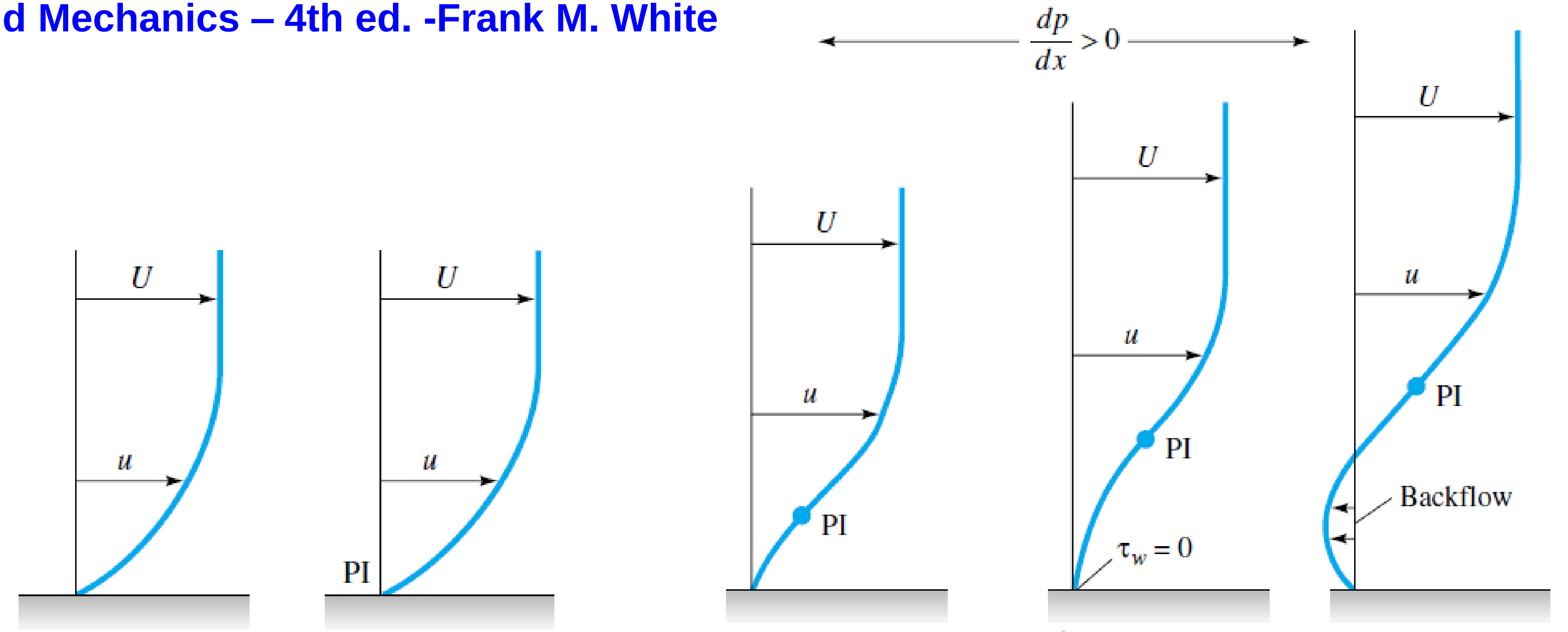
Fenômenos de Transporte I

Fluid Mechanics – 4th ed. -Frank M. White

ESCOAMENTO EXTERNO

EFEITO DO GRADIENTE DE PRESSÃO NO PERFIL DE VELOCIDADES

Fluid Mechanics – 4th ed. -Frank M. White



(*a*) Favorable gradient:
$\frac{dU}{dx} > 0$
$\frac{dp}{dx} < 0$
No separation, PI inside wall

(*b*) Zero gradient:
$\frac{dU}{dx} = 0$
$\frac{dp}{dx} = 0$
No separation, PI at wall

