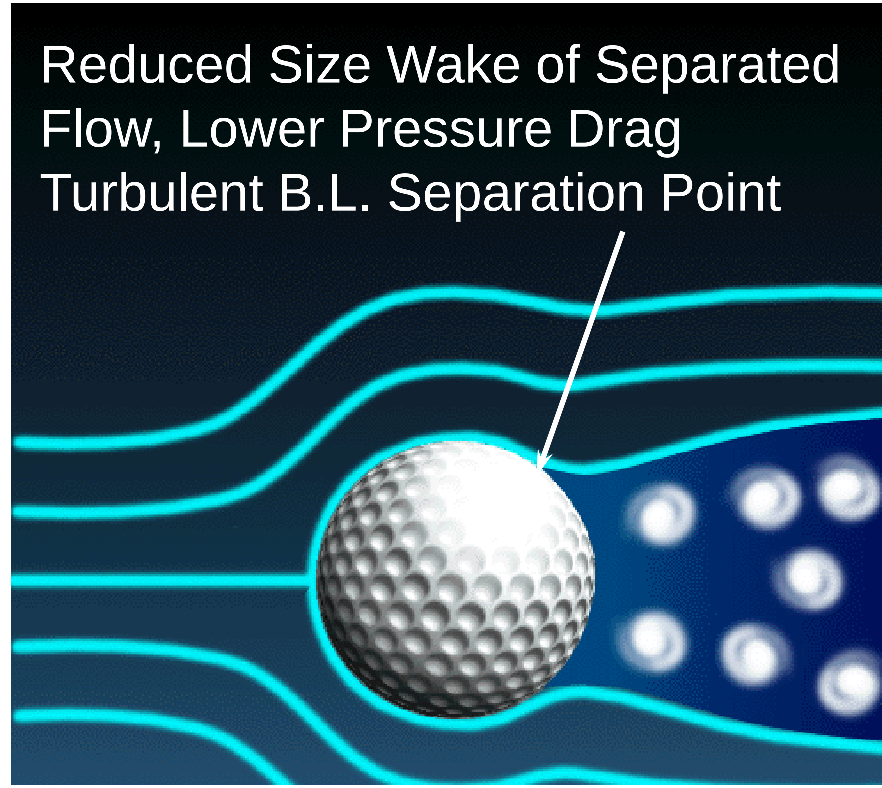


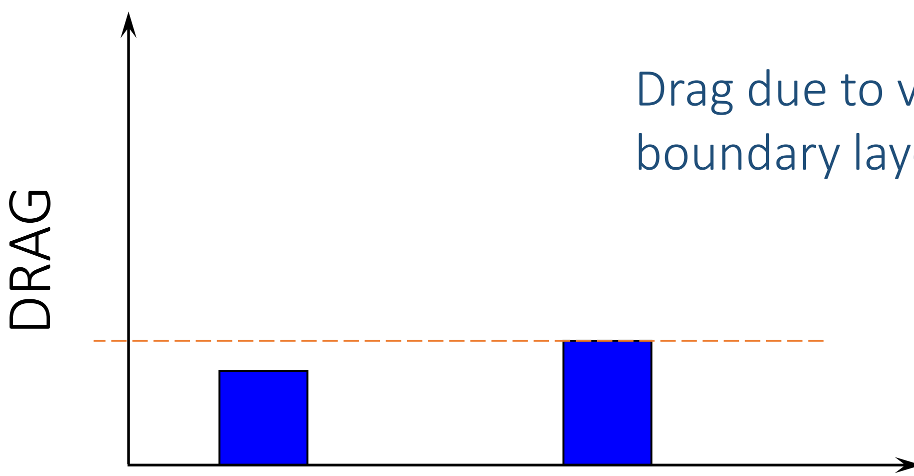
GOLF BALL AERODYNAMICS



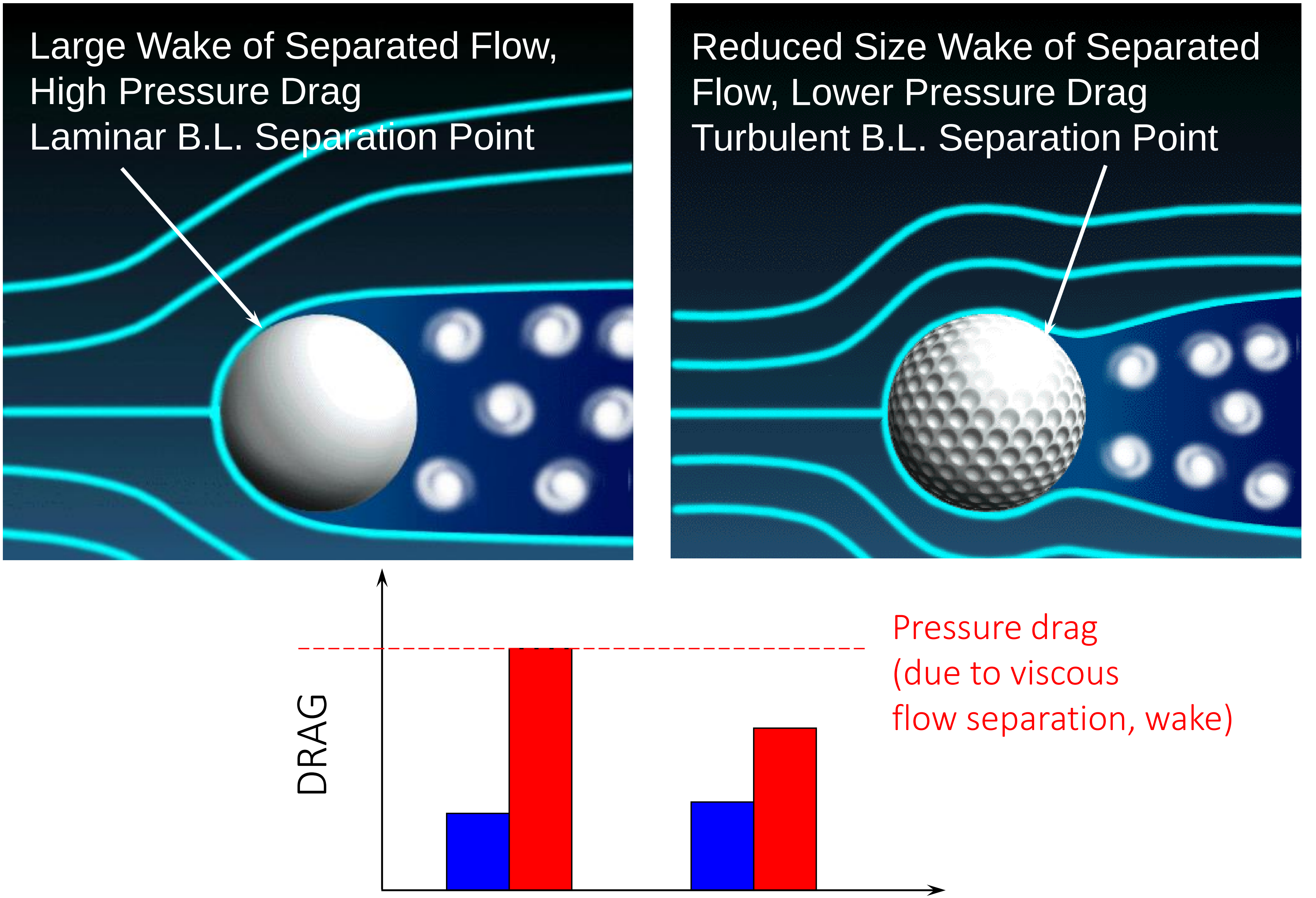


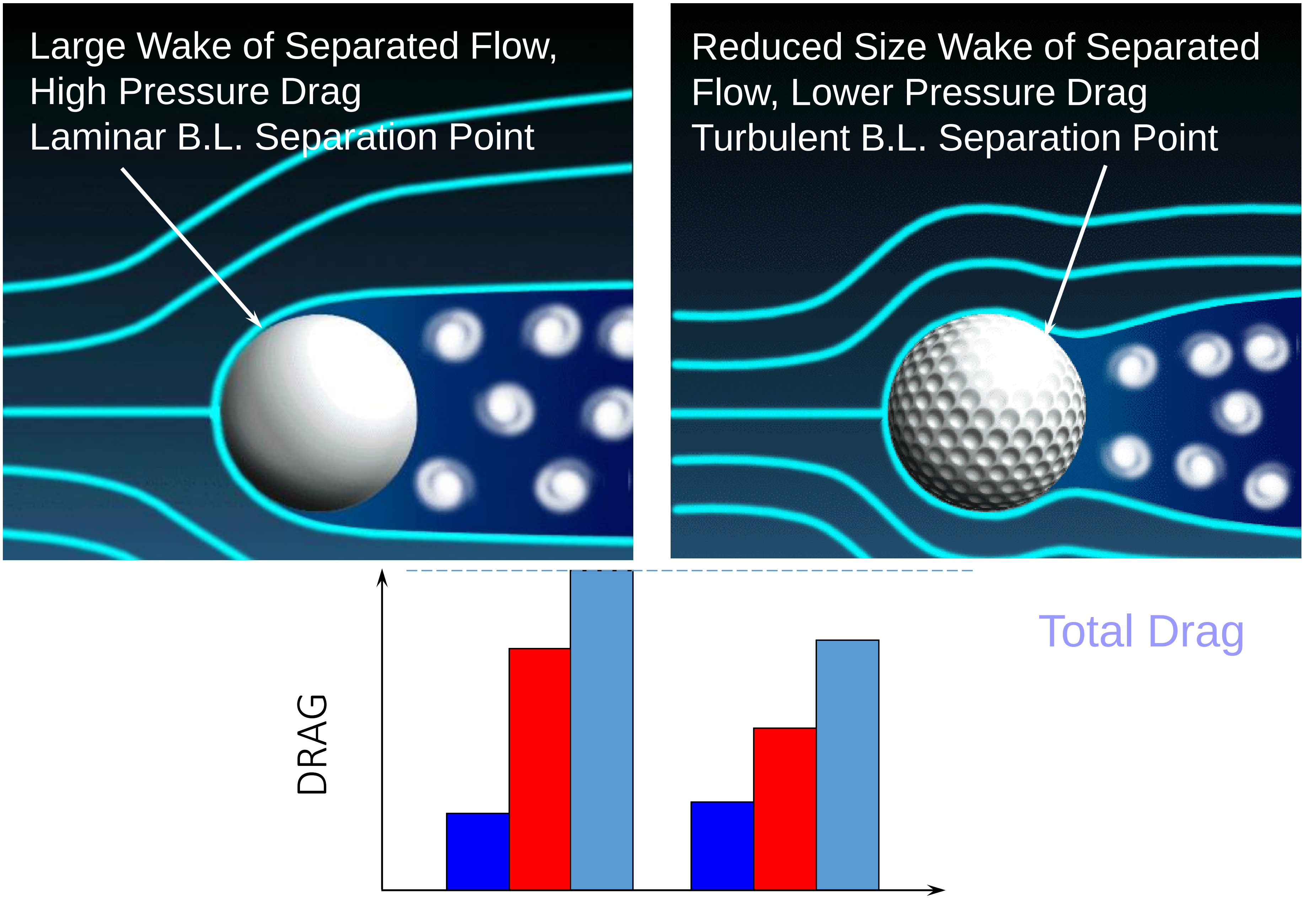






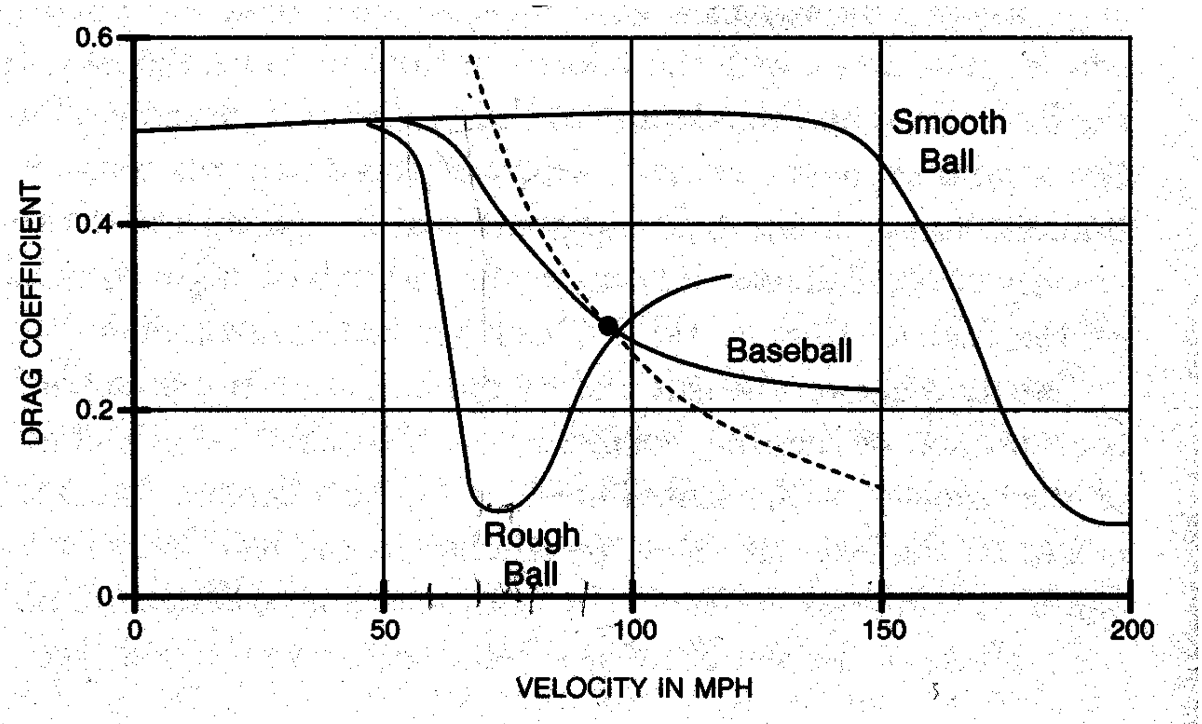
Drag due to viscous boundary layer skin friction


Large Wake of Separated Flow,
High Pressure Drag
Laminar B.L. Separation Point
Reduced Size Wake of Separated
Flow, Lower Pressure Drag
Turbulent B.L. Separation Point
DRAG
Pressure drag
(due to viscous
flow separation, wake)


Large Wake of Separated Flow,
High Pressure Drag
Laminar B.L. Separation Point
Reduced Size Wake of Separated
Flow, Lower Pressure Drag
Turbulent B.L. Separation Point
DRAG
Total Drag

Baseball

- At the velocities of 50 to 130 mph dominant in baseball the air passes over a smooth ball in a highly resistant flow.
- Turbulent flow does not occur until nearly 200 mph for a smooth ball
- A rough ball (say one with raised stitches like a baseball) induces turbulent flow
- A baseball batted 400 feet would only travel 300 feet if it was smooth.



Adverse pressure gradients (Tennis ball)

- Separation of the boundary layers occurs whenever the flow tries to decelerate quickly, that is whenever the pressure gradient is positive (adverse pressure gradient-pressure increases).
- In the case of the tennis ball, the flow initially accelerates on the upstream side of the ball, while the local pressure decreases in accord with Bernoulli's equation.

- Near the top of the ball the local external pressure increases and the flow should decelerate as 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.

