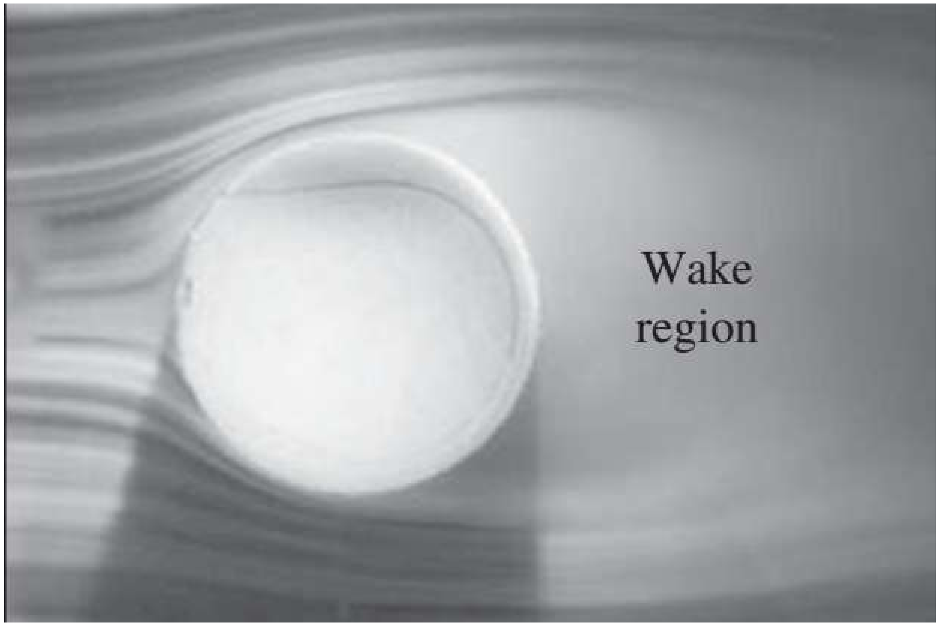
Flow over Immersed Bodies



Instructor: Joaquín Valencia

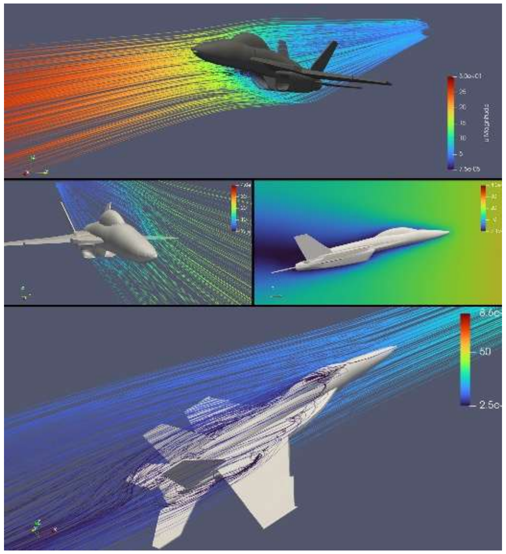
ME 3140

Content

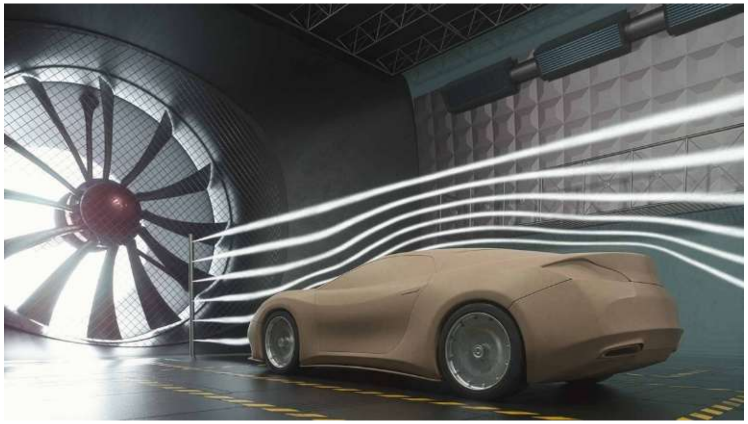
Content

- **Introduction**

Introduction: Applications

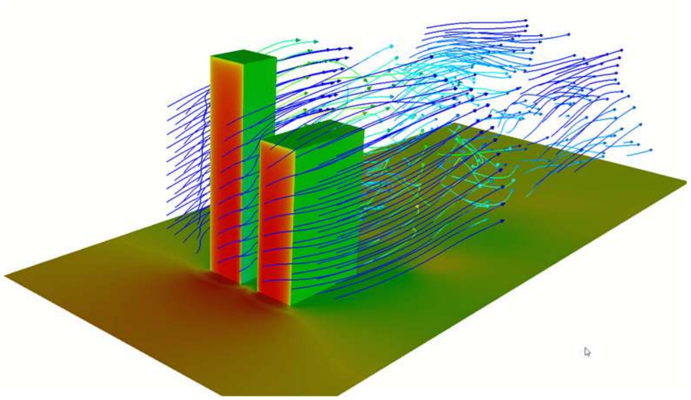


(a) Aircraft



(b) Automobiles

(c) Bird

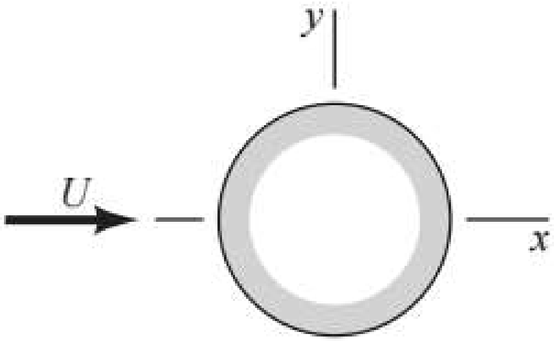


(d) Buildings

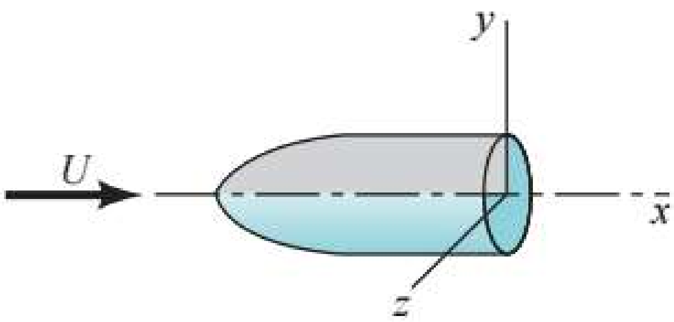
(e) Wing tunnel

Introduction:
Flow Classification

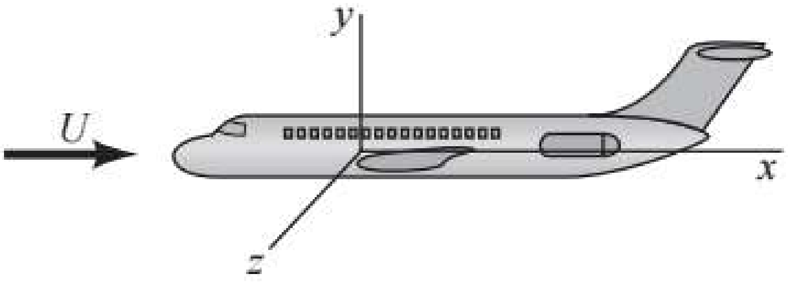
Flow Classification



(a) Two-dimensional



(b) Axisymmetric



(c) Three-Dimensional

Content

- Introduction
- **Drag and Lift**

Drag and Lift

Drag is the **force a flowing fluid exerts on a body in the direction of the flow**, i.e., the resistive “push” that opposes the body’s motion through the fluid

Drag Force, F_D

$$dF_D = -PdA\cos\theta + \tau_w dA\sin\theta$$

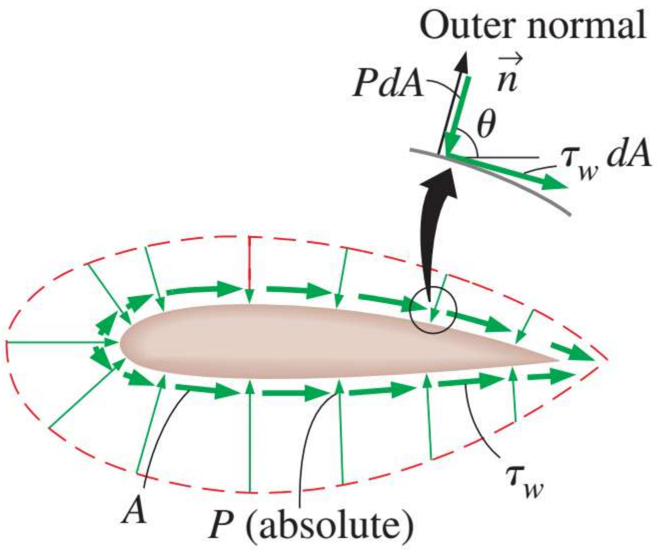
$$F_D = \int dF_D = \int(-P\cos\theta - \tau_w\sin\theta)dA$$

P: Local pressure acting normal to the surface.

θ: angle that the outer normal of dA makes with the positive flow direction.

dA: differential surface area element.

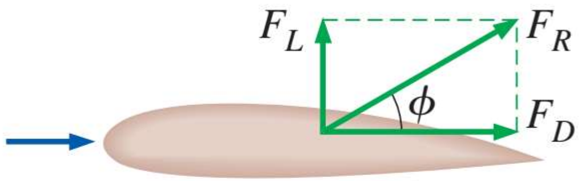
τ_w: Wall shear stress.



Lift Force, F_L

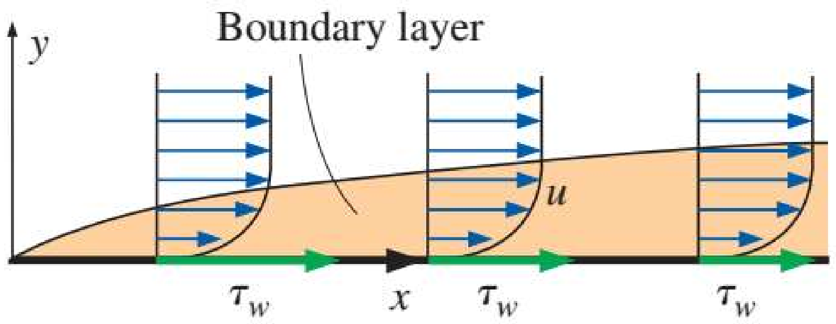
$$dF_L = -PdA\sin\theta - \tau_w dA\cos\theta$$

$$F_L = \int dF_L = -\int(P\sin\theta + \tau_w\cos\theta)dA$$

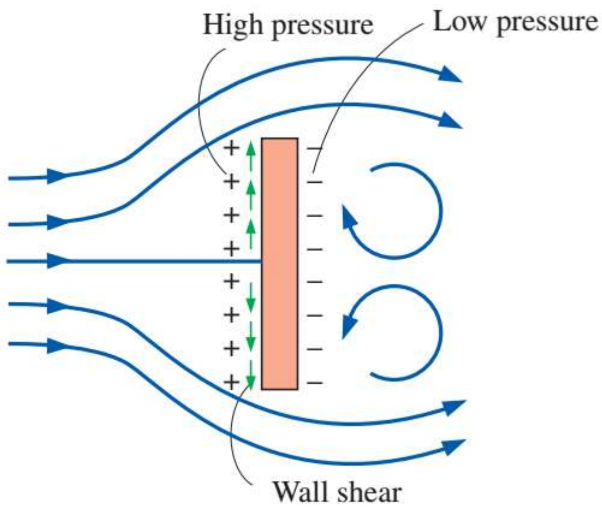


$$F_D = F_R\cos\phi$$
$$F_L = F_R\sin\phi$$

Drag and Lift



Drag force acting on a flat plate parallel to the flow.



Drag force acting on a flat plate normal to the flow.

Drag coefficient, C_D

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

ρ: density of the fluid.