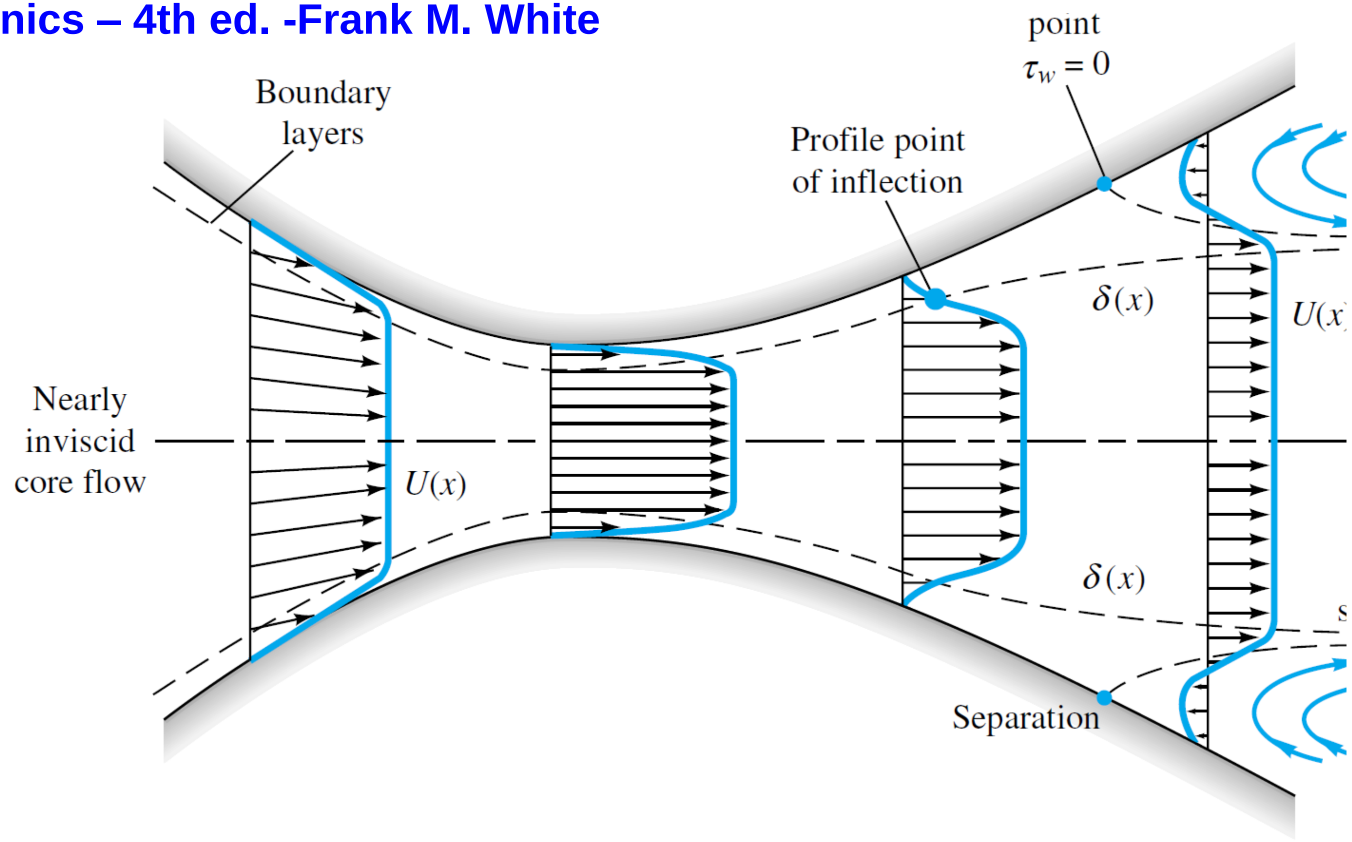
(*c*) Weak adverse gradient:
$\frac{dU}{dx} < 0$
$\frac{dp}{dx} > 0$
No separation, PI in the flow

(*d*) Critical adverse gradient:
Zero slope at the wall:
Separation

(*e*) Excessive adverse gradient:
Backflow at the wall:
Separated flow region

EFEITO DO GRADIENTE DE PRESSÃO NO PERFIL DE VELOCIDADES

Fluid Mechanics – 4th ed. -Frank M. White



Nozzle:	*Throat*:	*Diffuser*:
Decreasing pressure and area	Constant pressure and area	Increasing pressure and area
Increasing velocity	Velocity constant	Decreasing velocity
Favorable gradient	Zero gradient	Adverse gradient (boundary layer thickens)