FA
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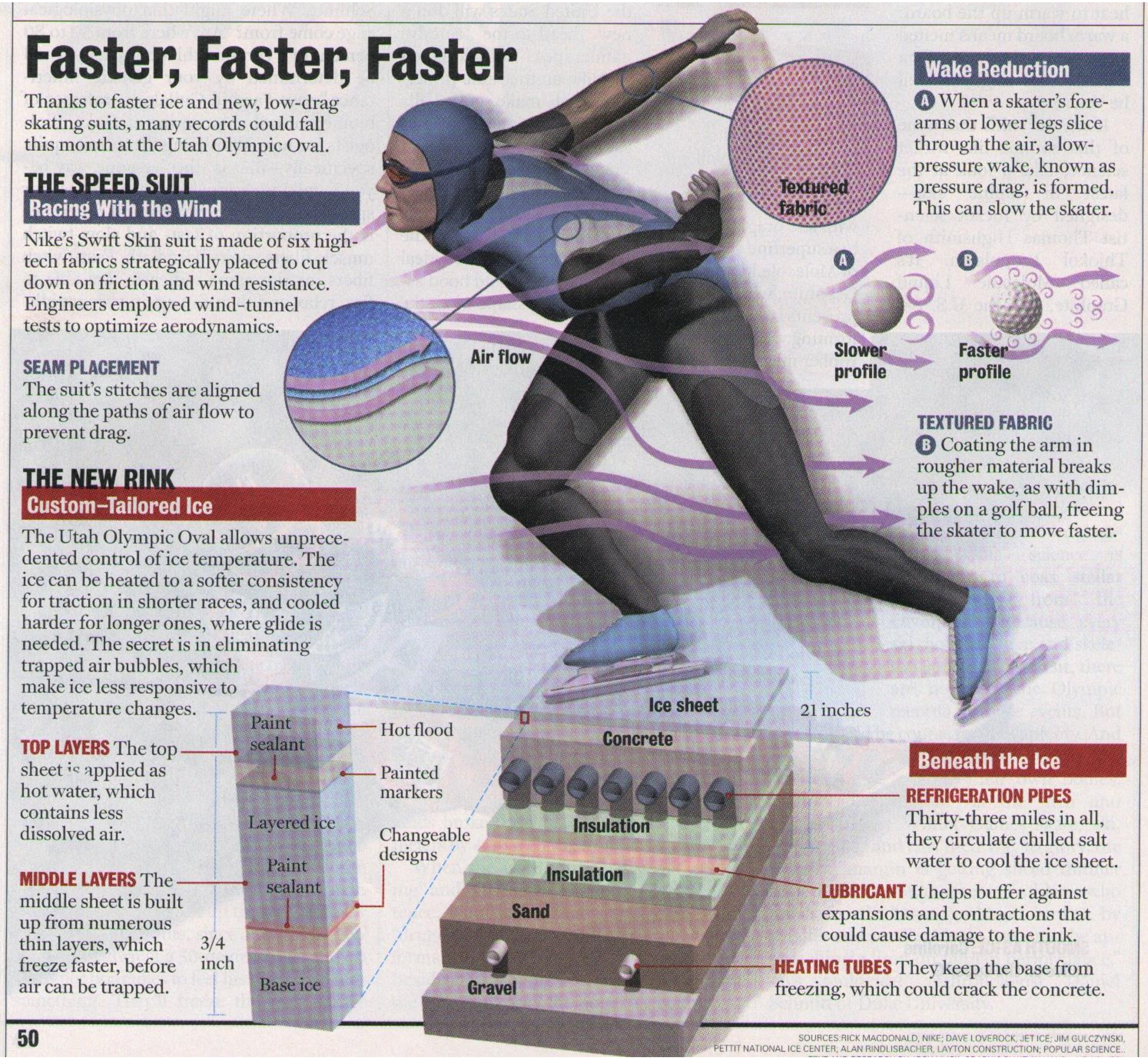


Faster, Faster, Faster

Thanks to faster ice and new, low-drag skating suits, many records could fall this month at the Utah Olympic Oval.

THE SPEED SUIT
Racing With the Wind

Nike's Swift Skin suit is made of six high-tech fabrics strategically placed to cut down on friction and wind resistance. Engineers employed wind-tunnel tests to optimize aerodynamics.

SEAM PLACEMENT The suit's stitches are aligned along the paths of air flow to prevent drag.

THE NEW RINK
Custom-Tailored Ice

The Utah Olympic Oval allows unprecedented control of ice temperature. The ice can be heated to a softer consistency for traction in shorter races, and cooled harder for longer ones, where glide is needed. The secret is in eliminating trapped air bubbles, which make ice less responsive to temperature changes.

TOP LAYERS The top sheet is applied as hot water, which contains less dissolved air.

MIDDLE LAYERS The middle sheet is built up from numerous thin layers, which freeze faster, before air can be trapped.

Wake Reduction

A When a skater's forearms or lower legs slice through the air, a low-pressure wake, known as pressure drag, is formed. This can slow the skater.

TEXTURED FABRIC
B Coating the arm in rougher material breaks up the wake, as with dimples on a golf ball, freeing the skater to move faster.

Beneath the Ice

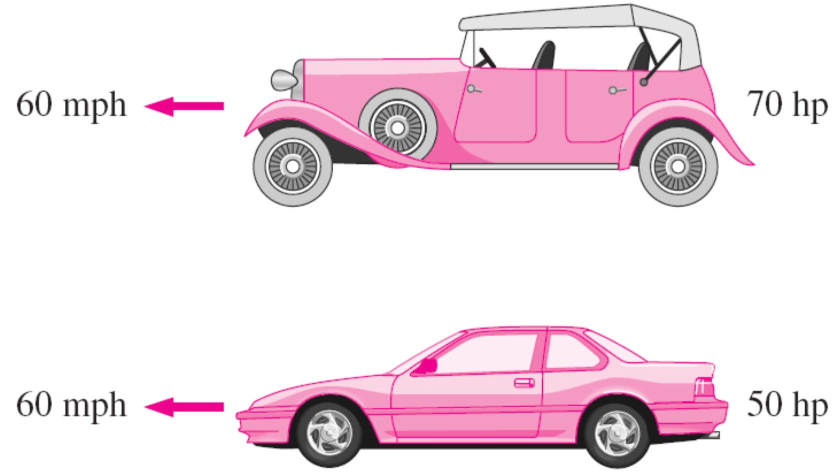
REFRIGERATION PIPES Thirty-three miles in all, they circulate chilled salt water to cool the ice sheet.