V: upstream velocity.

A: frontal area.

$\frac{1}{2}\rho V^2$: dynamic pressure.

Lift coefficient, C_L

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

Average drag and lift coefficients

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

Drag and Lift

Example 1

The drag coefficient of a car at the design conditions of 1 atm, 70°F, and 60 mi/h is to be determined experimentally in a large wind tunnel in a full-scale test (Fig. E-1). The frontal area of the car is 22.26 ft^2. If the force acting on the car in the flow direction is measured to be 68 lbf, determine the drag coefficient of this car.

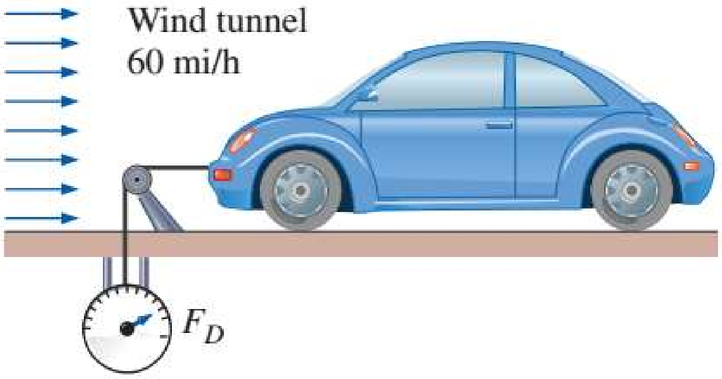


Figure E-1

Content

- Introduction
- Drag and Lift
- **Friction and Pressure Drag**

Friction and Pressure Drag

Skin friction drag (also called **friction drag)** is the portion of the total drag force that comes **directly from the wall shear stress** $\tau_w$acting along the surface, caused by **frictional (viscous) effects** between the fluid and the body.

$$C_{D,\text{friction}} = \frac{F_{D,\text{friction}}}{\frac{1}{2}\rho V^2 A}$$

Pressure drag (also called **form drag)** is the portion of the total drag force that comes **directly from the pressure** Pacting on the body's surface, and it depends strongly on the **shape (form)** of the body.

$$C_{D,\text{pressure}} = \frac{F_{D,\text{pressure}}}{\frac{1}{2}\rho V^2 A}$$

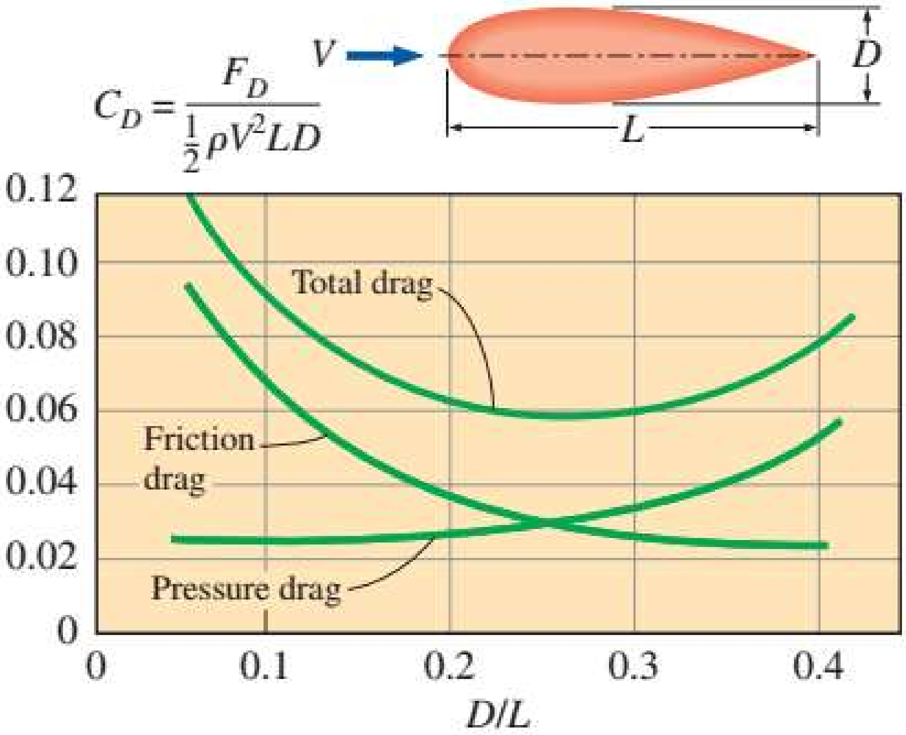
Total drag coefficient

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

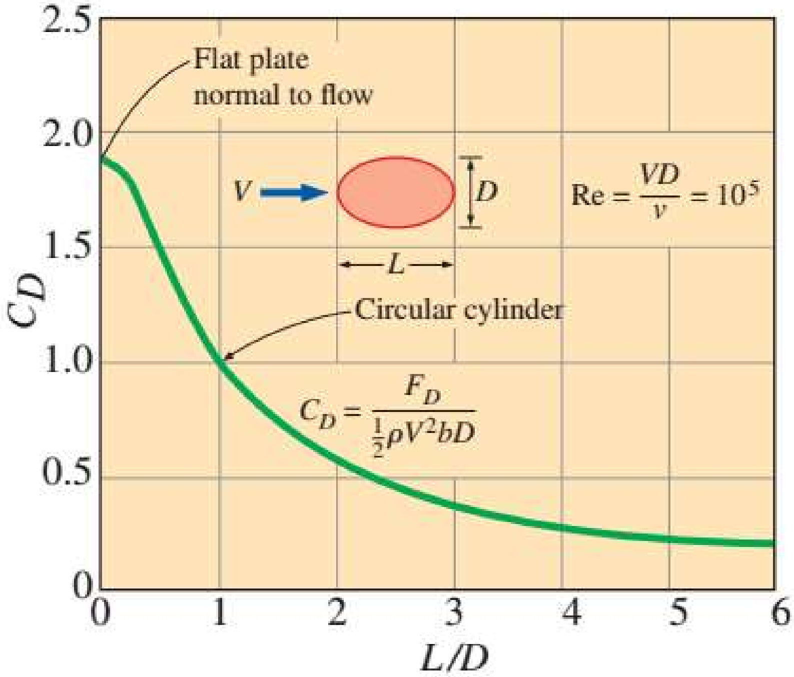
Drag force

$$F_D = F_{D,\text{friction}} + F_{D,\text{pressure}}$$

Friction and Pressure Drag



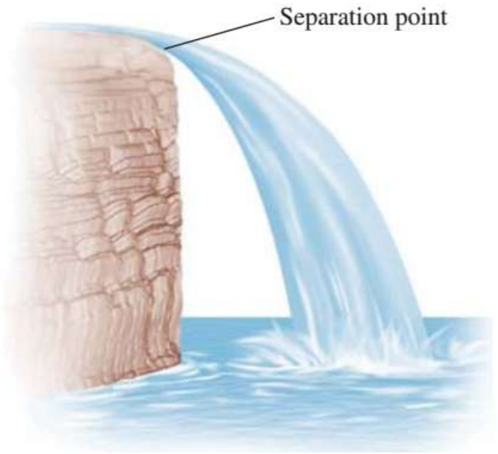
The variation of friction, pressure, and total drag coefficients of a two-dimensional streamlined strut with thickness-to-chord length ratio for $Re = 5 \times 10^4$.



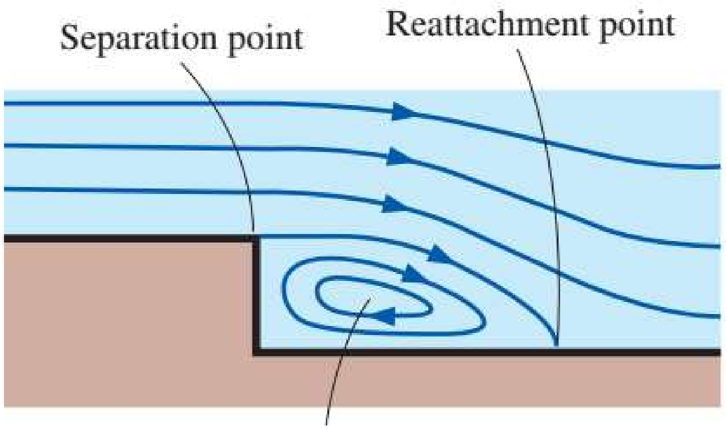
The variation of the drag coefficient of a long elliptical cylinder with aspect ratio.

Friction and Pressure Drag: Flow Separation

Flow separation is the phenomenon where a fluid flowing over a surface **can no longer remain attached**, especially on the **back side of a curved body at sufficiently high velocity**, and the stream **detaches from the surface** at a separation point.



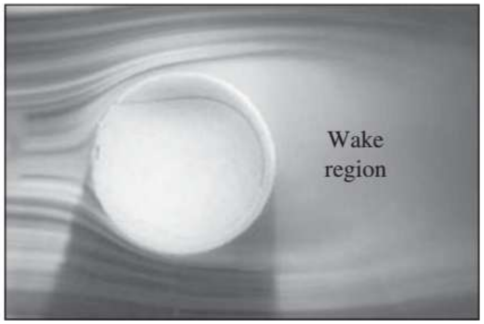
Flow separation in a waterfall.



Flow separation over a backward-facing step along a wall.

Separated region: Enclosed, low-pressure zone behind the body where the flow recirculates after separation, ending when the streams reattach.

Wake: Downstream trail where the flow remains slower than upstream until velocity recovers.



Friction and Pressure Drag:
Flow Separation

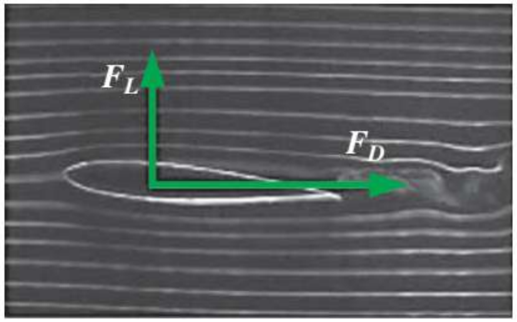
Angle of attack (α): The angle between the incoming fluid stream (relative wind) and the wing’s **chord line**.

Chord (chord line): The straight line that connects the **nose (leading edge)** of the wing to the **trailing edge**.

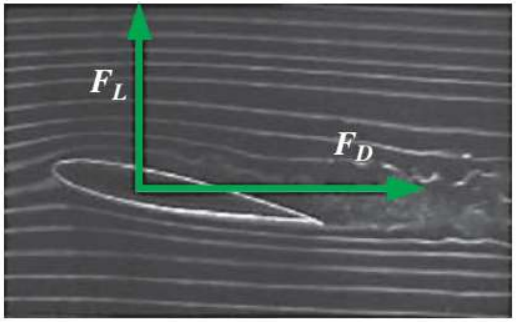
Stall (stalling): A condition where **flow separation** occurs on the **top surface** of the wing, causing a **drastic reduction in lift**.

Vortices: circulating or rotating fluid structures that form in the **wake region** as a result of flow separation.