Fluid Mechanics – 4th ed. -Frank M. White

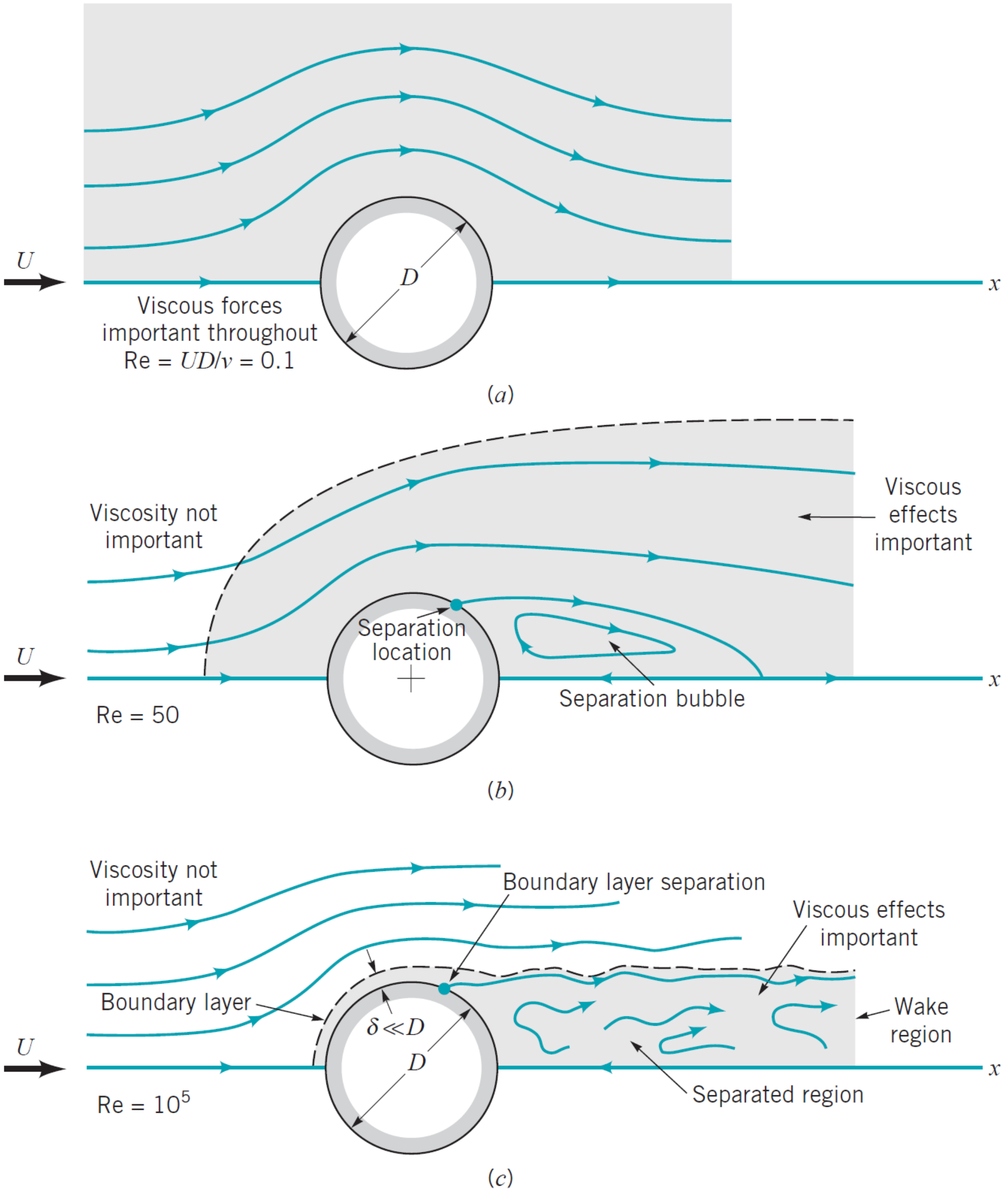
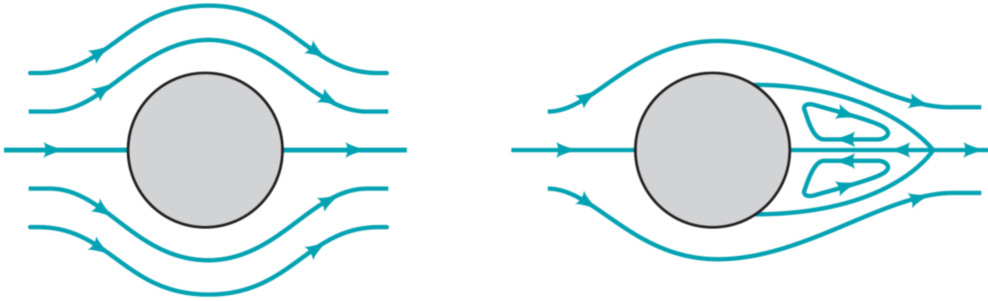


FIGURE 9.6 **Character of the steady, viscous flow past a circular cylinder: (*a*) low Reynolds number flow, (*b*) moderate Reynolds number flow, (*c*) large Reynolds number flow.**

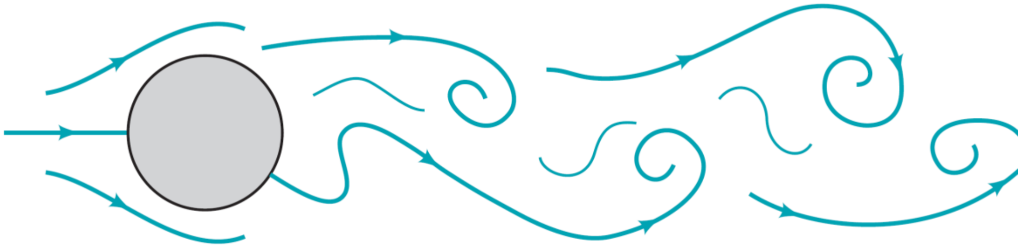


No separation

(*A*)

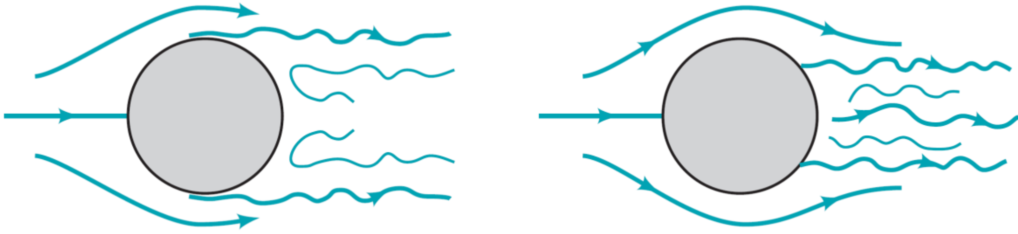
Steady separation bubble

(*B*)