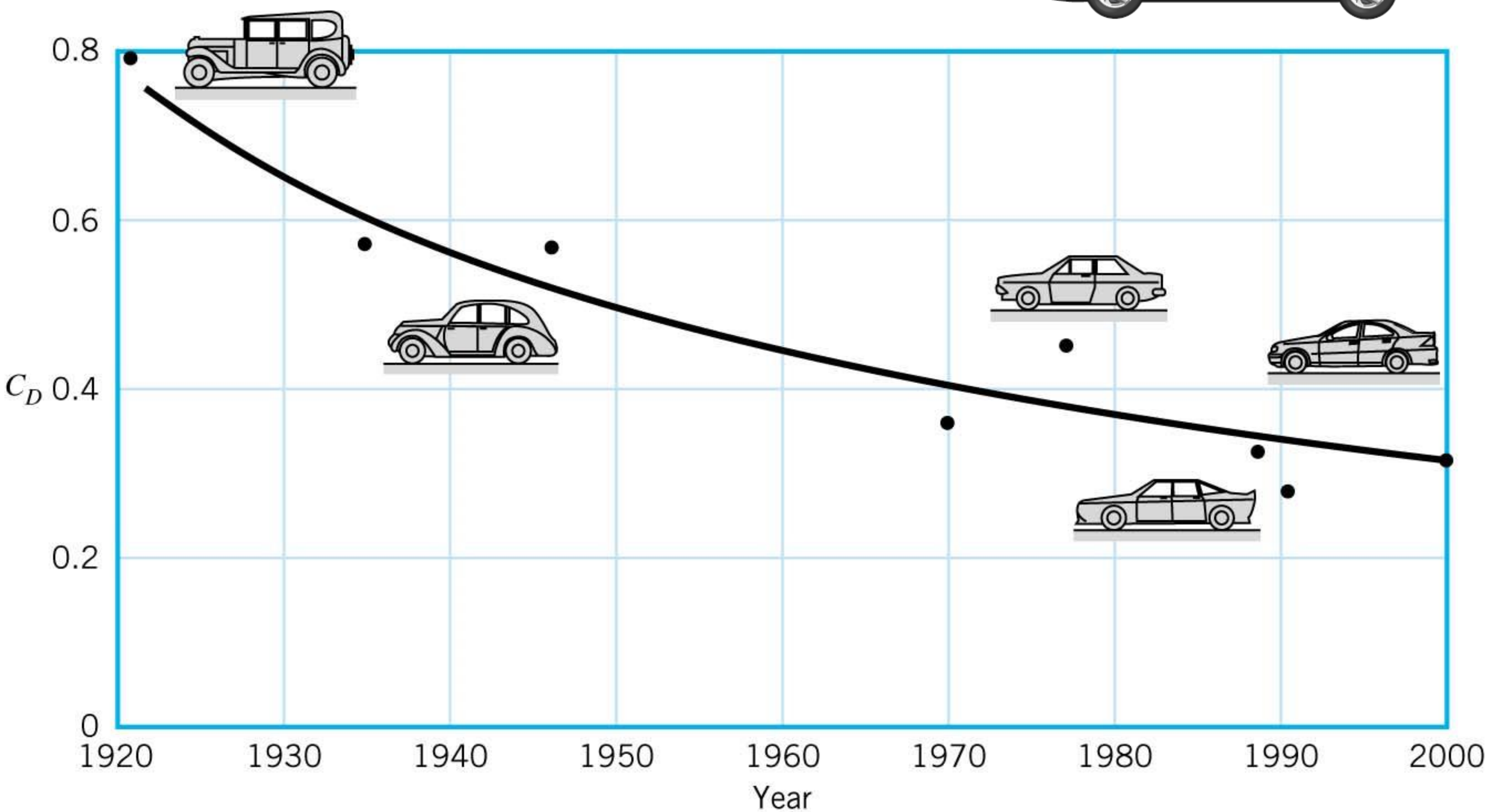
LUBRICANT It helps buffer against expansions and contractions that could cause damage to the rink.

HEATING TUBES They keep the base from freezing, which could crack the concrete.

SOURCES: RICK MACDONALD, NIKE; DAVE LOVEROCK, JET ICE; JIM GULCZYNSKI, PETTIT NATIONAL ICE CENTER; ALAN RINDLISBACHER, LAYTON CONSTRUCTION; POPULAR SCIENCE.