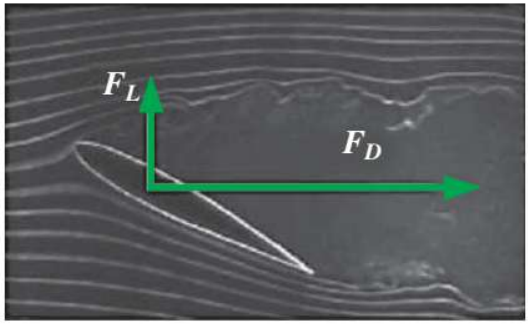
Vortex shedding: the **periodic formation and release of vortices** downstream of a body into the wake,



(*a*) 5°



(*b*) 15°



(*c*) 30°

Content

- Introduction
- Drag and Lift
- Friction and Pressure Drag
- **Drag Coefficients of Common Geometries**

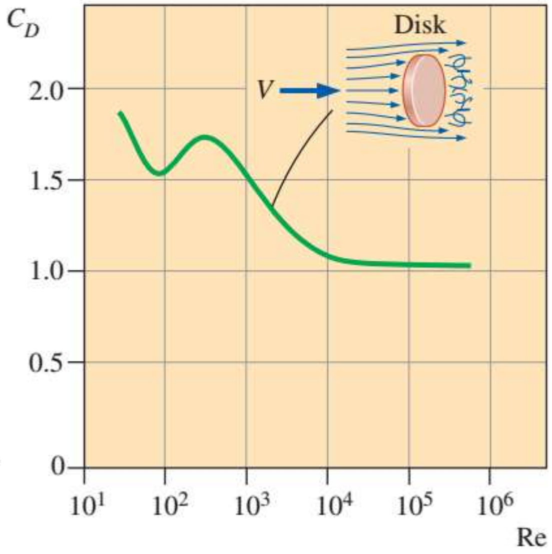
Drag Coefficient of Common Geometries

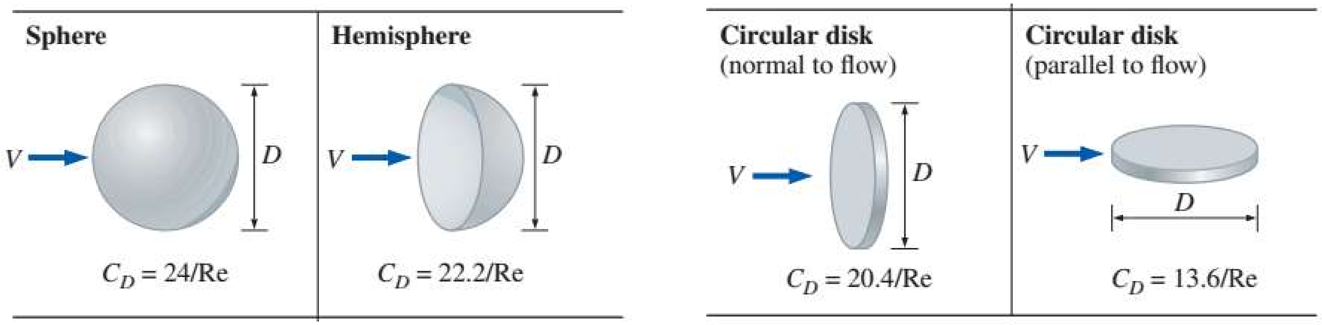
The **drag coefficient** depends on Reynolds number at low Re, but is usually almost constant at high Re (10^4) because the flow becomes turbulent—except for rounded bodies like cylinders and spheres.

Drag Coefficient of a Sphere in Creeping Flow

$$C_D = \frac{24}{Re} \qquad Re \leq 1$$

$$\rightarrow F_D = C_D A \frac{\rho V^2}{2} = 3\pi\mu V D \quad \text{(known as Stokes' law)}$$





Drag coefficients C_D at low Reynolds numbers ($Re \leq 1$ where $Re = VD/\nu$ and $A = \pi D^2/4$).

Drag Coefficient of Common Geometries

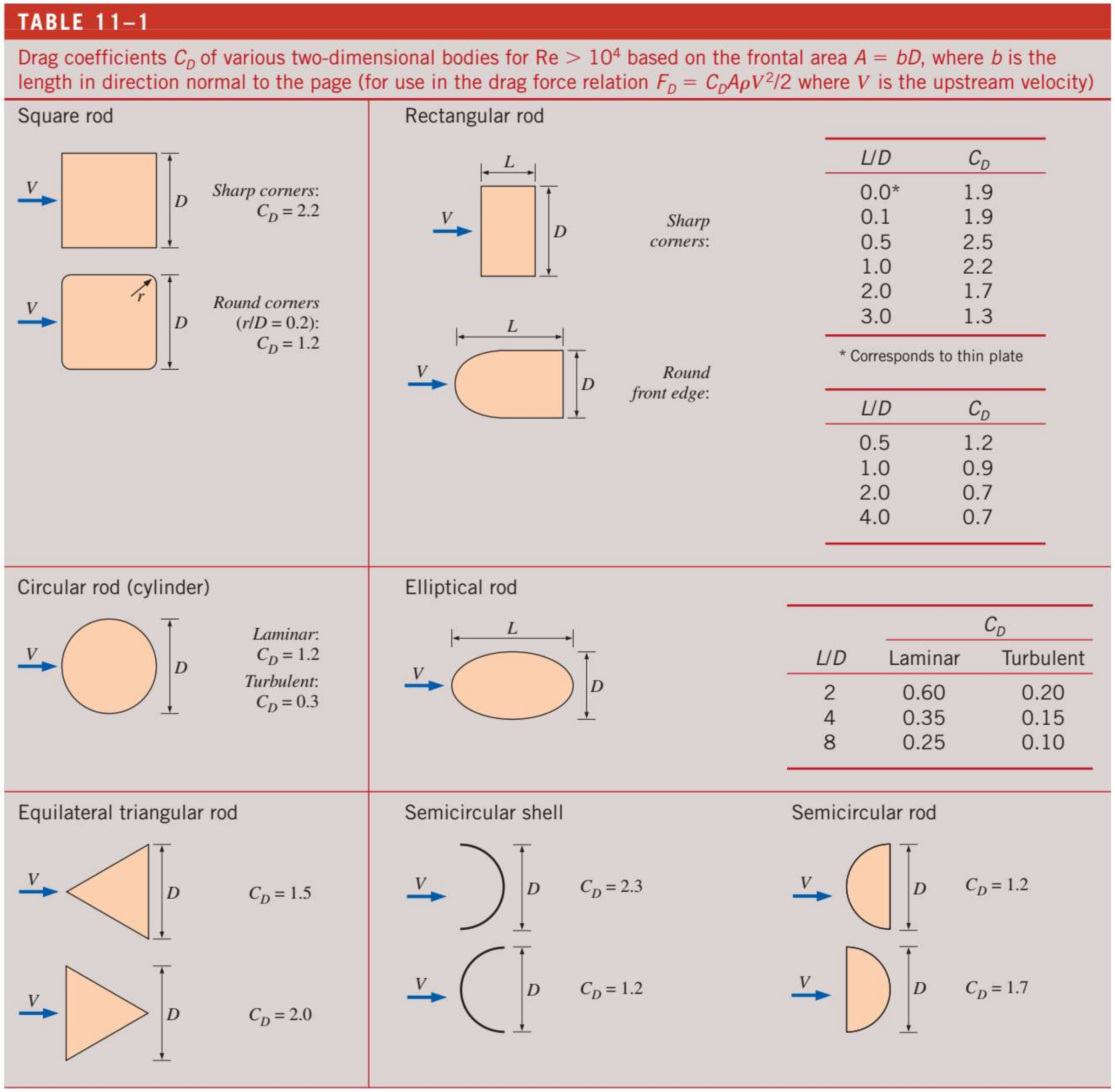


TABLE 11–1

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 the page (for use in the drag force relation $F_D = C_D A \rho V^2/2$ where 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

Equilateral triangular rod

$C_D = 1.5$

$C_D = 2.0$

Semicircular shell

$C_D = 2.3$

$C_D = 1.2$

Semicircular rod

$C_D = 1.2$

$C_D = 1.7$

Drag Coefficient of Common Geometries

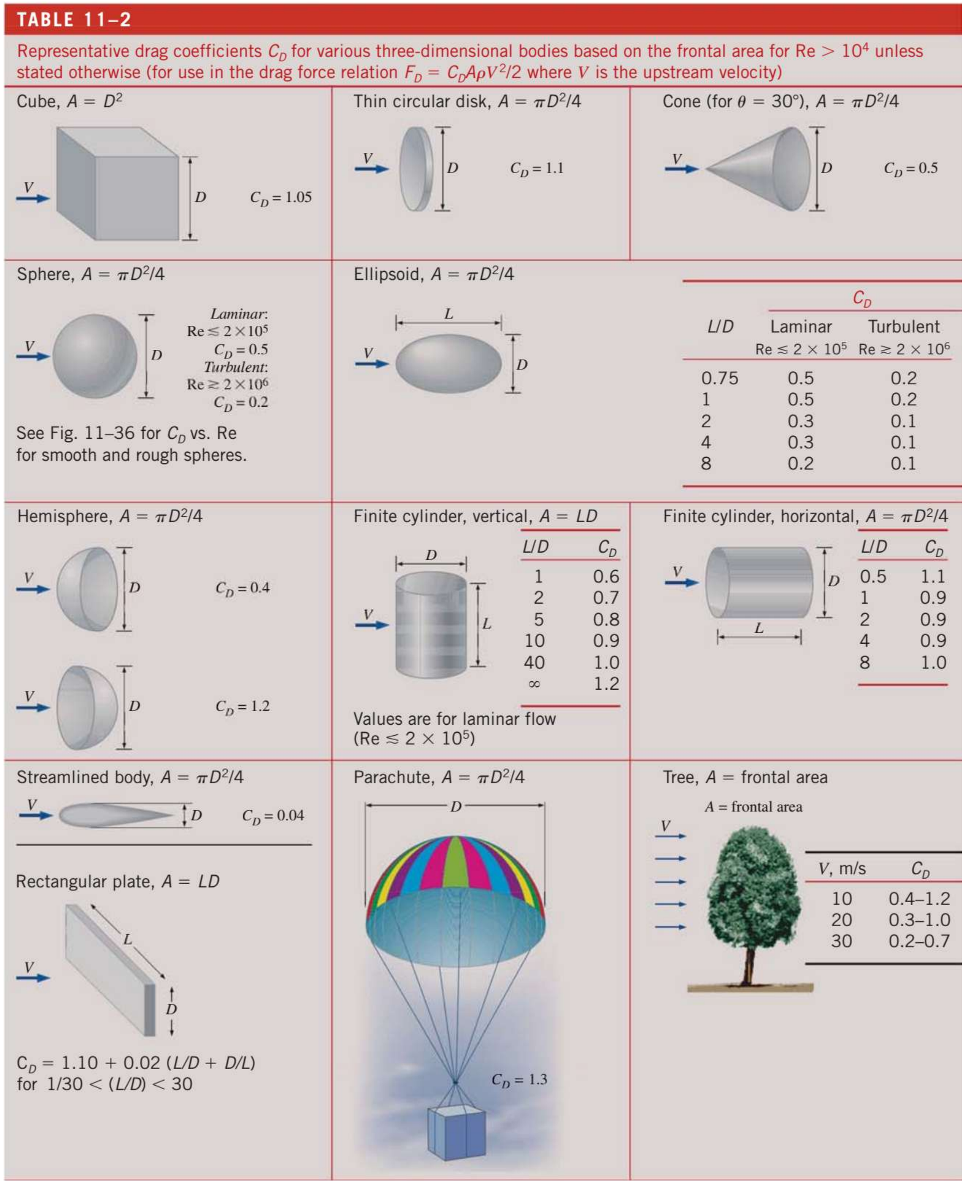


TABLE 11–2

Representative drag coefficients C_D for various three-dimensional bodies based on the frontal area for Re > 10^4 unless stated otherwise (for use in the drag force relation $F_D = C_D A \rho V^2/2$ where 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:
$\mathrm{Re} \lesssim 2 \times 10^5$
$C_D = 0.5$
Turbulent:
$\mathrm{Re} \gtrsim 2 \times 10^6$
$C_D = 0.2$

See Fig. 11–36 for C_D vs. Re for smooth and rough spheres.