Oscillating Karman vortex street wake

(*C*)



Laminar boundary layer, wide turbulent wake

(*D*)

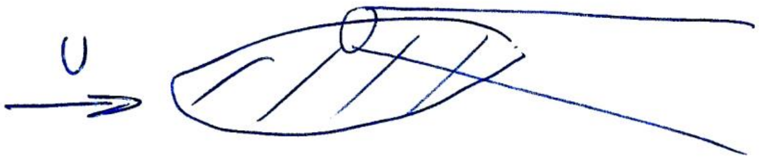
Turbulent boundary layer, narrow turbulent wake

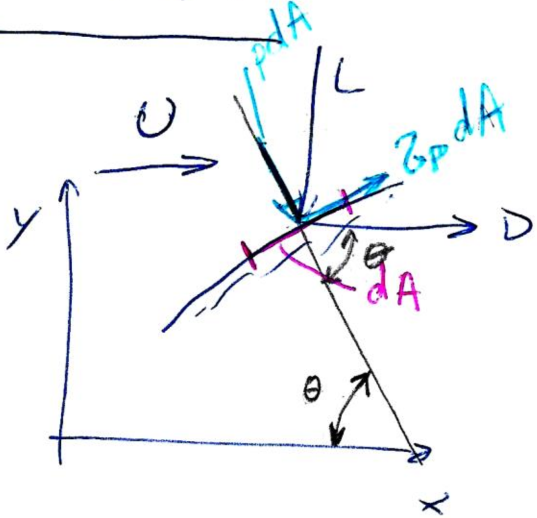
(*E*)

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*).

ESCOAMENTO SOBRE CORPOS IMERSOS

Arrasto e Sustentação.





$$dF_x = p\,dA(\cos\theta) + \tau_p dA \,\mathrm{sen}\,\theta$$

$$dF_y = -(p\,dA)\,\mathrm{sen}\,\theta + (\tau_p dA)\cos\theta$$

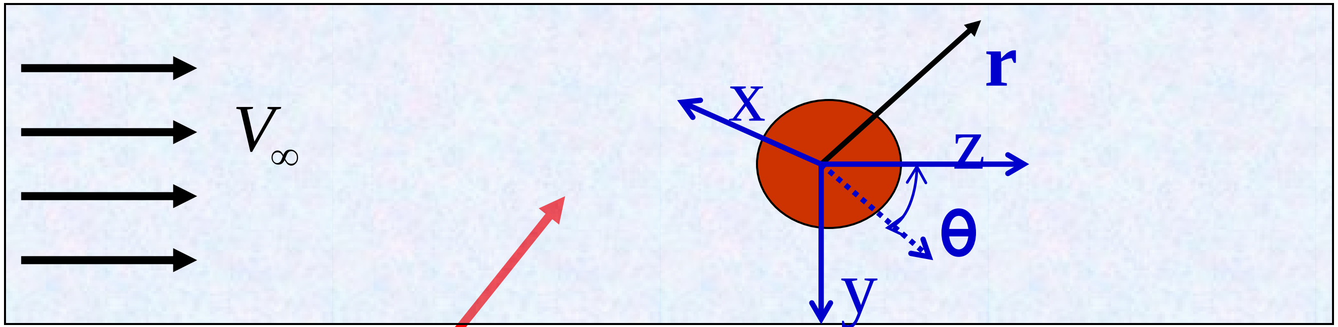
$$D = \int dF_x = \int p \cos\theta\, dA + \int \tau_p \,\mathrm{sen}\,\theta\, dA$$

$$L = \int dF_y = -\int p\,\mathrm{sen}\,\theta\, dA + \int \tau_p \cos\theta\, dA$$

$$C_L = \frac{L}{\frac{1}{2}\rho U^2 A} \quad \text{e} \quad C_D = \frac{D}{\frac{1}{\rho}\rho U^2 A}$$

A - área característica. Normalmente é a área frontal (i.e) a área projetada.

”Lei” de Stokes – Meio Contínuo



Fluido => Equação de Navier-Stokes – pressão e velocidades

$$\rho\left(\cancel{\frac{\partial \vec{V}}{\partial t}} + \cancel{\vec{V}.\nabla\vec{V}}\right) = \nabla P + \mu \nabla^2 \vec{V}$$