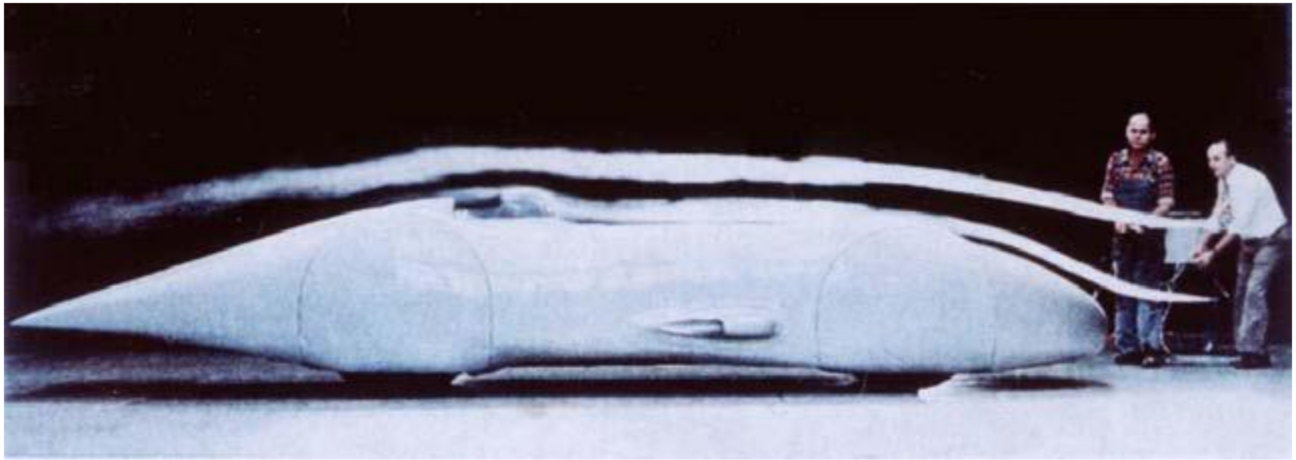
History of Automobiles





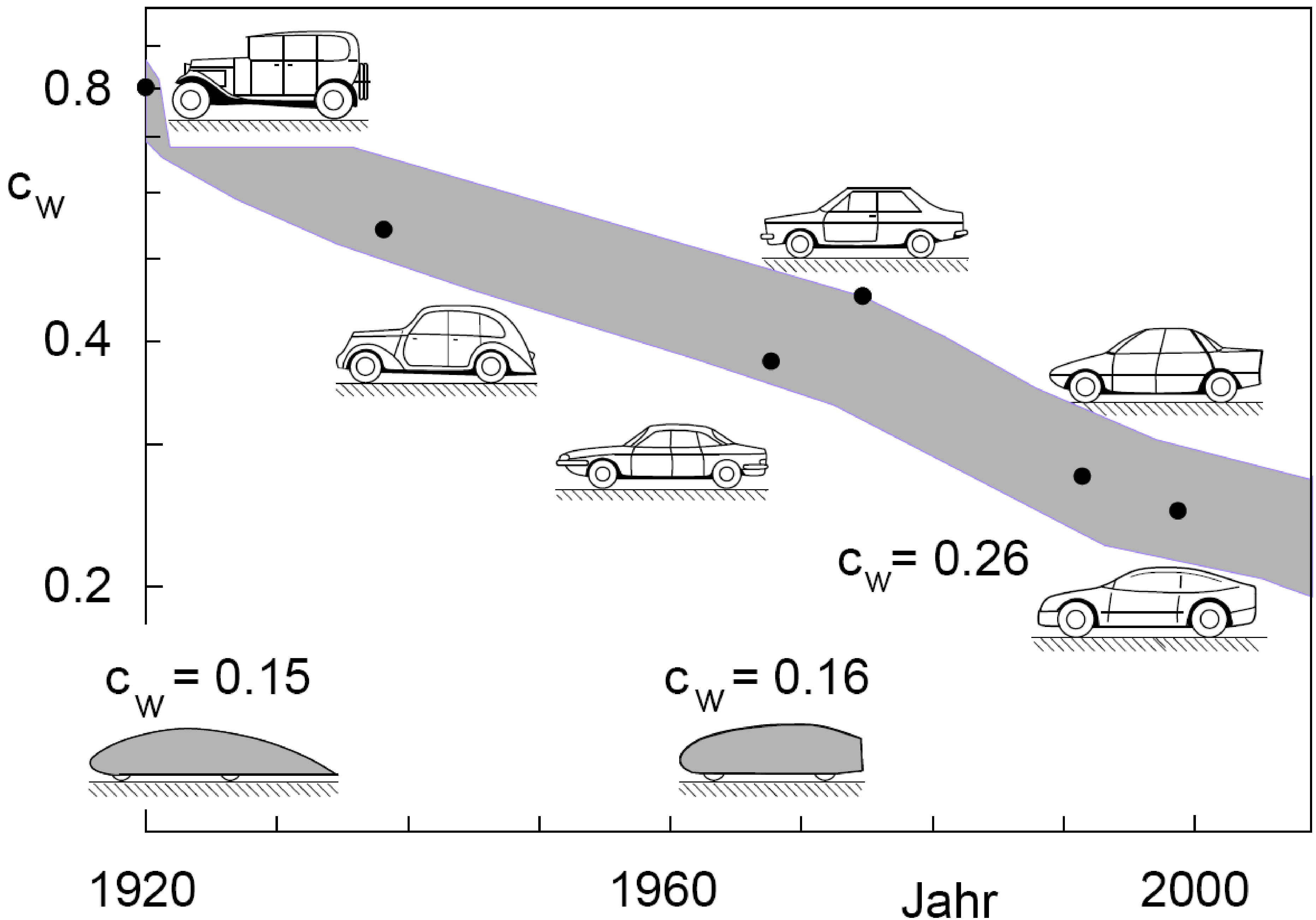
History of Automobiles

C_D = 0.365 1937

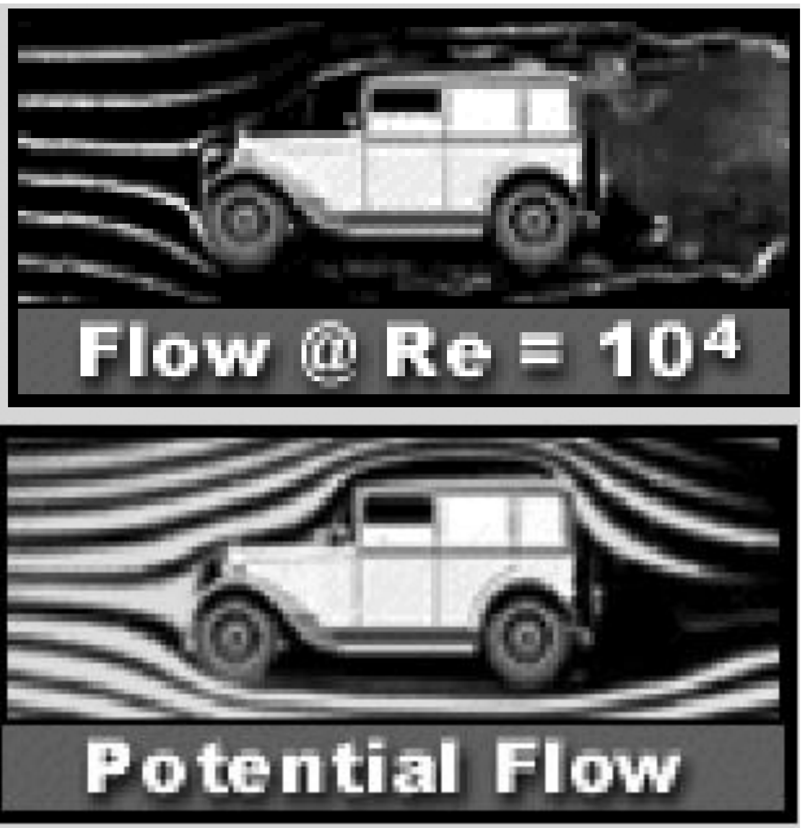


C_D = 0.170 1938

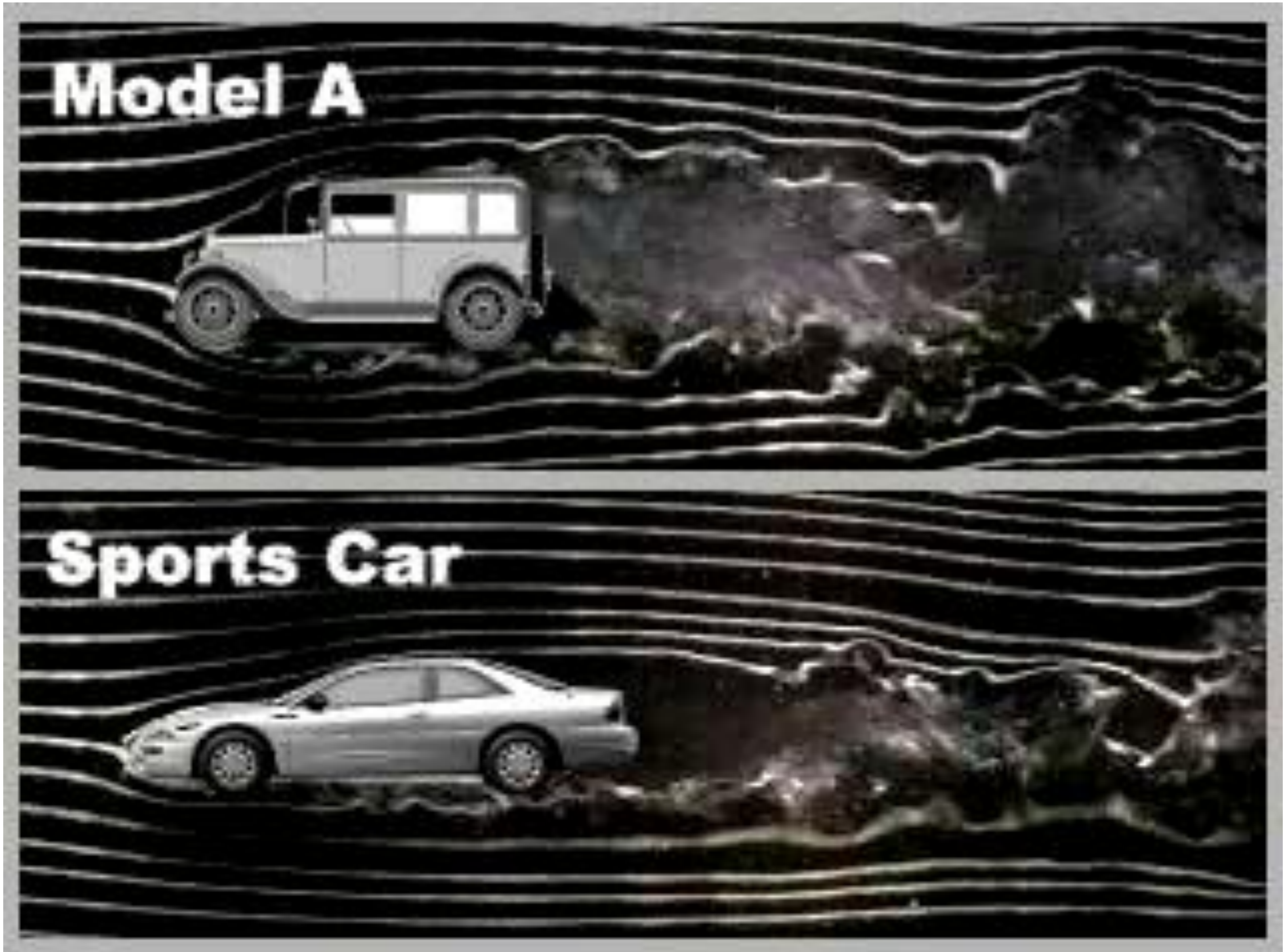
Mercedes-Benz W125 in a wind tunnel


0.8
c_W
0.4
0.2
$c_W = 0.26$
$c_W = 0.15$
$c_W = 0.16$
1920
1960
Jahr
2000

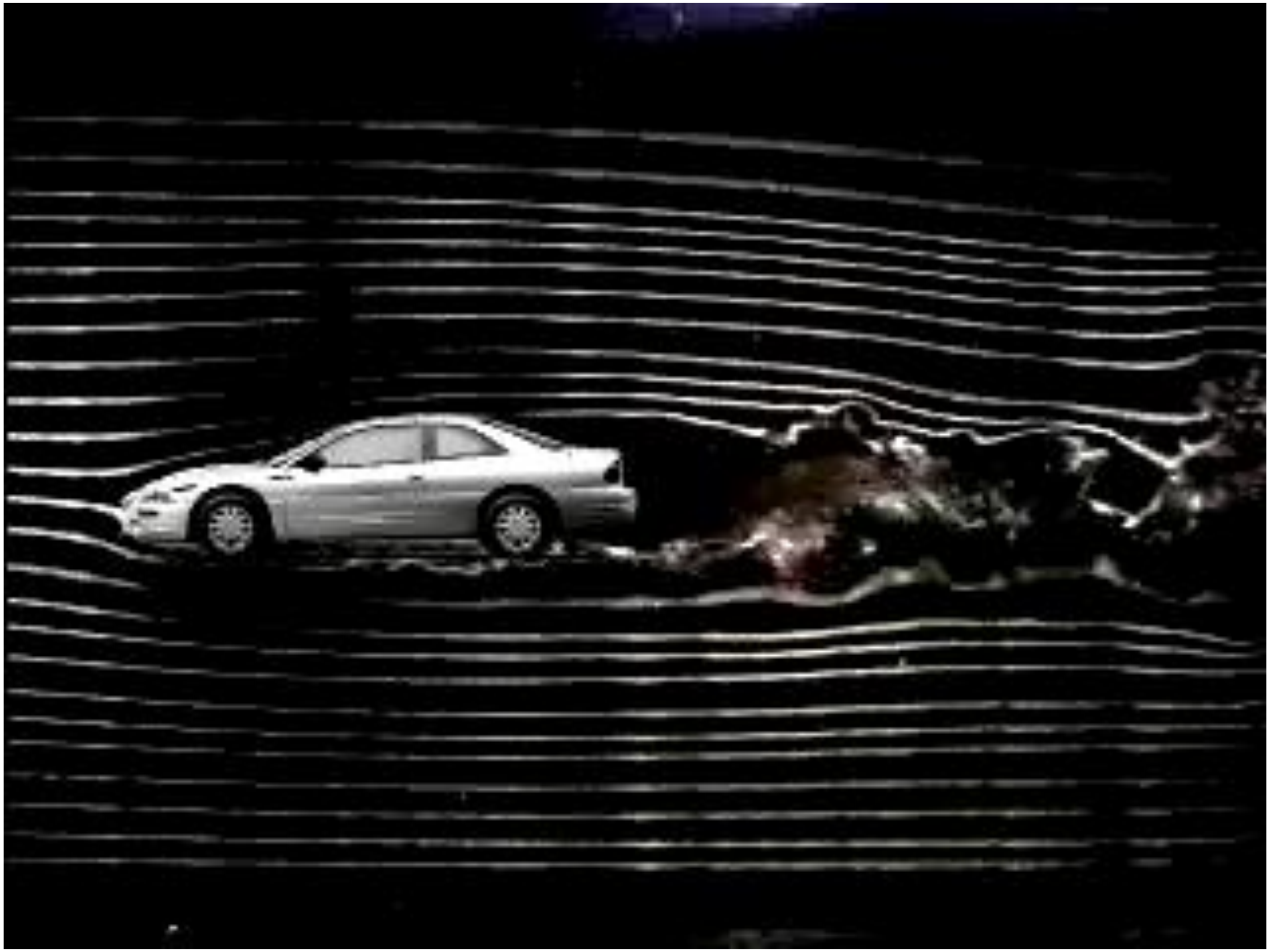
History of Automobiles