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

	C_D	
L/D	Laminar $\mathrm{Re} \lesssim 2 \times 10^5$	Turbulent $\mathrm{Re} \gtrsim 2 \times 10^6$
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

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

$C_D = 0.4$

$C_D = 1.2$

Finite cylinder, vertical, $A = LD$

L/D	C_D
1	0.6
2	0.7
5	0.8
10	0.9
40	1.0
∞	1.2

Values are for laminar flow ($\mathrm{Re} \lesssim 2 \times 10^5$)

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

$C_D = 0.04$

Rectangular plate, $A = LD$

$C_D = 1.10 + 0.02\,(L/D + D/L)$ for $1/30 < (L/D) < 30$

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

$C_D = 1.3$

Tree, A = frontal area

V, m/s	C_D
10	0.4–1.2
20	0.3–1.0
30	0.2–0.7

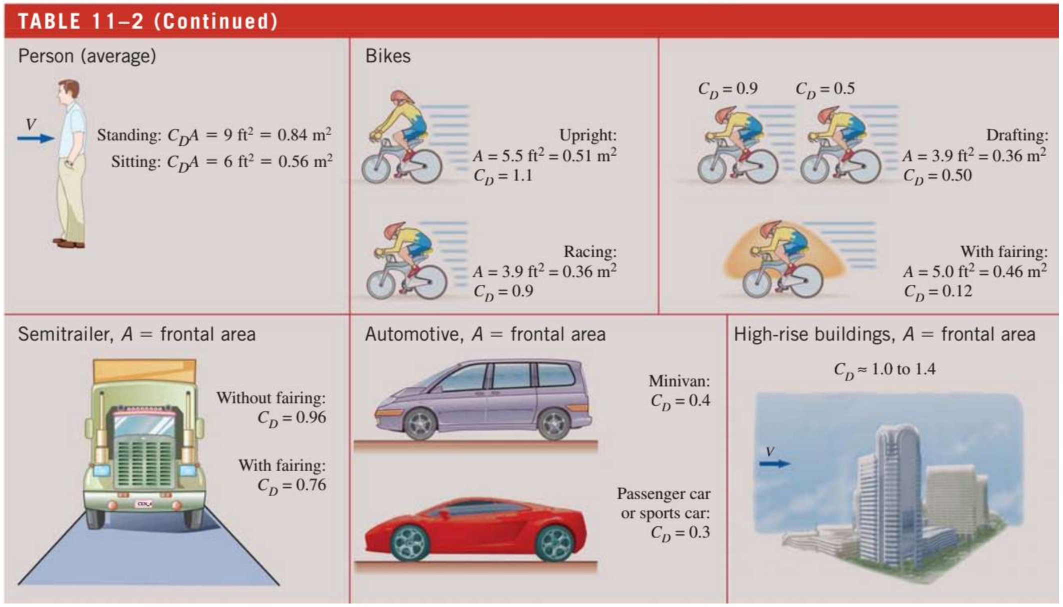


TABLE 11–2 (Continued)

Person (average)

Standing: $C_D A = 9\ \mathrm{ft}^2 = 0.84\ \mathrm{m}^2$
Sitting: $C_D A = 6\ \mathrm{ft}^2 = 0.56\ \mathrm{m}^2$

Bikes

Upright:
$A = 5.5\ \mathrm{ft}^2 = 0.51\ \mathrm{m}^2$
$C_D = 1.1$

Racing:
$A = 3.9\ \mathrm{ft}^2 = 0.36\ \mathrm{m}^2$
$C_D = 0.9$

$C_D = 0.9$ $C_D = 0.5$

Drafting:
$A = 3.9\ \mathrm{ft}^2 = 0.36\ \mathrm{m}^2$
$C_D = 0.50$

With fairing:
$A = 5.0\ \mathrm{ft}^2 = 0.46\ \mathrm{m}^2$
$C_D = 0.12$

Semitrailer, A = frontal area

Without fairing:
$C_D = 0.96$

With fairing:
$C_D = 0.76$

Automotive, A = frontal area

Minivan:
$C_D = 0.4$

Passenger car or sports car:
$C_D = 0.3$

High-rise buildings, A = frontal area

$C_D \approx 1.0$ to 1.4

Drag Coefficient of Common Geometries

Example 2

Two common methods of improving fuel efficiency of a vehicle are to reduce the drag coefficient and the frontal area of the vehicle. Consider a car (Fig. E-2) whose width (W) and height (H) are 1.85 m and 1.70 m, respectively, with a drag coefficient of 0.30. Determine the amount of fuel and money saved per year as a result of reducing the car height to 1.55 m while keeping its width the same. Assume the car is driven 18,000 km a year at an average speed of 95 km/h. Take the density and price of gasoline to be 0.74 kg/L and \$0.95/L, respectively. Also take the density of air to be 1.20 kg/m^3, the heating value of gasoline to be 44,000 kJ/kg, and the overall efficiency of the car's drive train to be 30 percent.

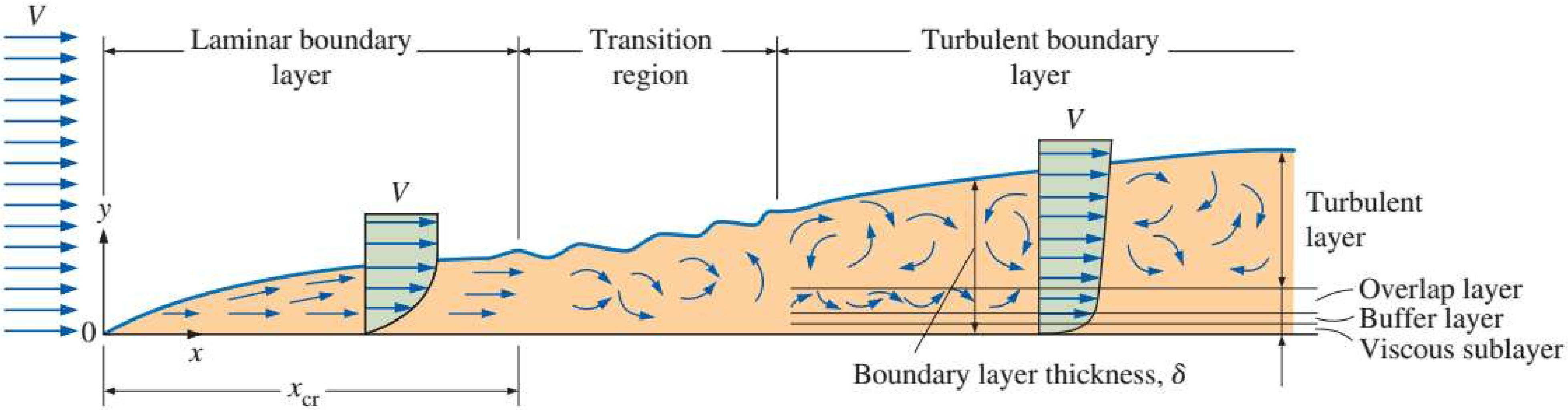
Figure E-2

Content

- Introduction
- Drag and Lift
- Friction and Pressure Drag
- Drag Coefficients of Common Geometries
- **Parallel Flow Over Flat Plates**

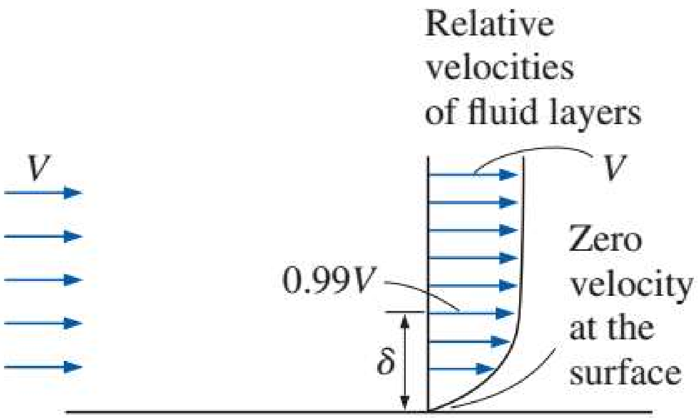
Parallel Flow Over Flat Plates

The development of the **boundary layer for flow over a flat plate**, and the different flow regimes.



Velocity boundary layer: The region of flow above the plate where the effects of **viscous shearing forces** (due to fluid viscosity) are significant and influence the velocity distribution.

Boundary layer thickness (δ) is the distance from the the surface to the point where the flow velocity reaches **99% of the free-stream velocity**.



Parallel Flow Over Flat Plates

Flow over a flat plate

Pressure drag: $C_{\text{D,pressure}} = 0$ **Friction drag coefficient:** $C_{\text{D}} = C_{\text{D,friction}} = C_f$

Pressure force: $F_{\text{D,pressure}} = 0$ **Friction force:** $F_{\text{D}} = F_{\text{D,friction}} = F_f = C_f A \frac{\rho V^2}{2}$

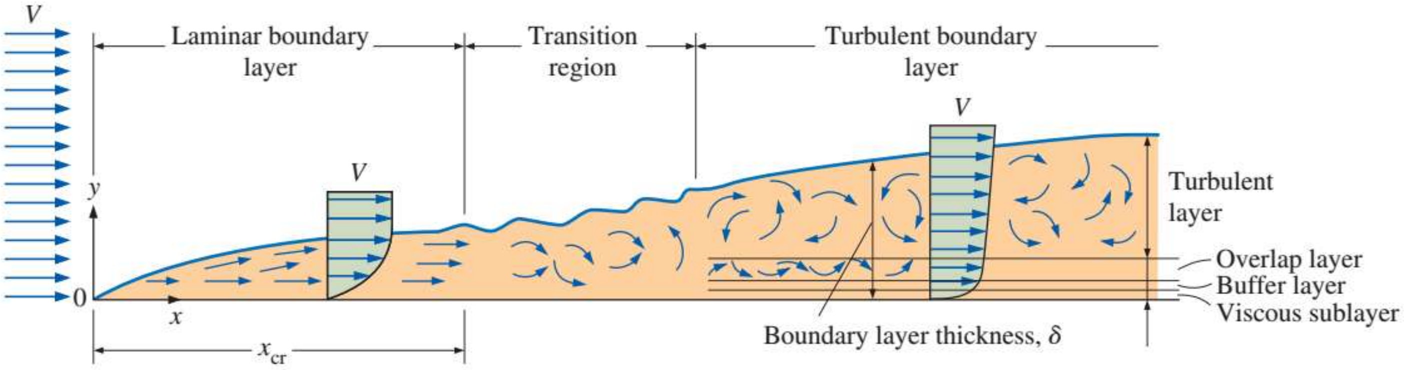
Turbulent boundary layer

Viscous sublayer: Very thin region next to the wall where **viscous effects dominate**; velocity profile is **nearly linear** and flow is nearly parallel.

Buffer layer: Lies above the viscous sublayer; **turbulence starts to matter**, but **viscous effects still dominate**.

Overlap layer: Above the buffer layer; **turbulent effects are more significant**, but **not yet dominant**.

Turbulent (outer) layer: Farthest from the wall; **turbulence dominates** over viscous effects.