Regime permanente

Re <<1

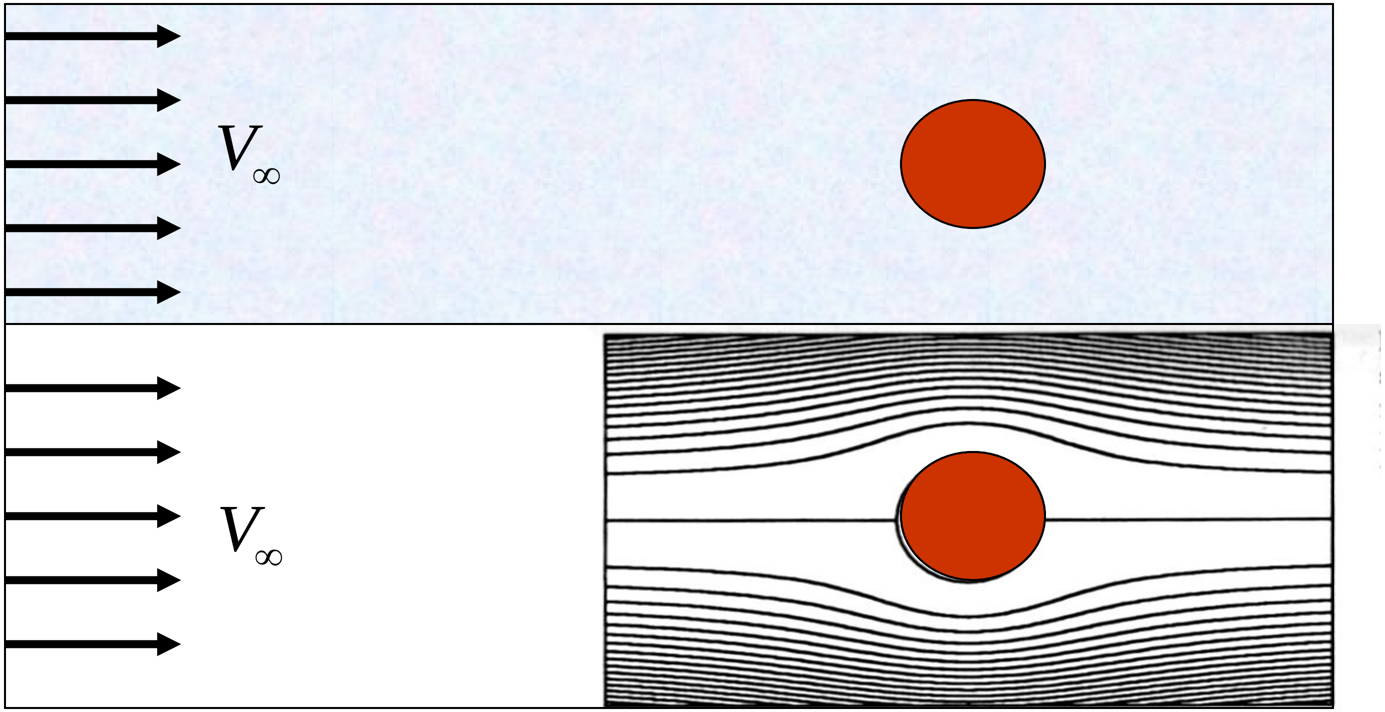
•Cond. de contorno:
$$\begin{cases} r \to \infty\ ,\ \vec{V} = V_\infty \\ r = R_P\ ,\ \vec{V} = 0 \\ r \to \infty\ ,\ \ p = p_0 \end{cases}$$

$$\boxed{p = p_0 - \frac{3\mu V_\infty}{2R_P}\left(\frac{R_P}{r}\right)^2 \cos\theta}$$

$$\boxed{V_r = V_\infty \cos\theta\left[1 - \frac{3}{2}\left(\frac{R_P}{r}\right) + \frac{1}{2}\left(\frac{R_P}{r}\right)^3\right]}$$

$$\boxed{V_\theta = -V_\infty sen\theta\left[1 - \frac{3}{4}\left(\frac{R_P}{r}\right) - \frac{1}{4}\left(\frac{R_P}{r}\right)^3\right]}$$