History of Cars



History of Cars



Automobile Drag

Scion XB	Porsche 911
	
$C_D = 1.0$, $A = 25\ ft^2$, $C_DA = 25 ft^2$	$C_D = 0.28$, $A = 10\ ft^2$, $C_DA = 2.8 ft^2$

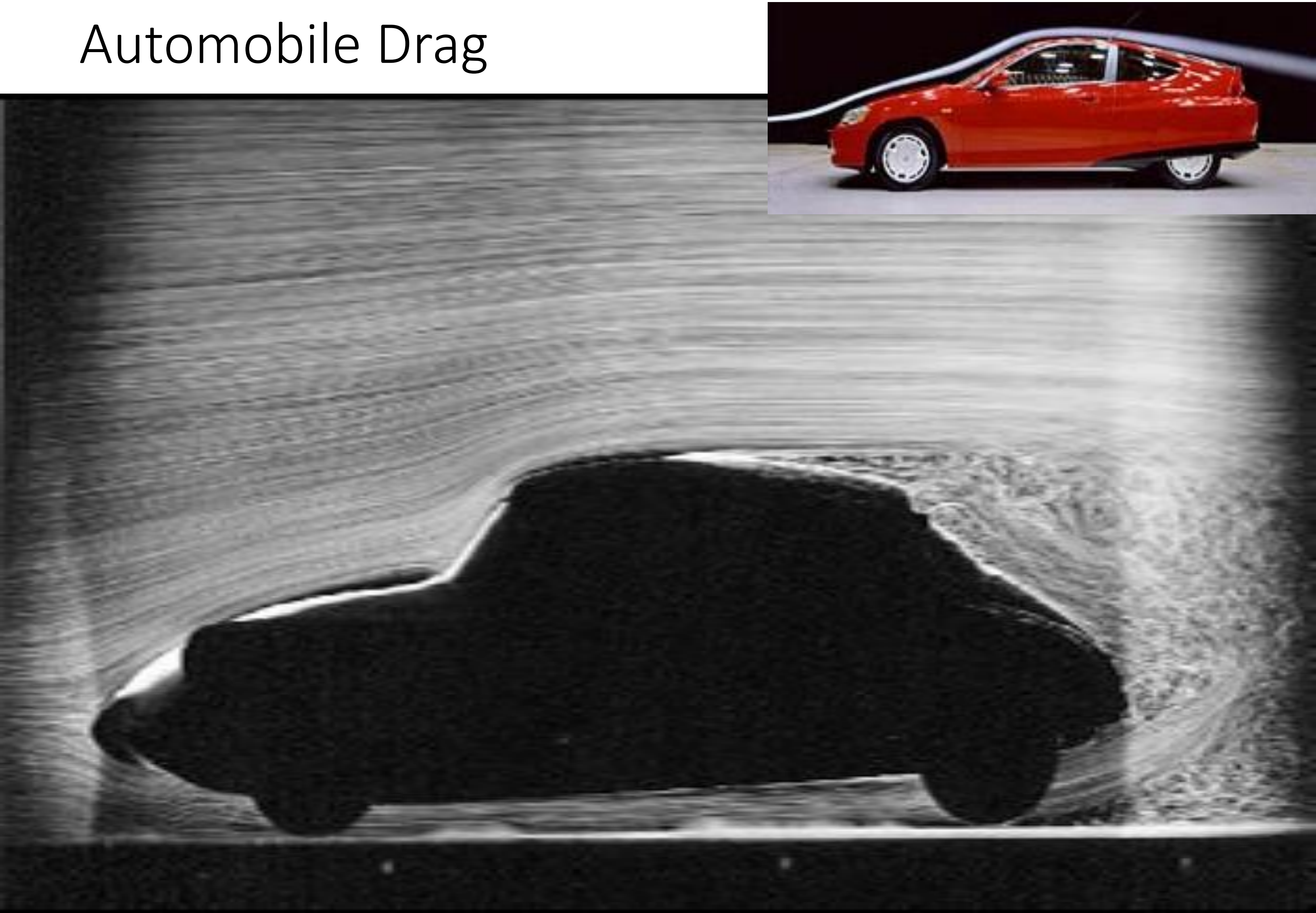
- Drag force $F_D = 1/2 \rho V^2 (C_D A)$ will be ~ 10 times larger for Scion XB
- Source is large C_D and large projected area
- Power consumption $P = F_D V = 1/2 \rho V^3 (C_D A)$ for both scales with V^3!