Parallel Flow Over Flat Plates

Laminar-to-turbulent transition depends on factors like **surface geometry, surface roughness, upstream velocity, surface temperature, and the type of fluid,** and it is most conveniently characterized using the Reynolds number.

$$Re_x = \frac{\rho V x}{\mu} = \frac{V x}{\nu}$$

V: upstream velocity

x: characteristic length of the geometry

Critical Reynold number: $Re_{x,cr} = \frac{\rho V x_{cr}}{\mu} = 5 \times 10^5$

Boundary layer thickness and the local friction coefficient at location x for laminar flow over a flat plate

Laminar:	$\delta = \frac{4.91x}{Re_x^{1/2}}$	$C_{f,x} = \frac{0.664}{Re_x^{1/2}}$	$Re_x < 5 \times 10^5$
Turbulent:	$\delta = \frac{0.38x}{Re_x^{1/5}}$	$C_{f,x} = \frac{0.059}{Re_x^{1/5}}$	$5 \times 10^5 < Re_x < 10^7$

Parallel Flow Over Flat Plates

Average friction coefficients over a flat plate for combined laminar and turbulent flow conditions:

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

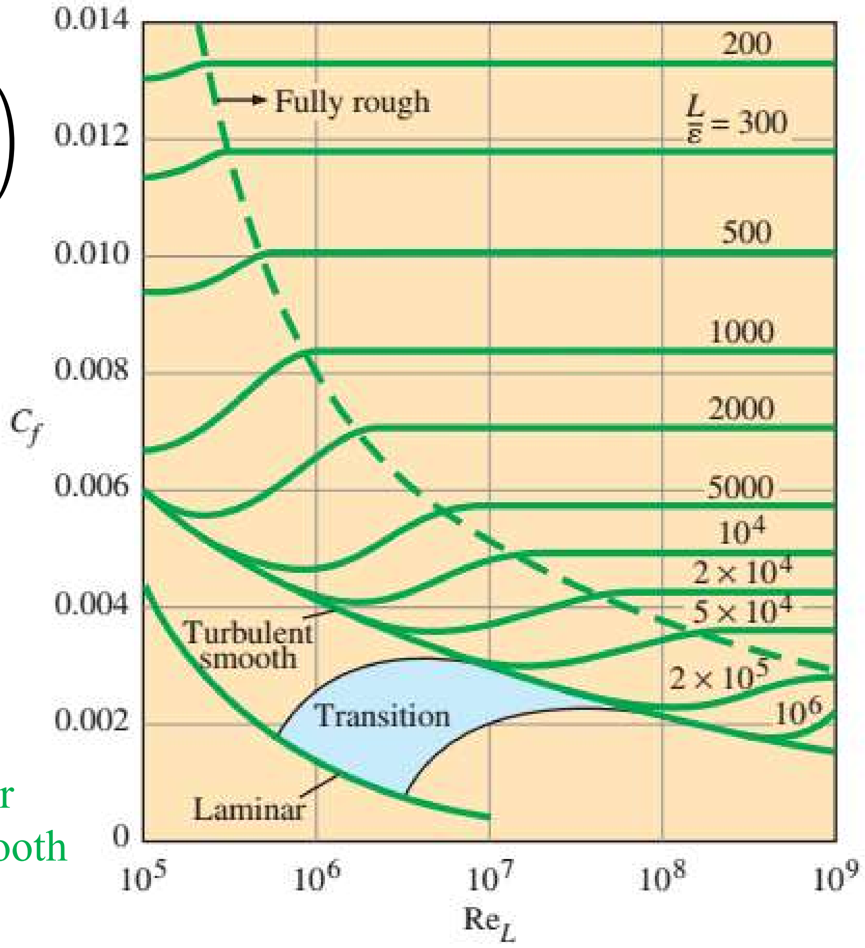
$$C_f = \frac{0.074}{Re_L^{1/5}} - \frac{1742}{Re_L} \qquad 5 \times 10^5 < Re_L < 10^7$$

Fully rough turbulent regime:

$$C_f = \left(1.89 - 1.62 \log \frac{\varepsilon}{L}\right)^{-2.5}$$

ε: surface roughness

L: length of the plate



Friction coefficient for parallel flow over smooth and rough flat plates.

Parallel Flow Over Flat Plates

Example 3

Engine oil at 40°C flows over a 5-m-long flat plate with a free-stream velocity of 2 m/s (Fig. E-3). Determine the drag force acting on the top side of the plate per unit width.

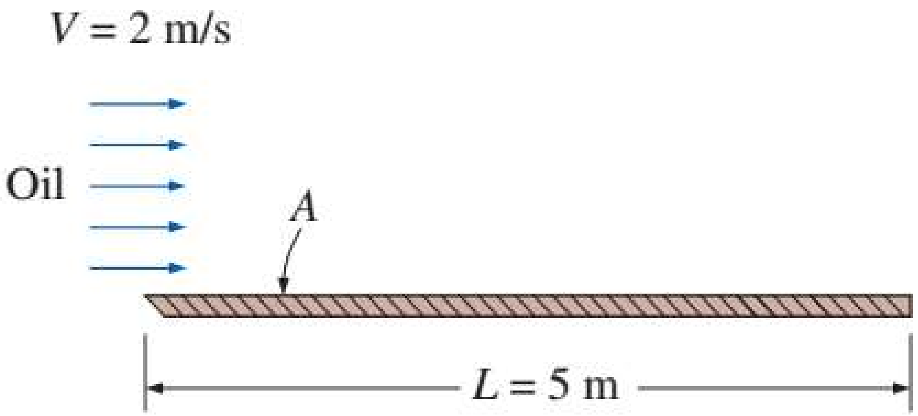


Figure E-3

Parallel Flow Over Flat Plates

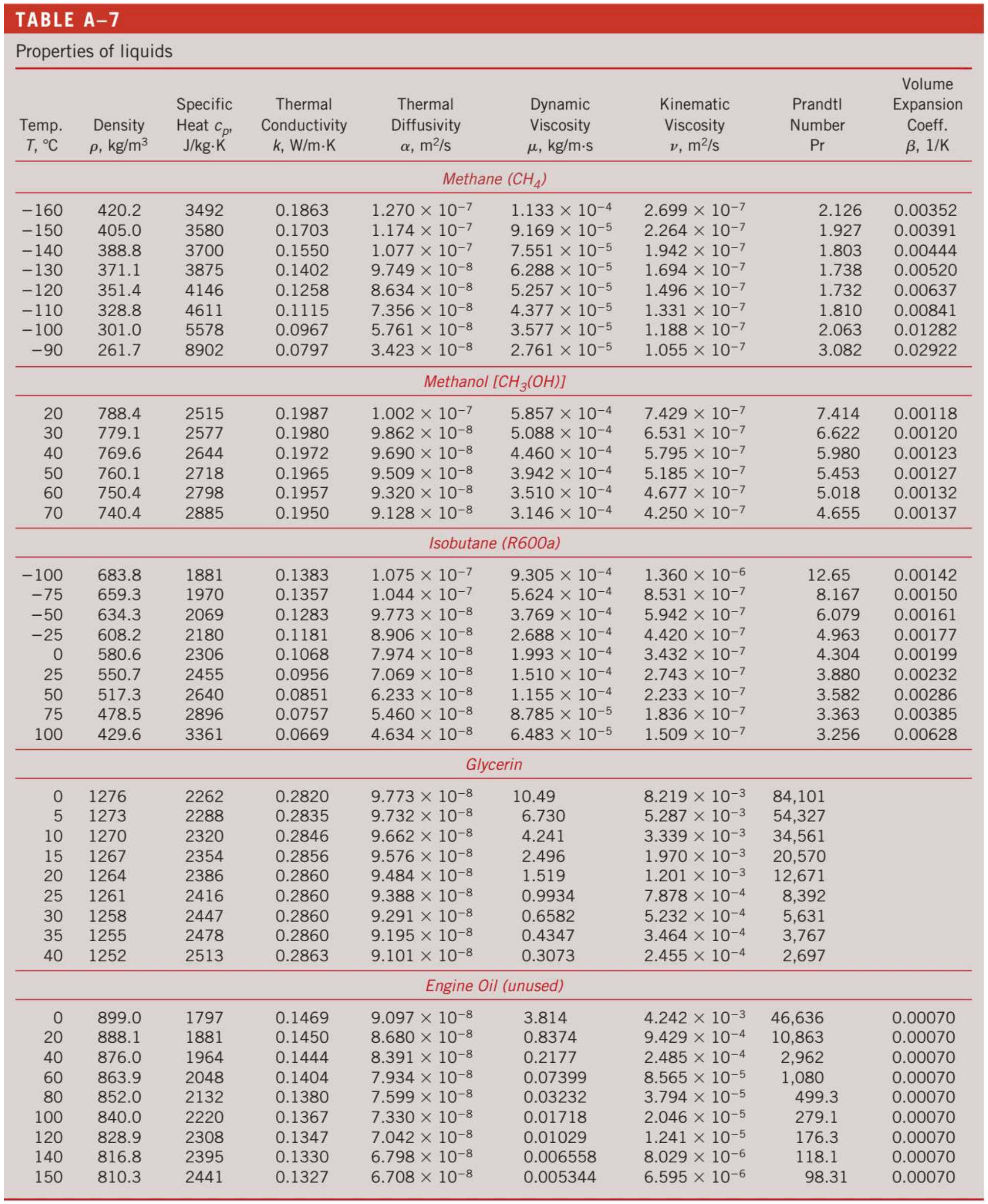


TABLE A–7

Properties of liquids

Temp. T, °C	Density ρ, kg/m^3	Specific Heat c_p, J/kg·K	Thermal Conductivity k, W/m·K	Thermal Diffusivity α, m^2/s	Dynamic Viscosity μ, kg/m·s	Kinematic Viscosity ν, m^2/s	Prandtl Number Pr	Volume Expansion Coeff. β, 1/K
Methane (CH_4)								
−160	420.2	3492	0.1863	1.270×10^{-7}	1.133×10^{-4}	2.699×10^{-7}	2.126	0.00352
−150	405.0	3580	0.1703	1.174×10^{-7}	9.169×10^{-5}	2.264×10^{-7}	1.927	0.00391
−140	388.8	3700	0.1550	1.077×10^{-7}	7.551×10^{-5}	1.942×10^{-7}	1.803	0.00444
−130	371.1	3875	0.1402	9.749×10^{-8}	6.288×10^{-5}	1.694×10^{-7}	1.738	0.00520
−120	351.4	4146	0.1258	8.634×10^{-8}	5.257×10^{-5}	1.496×10^{-7}	1.732	0.00637
−110	328.8	4611	0.1115	7.356×10^{-8}	4.377×10^{-5}	1.331×10^{-7}	1.810	0.00841
−100	301.0	5578	0.0967	5.761×10^{-8}	3.577×10^{-5}	1.188×10^{-7}	2.063	0.01282
−90	261.7	8902	0.0797	3.423×10^{-8}	2.761×10^{-5}	1.055×10^{-7}	3.082	0.02922
Methanol [$CH_3(OH)$]								
20	788.4	2515	0.1987	1.002×10^{-7}	5.857×10^{-4}	7.429×10^{-7}	7.414	0.00118
30	779.1	2577	0.1980	9.862×10^{-8}	5.088×10^{-4}	6.531×10^{-7}	6.622	0.00120
40	769.6	2644	0.1972	9.690×10^{-8}	4.460×10^{-4}	5.795×10^{-7}	5.980	0.00123
50	760.1	2718	0.1965	9.509×10^{-8}	3.942×10^{-4}	5.185×10^{-7}	5.453	0.00127
60	750.4	2798	0.1957	9.320×10^{-8}	3.510×10^{-4}	4.677×10^{-7}	5.018	0.00132
70	740.4	2885	0.1950	9.128×10^{-8}	3.146×10^{-4}	4.250×10^{-7}	4.655	0.00137
Isobutane (R600a)								
−100	683.8	1881	0.1383	1.075×10^{-7}	9.305×10^{-4}	1.360×10^{-6}	12.65	0.00142
−75	659.3	1970	0.1357	1.044×10^{-7}	5.624×10^{-4}	8.531×10^{-7}	8.167	0.00150
−50	634.3	2069	0.1283	9.773×10^{-8}	3.769×10^{-4}	5.942×10^{-7}	6.079	0.00161
−25	608.2	2180	0.1181	8.906×10^{-8}	2.688×10^{-4}	4.420×10^{-7}	4.963	0.00177
0	580.6	2306	0.1068	7.974×10^{-8}	1.993×10^{-4}	3.432×10^{-7}	4.304	0.00199
25	550.7	2455	0.0956	7.069×10^{-8}	1.510×10^{-4}	2.743×10^{-7}	3.880	0.00232
50	517.3	2640	0.0851	6.233×10^{-8}	1.155×10^{-4}	2.233×10^{-7}	3.582	0.00286
75	478.5	2896	0.0757	5.460×10^{-8}	8.785×10^{-5}	1.836×10^{-7}	3.363	0.00385
100	429.6	3361	0.0669	4.634×10^{-8}	6.483×10^{-5}	1.509×10^{-7}	3.256	0.00628
Glycerin								
0	1276	2262	0.2820	9.773×10^{-8}	10.49	8.219×10^{-3}	84,101	
5	1273	2288	0.2835	9.732×10^{-8}	6.730	5.287×10^{-3}	54,327	
10	1270	2320	0.2846	9.662×10^{-8}	4.241	3.339×10^{-3}	34,561	
15	1267	2354	0.2856	9.576×10^{-8}	2.496	1.970×10^{-3}	20,570	
20	1264	2386	0.2860	9.484×10^{-8}	1.519	1.201×10^{-3}	12,671	
25	1261	2416	0.2860	9.388×10^{-8}	0.9934	7.878×10^{-4}	8,392	
30	1258	2447	0.2860	9.291×10^{-8}	0.6582	5.232×10^{-4}	5,631	
35	1255	2478	0.2860	9.195×10^{-8}	0.4347	3.464×10^{-4}	3,767	
40	1252	2513	0.2863	9.101×10^{-8}	0.3073	2.455×10^{-4}	2,697	
Engine Oil (unused)								
0	899.0	1797	0.1469	9.097×10^{-8}	3.814	4.242×10^{-3}	46,636	0.00070
20	888.1	1881	0.1450	8.680×10^{-8}	0.8374	9.429×10^{-4}	10,863	0.00070
40	876.0	1964	0.1444	8.391×10^{-8}	0.2177	2.485×10^{-4}	2,962	0.00070
60	863.9	2048	0.1404	7.934×10^{-8}	0.07399	8.565×10^{-5}	1,080	0.00070
80	852.0	2132	0.1380	7.599×10^{-8}	0.03232	3.794×10^{-5}	499.3	0.00070
100	840.0	2220	0.1367	7.330×10^{-8}	0.01718	2.046×10^{-5}	279.1	0.00070
120	828.9	2308	0.1347	7.042×10^{-8}	0.01029	1.241×10^{-5}	176.3	0.00070
140	816.8	2395	0.1330	6.798×10^{-8}	0.006558	8.029×10^{-6}	118.1	0.00070
150	810.3	2441	0.1327	6.708×10^{-8}	0.005344	6.595×10^{-6}	98.31	0.00070