”Lei” de Stokes – Re < 1

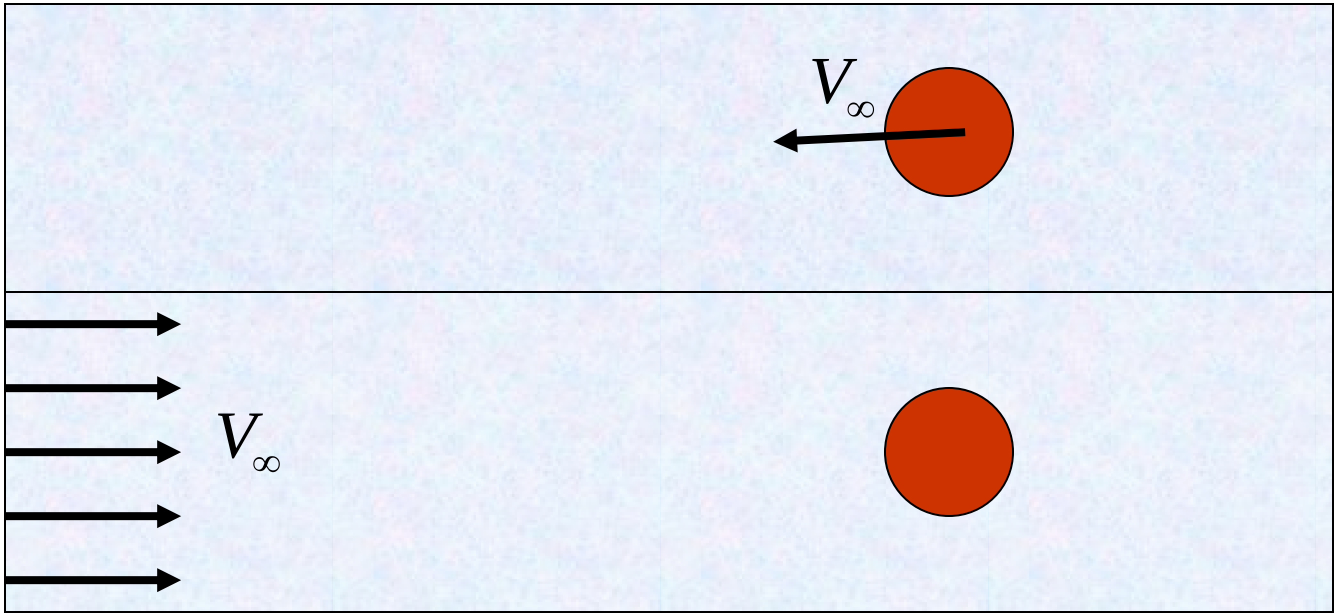


$$p = p_0 - \frac{3\mu V_\infty}{2R_P}\left(\frac{R_P}{r}\right)^2 \cos\theta$$

$$V_r = V_\infty \cos\theta\left[1 - \frac{3}{2}\left(\frac{R_P}{r}\right) + \frac{1}{2}\left(\frac{R_P}{r}\right)^3\right]$$

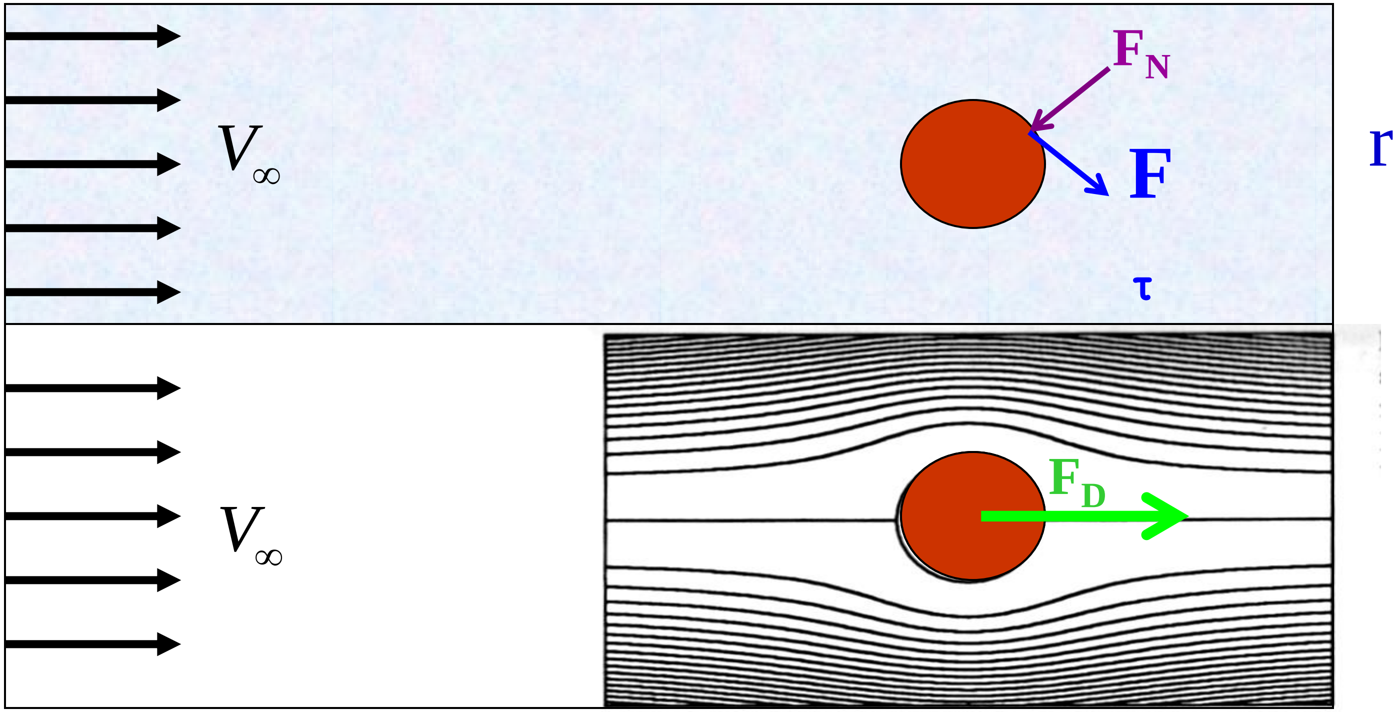
$$V_\theta = -V_\infty sen\theta\left[1 - \frac{3}{4}\left(\frac{R_P}{r}\right) - \frac{1}{4}\left(\frac{R_P}{r}\right)^3\right]$$