Electric Vehicles

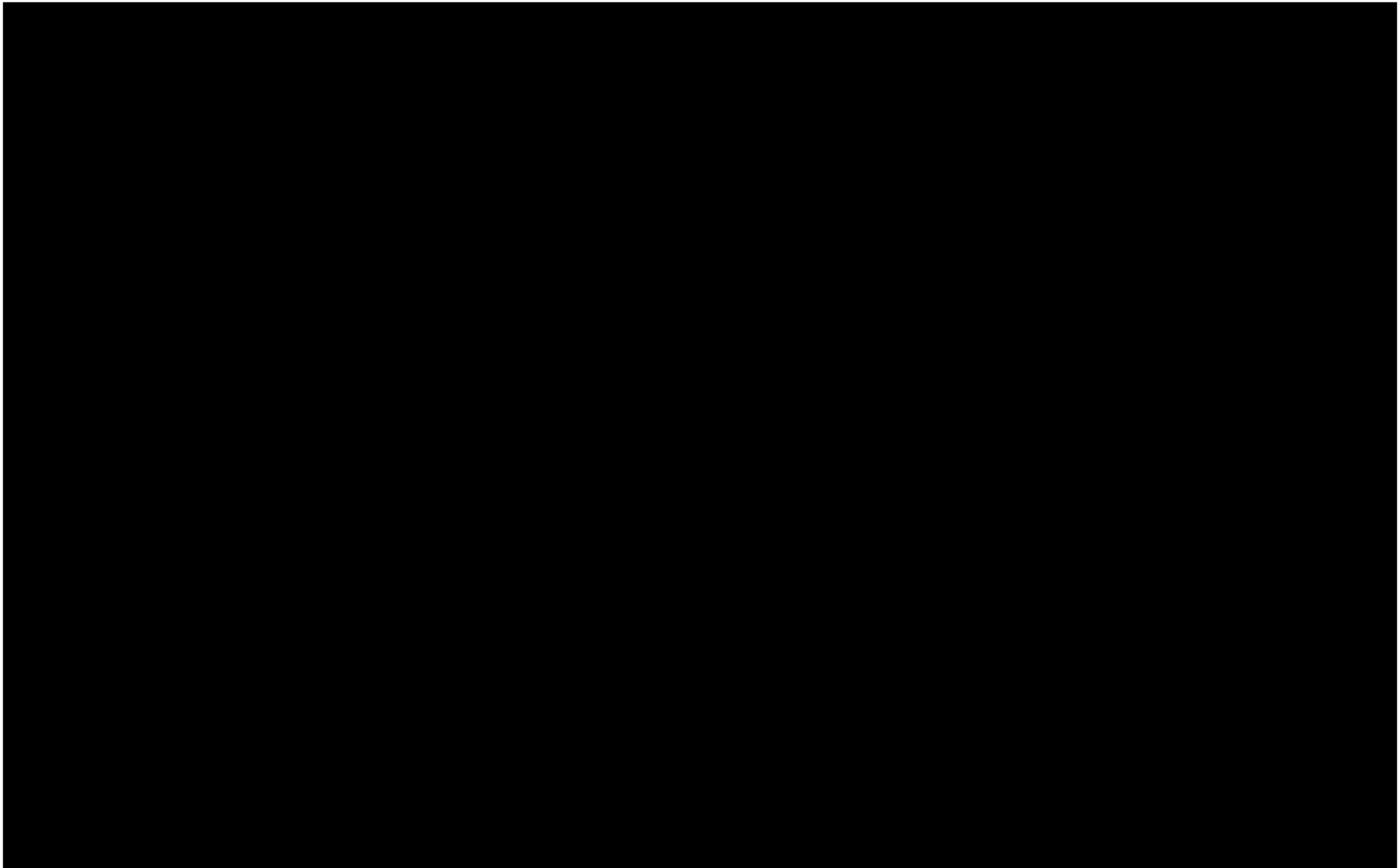
- Electric vehicles are designed to minimize drag.
- Typical cars have a coefficient drag of 0.30-0.40.
- The EV1 has a drag coefficient of 0.19.

Smooth connection to windshield

Automobile Drag



CFD simulation

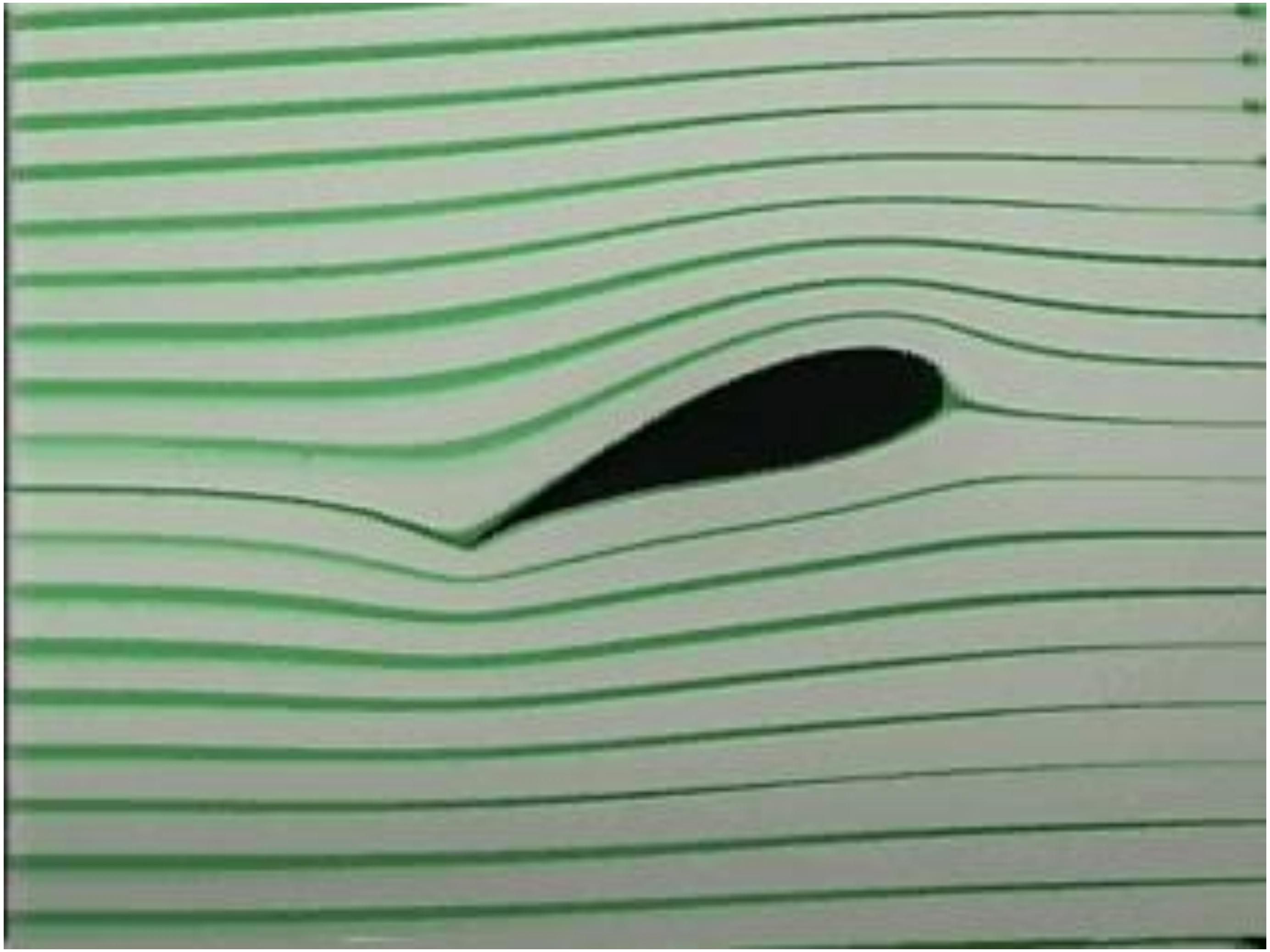


Challenge

$$Drag = \frac{C_d \rho U^2 A}{2}$$

- You are going on vacation and you can’t back all of your luggage in your Matrix. Should you put it on the roof rack or on the hitch?