Content

- Introduction
- Drag and Lift
- Friction and Pressure Drag
- Drag Coefficients of Common Geometries
- Parallel Flow Over Flat Plates
- **Flow Over Cylinders and Spheres**

Flow Over Cylinders and Spheres

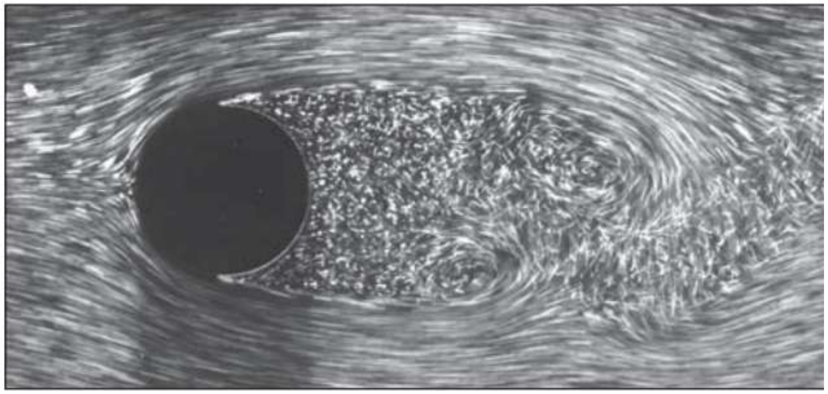
Reynold number for the case of cylinders and spheres:

$$Re = \frac{VD}{\nu}$$

V: uniform velocity of the fluid as it approaches the cylinder or sphere.

D: characteristic length (here, the **external diameter** of the cylinder/sphere).

ν: kinematic viscosity of the fluid.



Laminar boundary layer separation with a turbulent wake; flow over a circular cylinder at Re = 2000.

For $Re \leq 2 \times 10^5$ → laminar

For $2 \times 10^5 \leq Re \leq 2 \times 10^6$ → transional

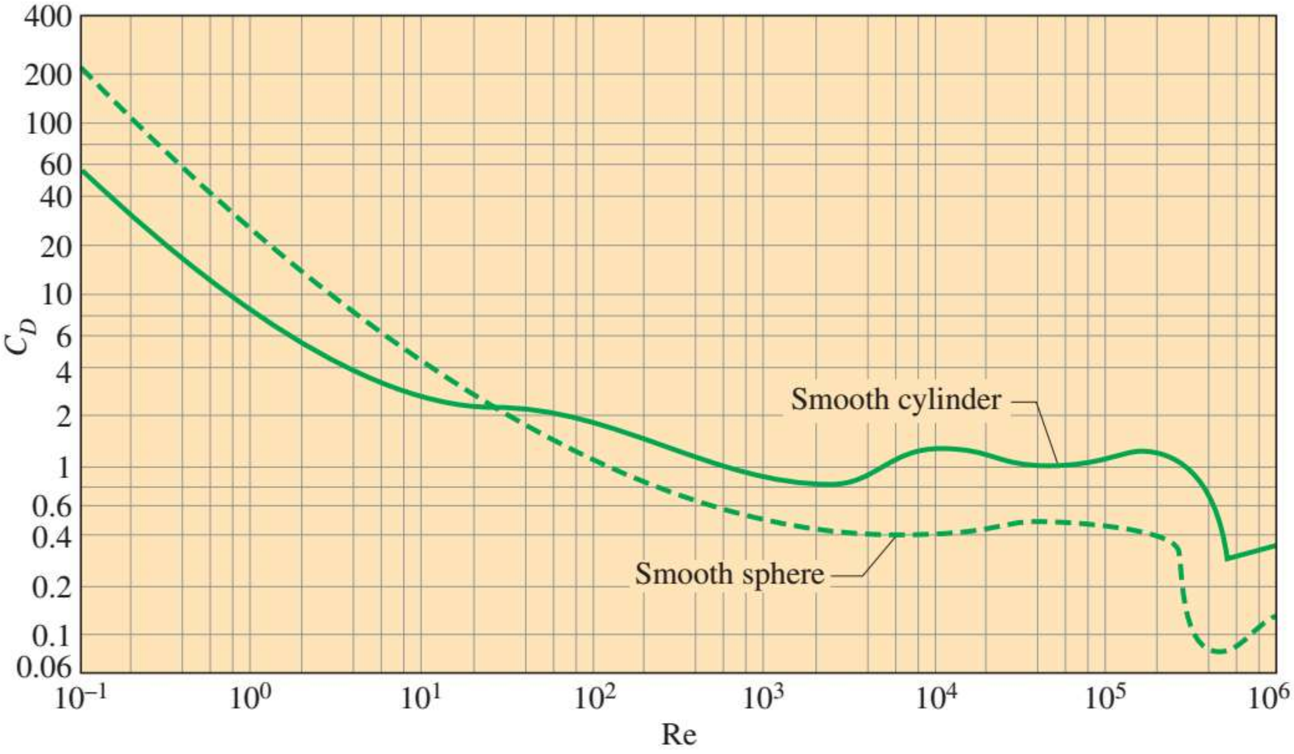
For $Re \geq 2 \times 10^6$ → fully turbulent

At **very low Reynolds numbers (Re ≪ 1)**, the flow smoothly follows the cylinder surface and recombines behind it without separation or turbulence.

Flow Over Cylinders and Spheres

Average Drag Coefficient (C_D) for a Smooth Cylinder and Sphere:

- For $Re \leq 1$ → creeping flow
- Separation begins near **Re ≈ 10**; vortex shedding begins near **Re ≈ 90**; separation grows up to **Re ≈ 10³**, where pressure drag dominates.
- For $10^3 < Re < 10^5$, C_D remains nearly constant, with a laminar boundary layer and a turbulent separated wake.
- For $10^5 < Re < 10^6$) (around $Re \approx 2 \times 10^5$), drag coefficient drops sharply because the boundary layer becomes turbulent. Reducing wake size and drag.



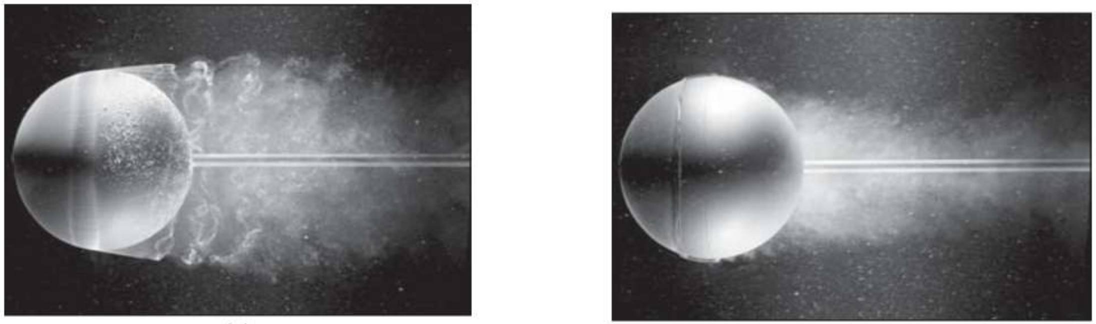
Average drag coefficient for cross-flow over a smooth circular cylinder and a smooth sphere.

- For $2 \times 10^5 < Re < 2 \times 10^6$, C_D reaches a minimum, then gradually increases to the fully turbulent value.

Flow Over Cylinders and Spheres

- For a cylinder, separation occurs around **80°** with a **laminar** boundary layer and around **140°** with a **turbulent** boundary layer (measured from the front stagnation point).

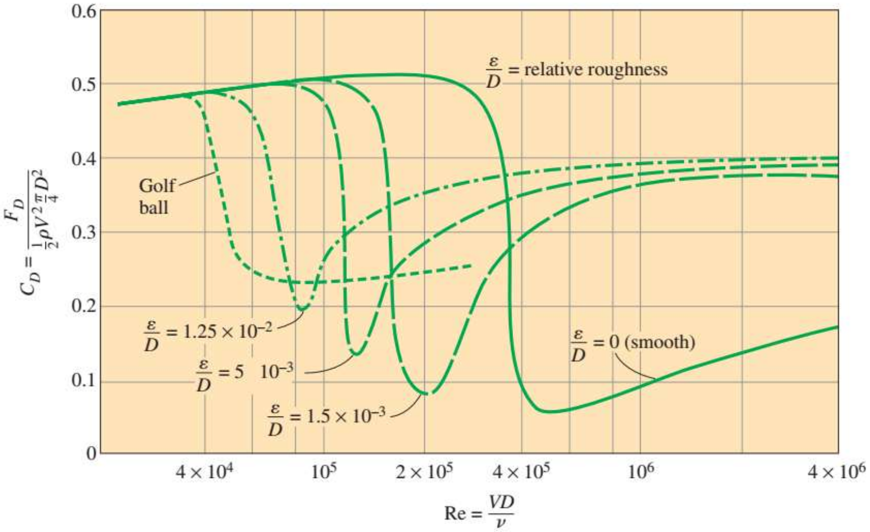
- Flow visualization of flow over (a) a smooth sphere at Re = 15,000, and (b) a sphere at Re = 30,000 with a trip wire. The delay of boundary layer separation is clearly seen by comparing the two photographs.



(a) (b)

Effect of Surface Roughness

Golf balls have dimples to trigger a turbulent boundary layer at lower Reynolds numbers. This delays flow separation, shrinks the wake, and causes a sharp drop in drag. For typical speeds (15–150 m/s), $Re < 4 \times 10^5$;dimples reduce the critical Reynolds number to about 4×10^4 ,cutting the drag coefficient by roughly half.



Flow Over Cylinders and Spheres

Example 4

A 2.2-cm-outer-diameter pipe is to span across a river at a 30-m-wide section while being completely immersed in water (Fig. E-4). The average flow velocity of water is 4 m/s, and the water temperature is 15°C. Determine the drag force exerted on the pipe by the river.