”Lei” de Stokes – Meio Contínuo



- Regime permanente
- Meio infinito
- Termos convectivos desconsiderados => Re <<1
- Fluido newtoniano
- Escoamento incompressível

”Lei” de Stokes – Força de Arraste (Drag)



r = R_P

$$\boxed{p = p_0 - \frac{3\mu V_\infty}{2R_P}\cos\theta} \Rightarrow \boxed{F_n = \int^A - p\, d\vec{A} = 2\pi\mu V_\infty R_P}$$

$$+$$

$$\boxed{\tau = \frac{3\mu V_\infty}{2R_P}\left(\frac{R_P}{r}\right)^4 sen\theta} \Rightarrow \boxed{F_\tau = \int^A \tau\, d\vec{A} = 4\pi\mu V_\infty R_P}$$

$$\boxed{F_D = 6\pi\mu V_\infty R_P}$$

Força de Arraste – Equacionamento Geral Coeficiente de Arrasto - CD

$$\boxed{C_D = \frac{F_D / A_P}{\rho V_\infty^2 / 2}} \qquad \boxed{\Rightarrow F_D = \frac{1}{2} C_D A_P \rho V_\infty^2 = \frac{1}{8} \pi C_D \rho D_P^2 V_\infty^2}$$

$$\boxed{\mathrm{Re} = \frac{\rho V_\infty D_P}{\mu} < 1} \;\Rightarrow\; \boxed{F_D = 6\pi\mu V_\infty R_P} \;\Rightarrow\; \boxed{C_D = 24 / \mathrm{Re}}$$

C_D	*Re*
$24/\mathrm{Re}$	$Re < 1$
$18{,}5\ \mathrm{Re}^{-0{,}6}$	$1 < Re < 10^3$
$0{,}44$	$10^3 < Re < 10^5$

”Lei” de Stokes – Força de Arraste (Drag)