Streamlines

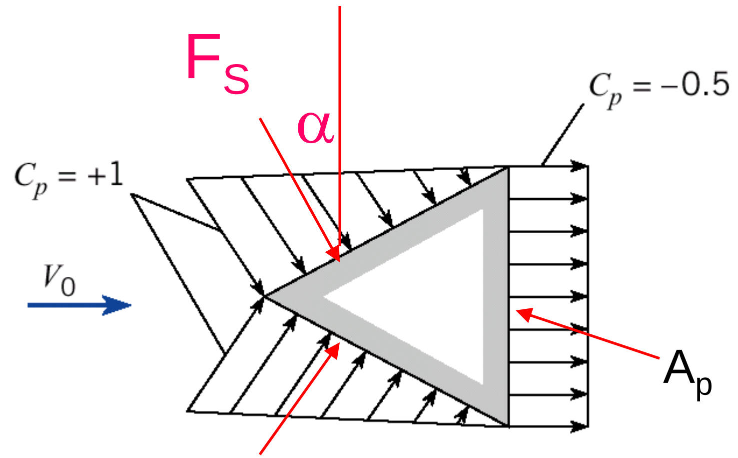


Example-1

- Given: Pressure distribution is shown, flow is left to right.

$$C_p = \frac{p}{\rho V^2 / 2}$$

- Find: Find C_D
- Solution: C_D is based on the projected area of the block from the direction of flow. Force on downstream face is:



$$\left(F_D\right)\Big|_{Drag} = C_p(\rho V^2/2)\ A_p = 0.5 A_p(\rho V^2/2)$$

The total force on each side face is:

$$F_S = C_p(\rho V^2/2) A_p = 0.5 A_p(\rho V^2/2)$$

The drag force on one face is:

$$\left(F_S\right)\Big|_{Drag} = F_S \sin\alpha = 0.5 A_p(\rho V^2/2) * 0.5$$

The total drag force is:

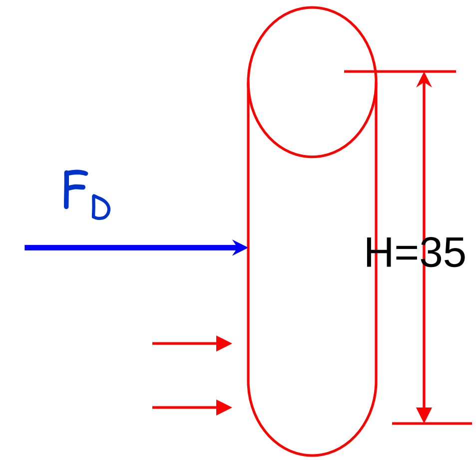
$$F_{Drag} = 2(F_S)\big|_{Drag} + (F_D)\big|_{Drag}$$

$$= 2*(0.5 A_p(\rho V^2/2)*0.5) + 0.5 A_p(\rho V^2/2) = A_p(\rho V^2/2) = C_D A_p(\rho V^2/2)$$

Coefficient of Drag is: $C_D = 1$

Example-2

- Given: Flag pole, 35 m high, 10 cm diameter, in 25-m/s wind, P_{atm} = 100 kPa, T=20°C
- Find: Moment at bottom of flag pole
- Solution:



Air properties at 20°C

$$\nu = 1.51x10^{-5}\, m^2/s,\ \rho = 1.20\, kg/m^3$$

$$\mathrm{Re} = \frac{VD}{\nu} = \frac{25*0.1}{1.51x10^{-5}} = 1.66x10^5$$

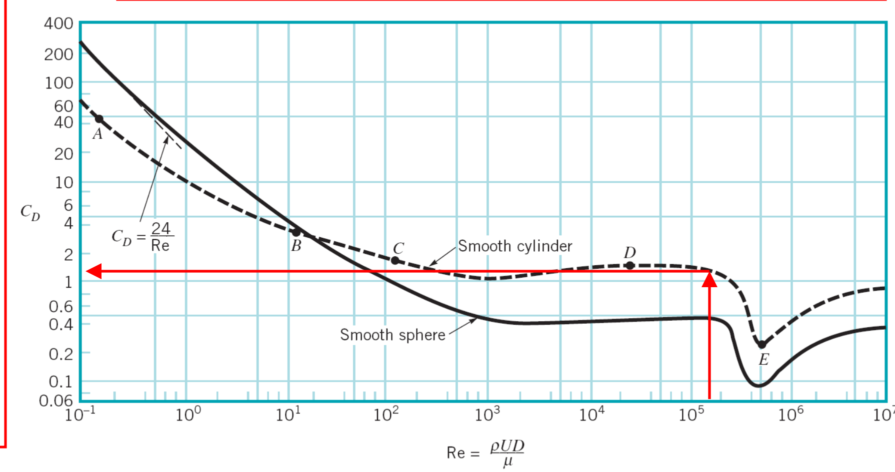
$$C_D = 1.1 \text{ (Fig. 9-21)}$$

$$F_D = C_D A_p \rho \frac{V^2}{2}$$

$$M = F_D \frac{H}{2} = C_D A_p \rho \frac{V_o^2}{2}\frac{H}{2}$$

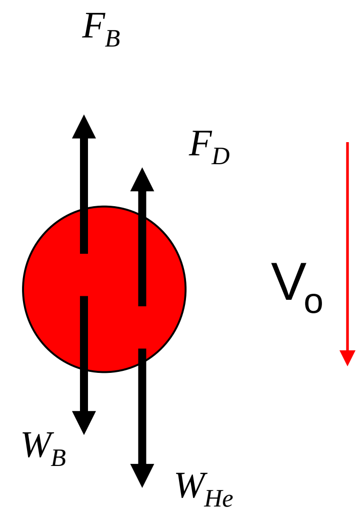
$$= 1.1*0.10*35*1.2*\frac{25^2}{2}*\frac{35}{2}$$

$$= 23\, kN \cdot m$$



Example-3

- Given: Spherical balloon 2-m diameter, filled with helium at std conditions. Empty weight = 3 N.
- Find: Velocity of ascent/descent.
- Solution:



$$\sum F_y = 0 = F_B + F_D - W_B - W_{He}$$

$$= \gamma_{air}\frac{\pi}{6}D^3 + F_D - 3 - \gamma_{He}\frac{\pi}{6}D^3$$

$$F_D = 3 - (\gamma_{air} - \gamma_{He})\frac{\pi}{6}D^3$$

$$= 3 - \gamma_{air}(1 - \frac{287}{2{,}077})\frac{\pi}{6}2^3$$

$$= -1.422\,N$$

$$F_D = C_D A_p \rho \frac{V_o^2}{2}$$

$$V_o = \sqrt{\frac{2F_D}{C_D A_p \rho}} = \sqrt{\frac{2*1.422}{C_D(\pi/4)*2^2*1.225}} = \sqrt{\frac{0.739}{C_D}}$$

Iteration 1: Guess C_D= 0.4 ??

$$V_o = \sqrt{\frac{0.739}{0.4}} = 1.36\,m/s$$

Check Re

$$\text{Re} = \frac{VD}{\nu} = \frac{1.36*2}{1.46x10^{-5}} = 1.86x10^5$$

Iteration 2: Chart $\xrightarrow{\text{Re}}$ C_D= 0.42

$$V_o = \sqrt{\frac{0.739}{0.42}} = 1.33\,m/s$$