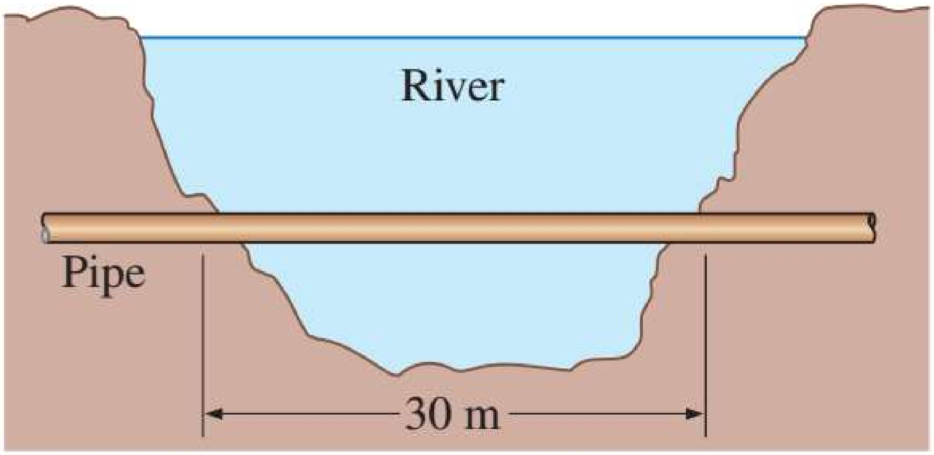


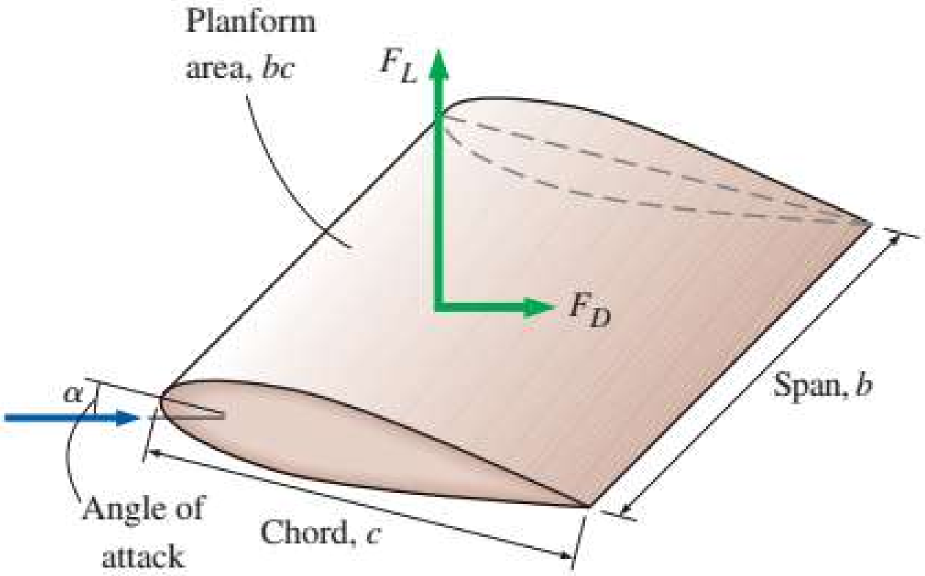
Figure E-4

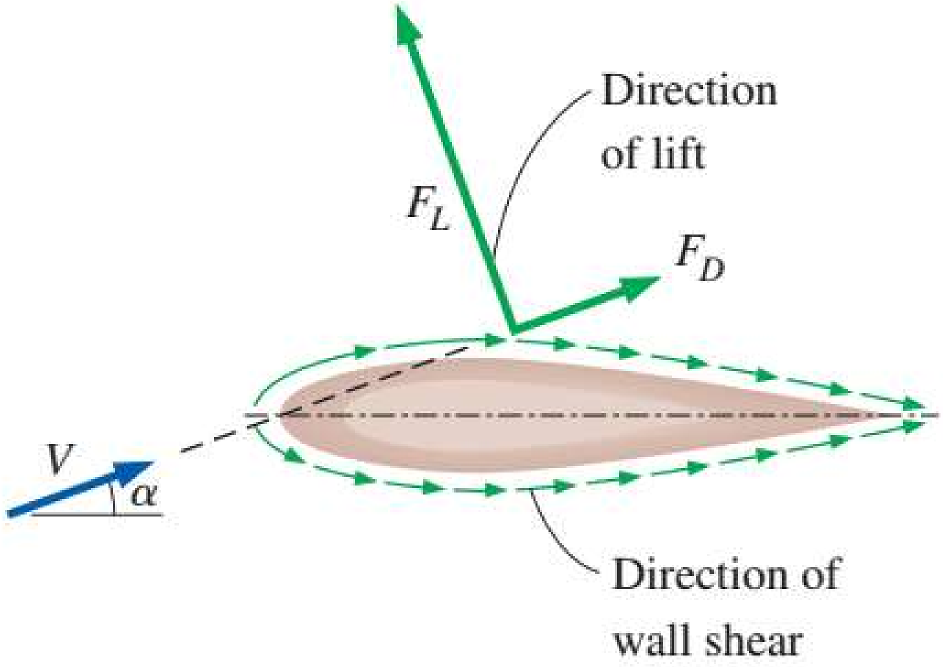
Content

- Introduction
- Drag and Lift
- Friction and Pressure Drag
- Drag Coefficients of Common Geometries
- Parallel Flow Over Flat Plates
- Flow Over Cylinders and Spheres
- **Lift**

Lift

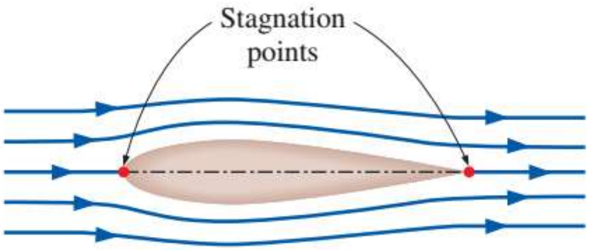
Lift is the component of the net force (due to viscous and pressure forces) perpendicular to the flow.



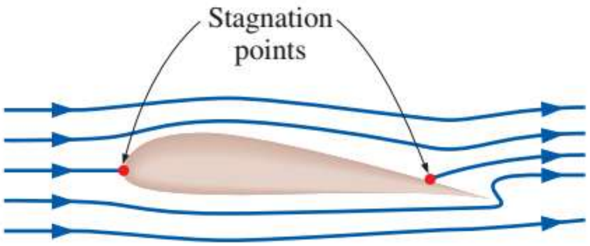


For airfoils, the contribution of viscous effects to lift is usually negligible since wall shear is parallel to the surfaces and thus nearly normal to the direction of lift.

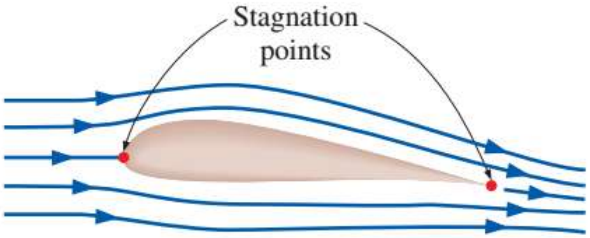
Lift



(*a*) Irrotational flow past a symmetrical airfoil (zero lift)

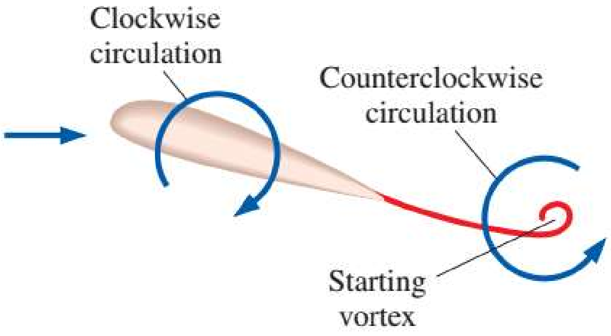


(*b*) Irrotational flow past a nonsymmetrical airfoil (zero lift)

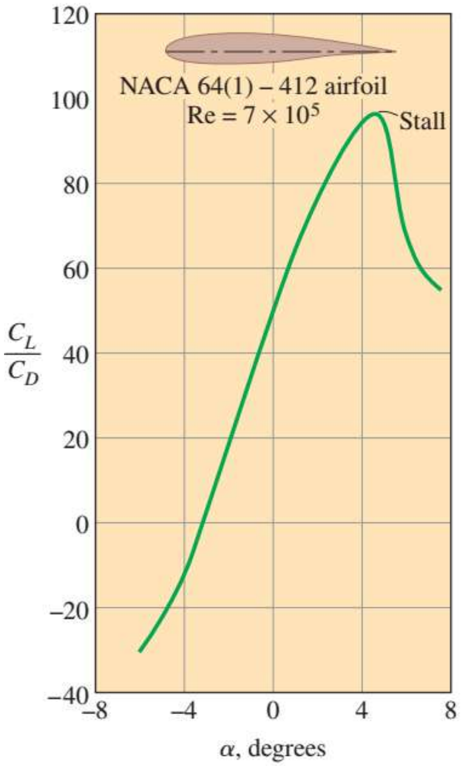


(*c*) Actual flow past a nonsymmetrical airfoil (positive lift)

Shortly after a sudden increase in angle of attack, a counterclockwise starting vortex is shed from the airfoil, while clockwise circulation appears around the airfoil, causing lift to be generated.



The variation of the lift-to-drag ratio with angle of attack for a two-dimensional airfoil.

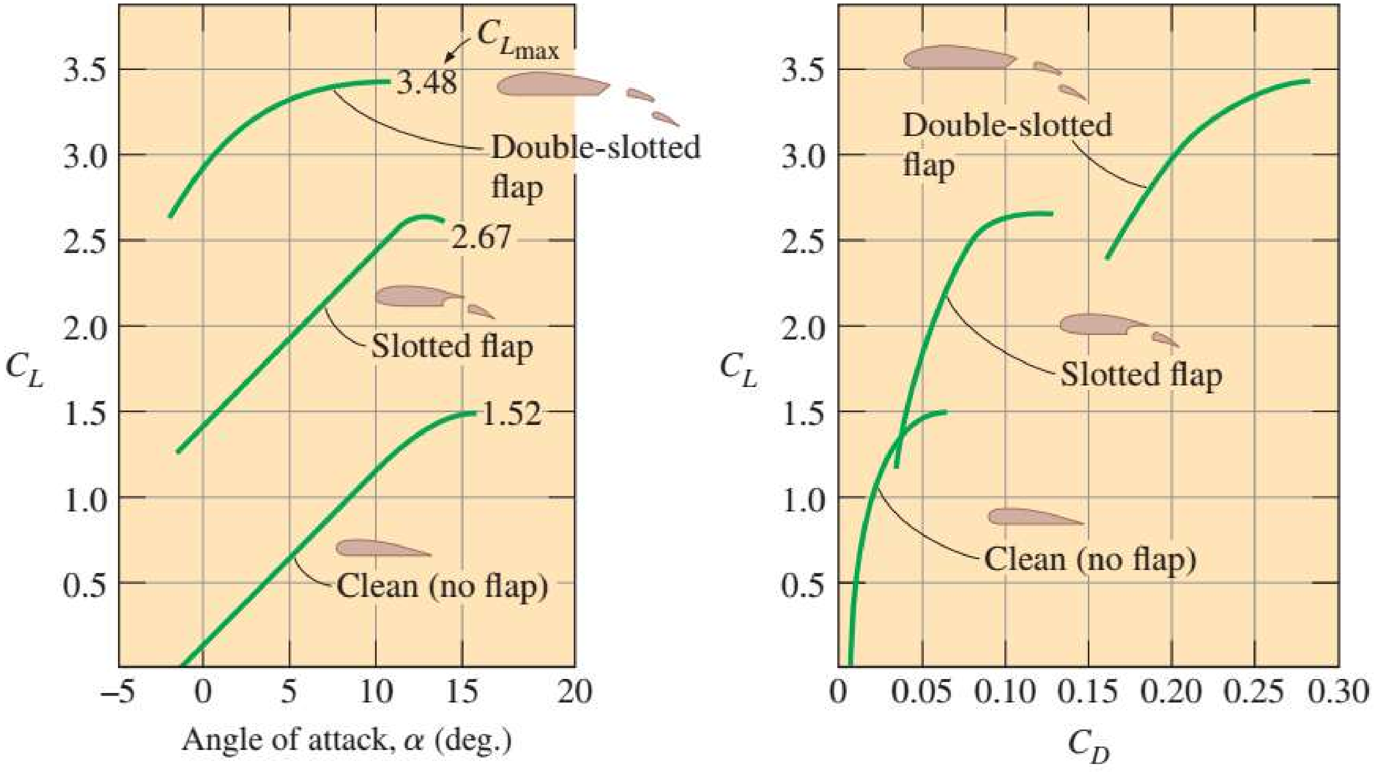


Lift

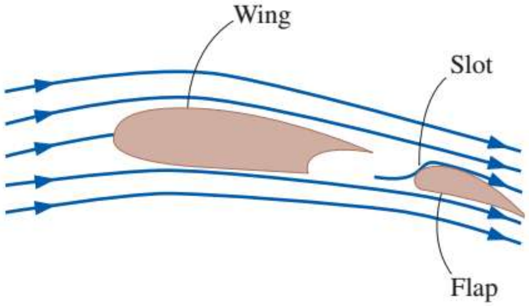
The lift and drag characteristics of an airfoil during takeoff and landing are changed by changing the shape of the airfoil through the use of movable flaps.

(*a*) Flaps extended (landing)

(*b*) Flaps retracted (cruising)

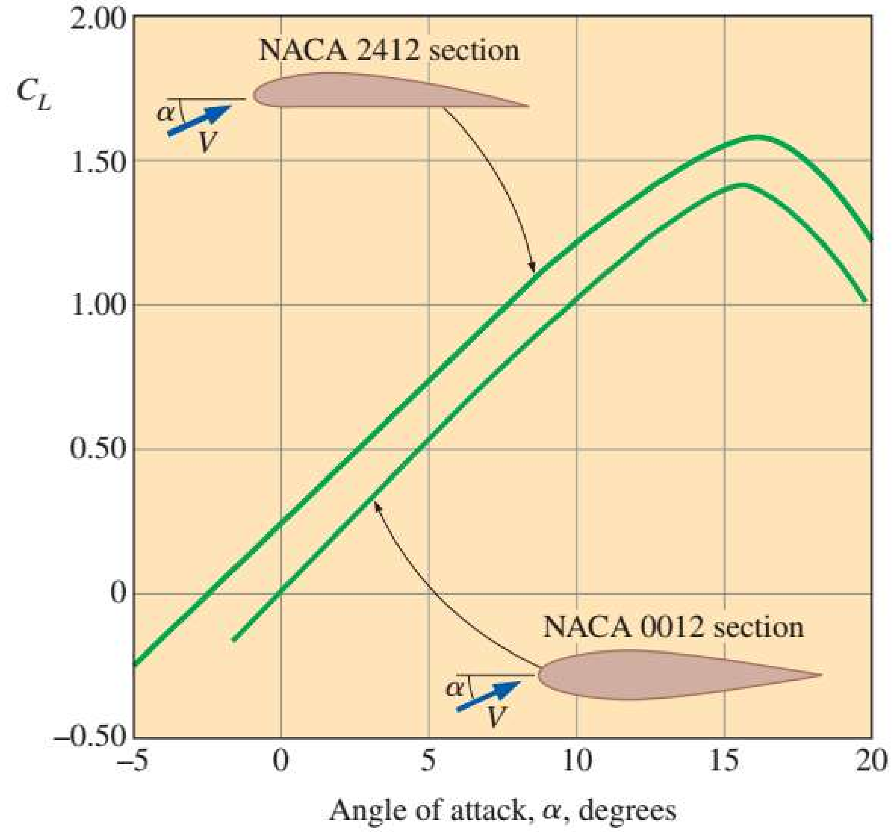


Effects of Flaps on the Lift and Drag Coefficients of a NACA 23012 Airfoil

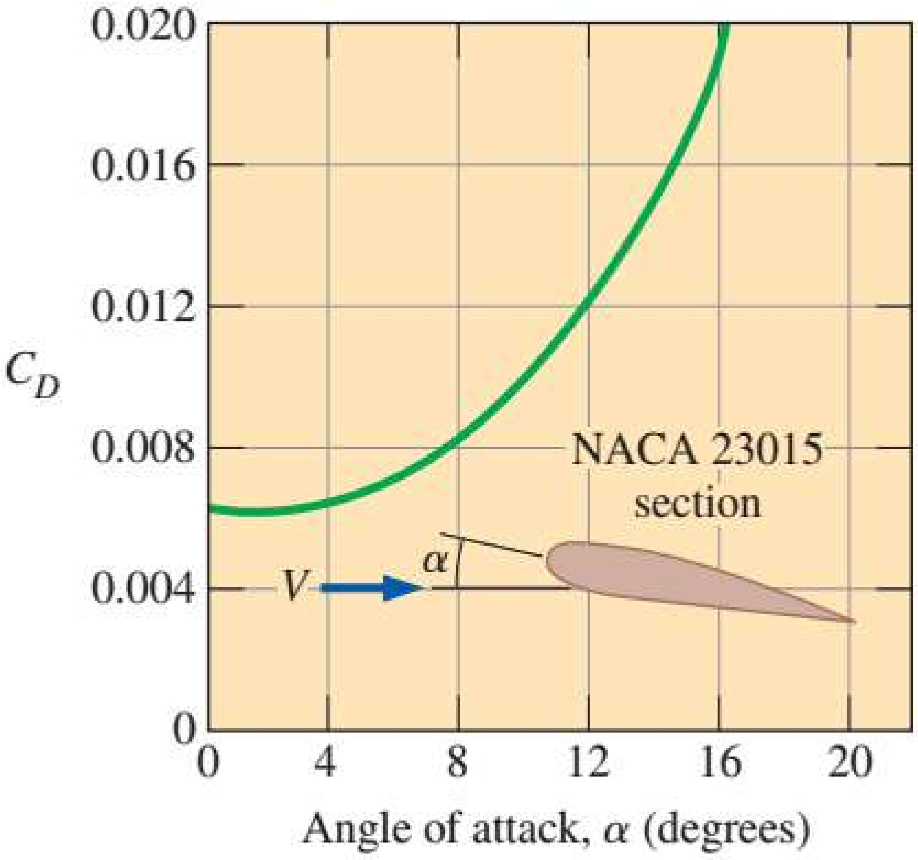


A flapped airfoil with a slot to prevent the separation of the boundary layer from the upper surface and to increase the lift coefficient.

Lift



The variation of the lift coefficient with angle of attack for a symmetrical and a nonsymmetrical airfoil.



The variation of the drag coefficient of an airfoil with angle of attack.

Lift

Finite-Span Wings and Induced Drag

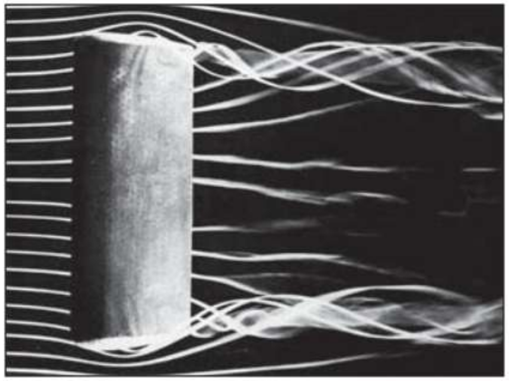
Aspect Ratio, AR

$$AR = \frac{b^2}{A} = \frac{b^2}{bc} = \frac{b}{c}$$

c: chord

b: span

Trailing vortices are visualized in various ways:



(a)

Smoke streaklines in a wind tunnel show vortex cores leaving the trailing edge of a rectangular wing.

(b)

Four engine contrails form in low-pressure regions, then merge into two counter-rotating trailing vortices that persist far downstream.

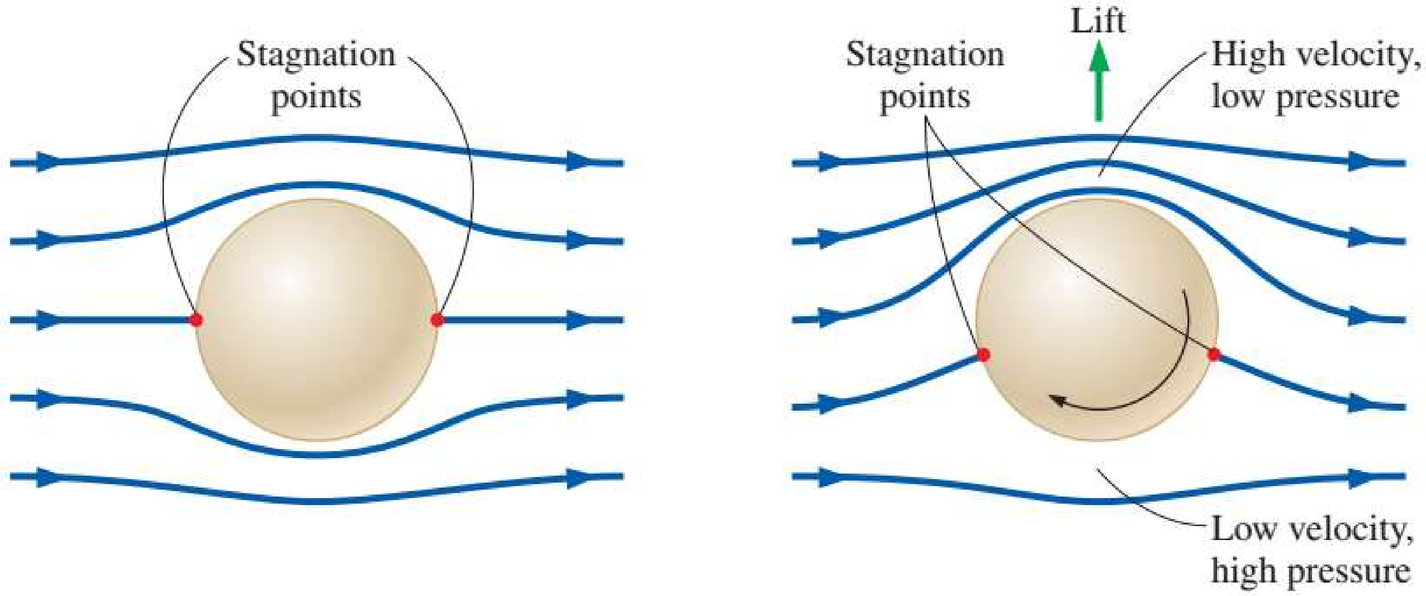
A crop duster flies through smoky air, revealing smoke swirling within a wingtip vortex.

(c)

Induced drag is the drag component caused by wingtip vortices; their interaction with the free stream creates a force component in the flow direction. Thus, total wing drag equals **induced drag (3-D effects)** plus **airfoil section drag (2-D effects)**.

Lift

Lift Generated by Spinning



(*a*) Potential flow over a stationary cylinder (*b*) Potential flow over a rotating cylinder

Generation of lift on a rotating circular cylinder for the case of “idealized” potential flow (the actual flow involves flow separation in the wake region).

Lift

Example 5

A commercial airplane has a total mass of 70,000 kg and a wing planform area of 150 m^2 (Fig. E-5). The plane has a cruising speed of 558 km/h and a cruising altitude of 12,000 m, where the air density is 0.312 kg/m3. The plane has double-slotted flaps for use during takeoff and landing, but it cruises with all flaps retracted. Assuming the lift and the drag characteristics of the wings can be approximated by NACA 23012 (Fig. E-5), determine (a) the minimum safe speed for takeoff and landing with and without extending the flaps, (b) the angle of attack to cruise steadily at the cruising altitude, and (c) the power that needs to be supplied to provide enough thrust to overcome wing drag.

Figure E-5

References

[1] Cengel Y., Cimbala, J. (2014). Fluid Mechanics: Fundamentals and Applications (3th Edition). New York: NY: McGraw-Hill Co.

[2] Munson, B.R., Young, D.F., Okiishi, T.H., and Huebsch, W.W. (2016). Fundamentals of Fluid Mechanics (8th Edition). John Wiley & Sons. ISBN 1119080703.