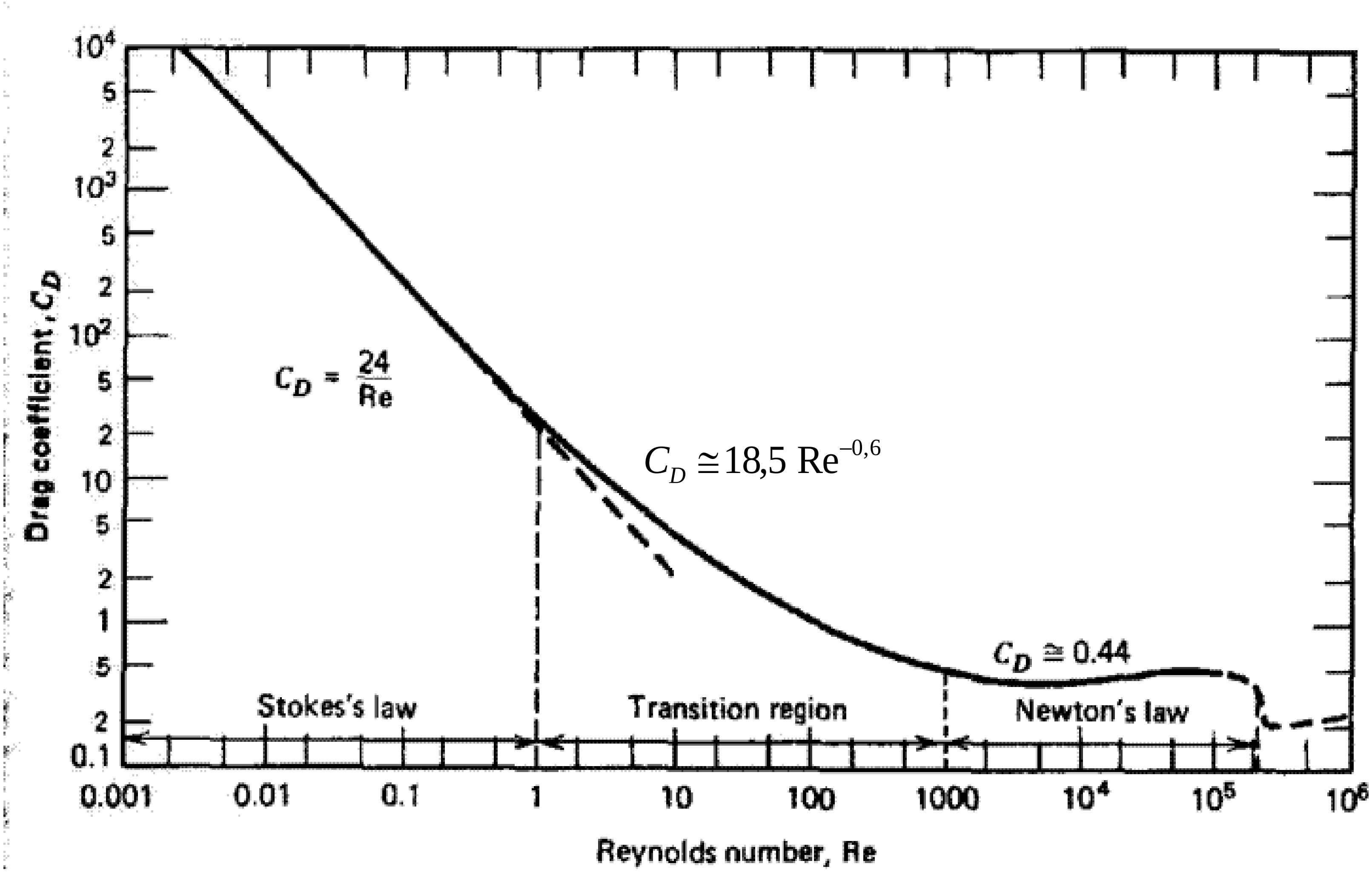
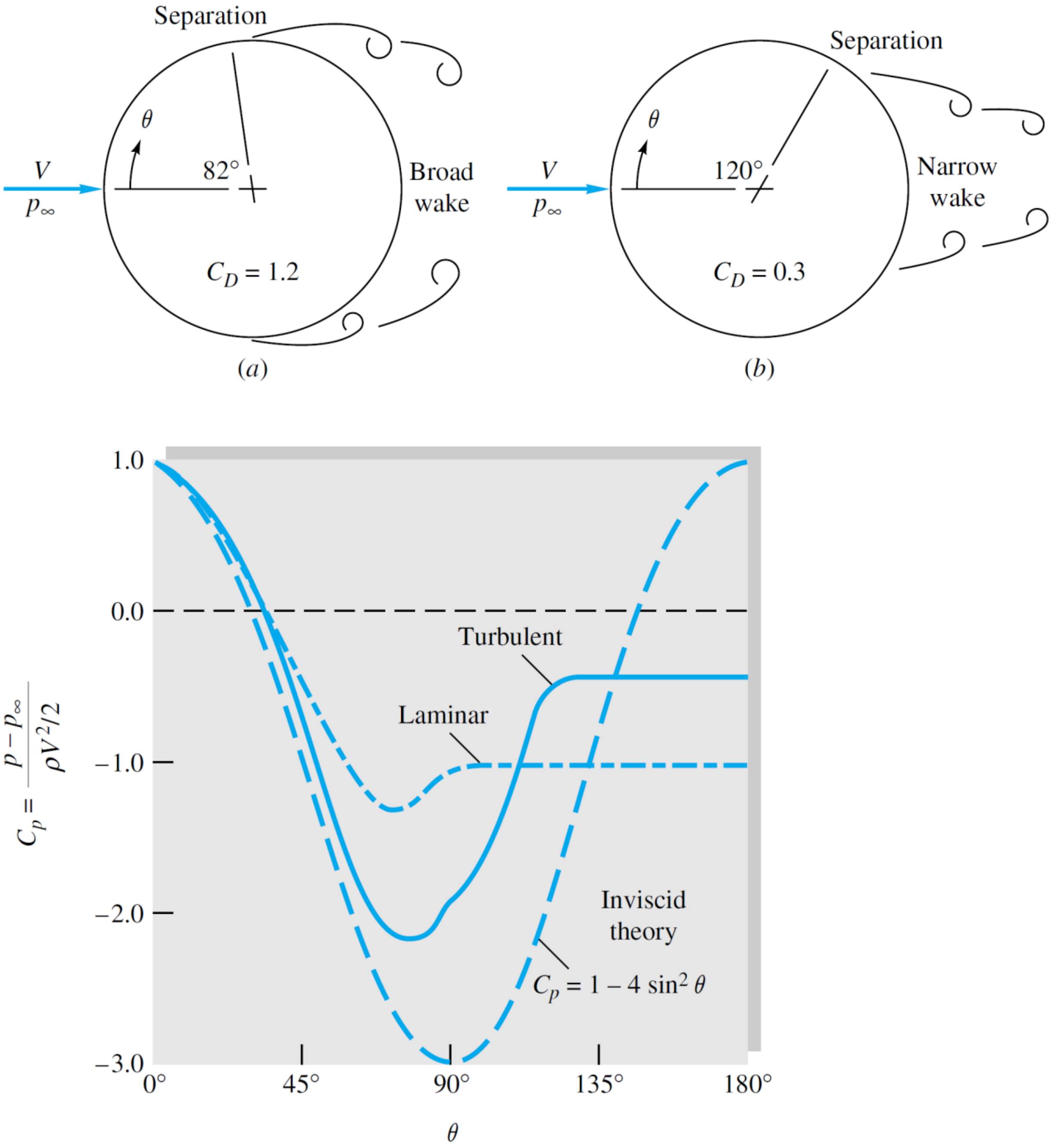
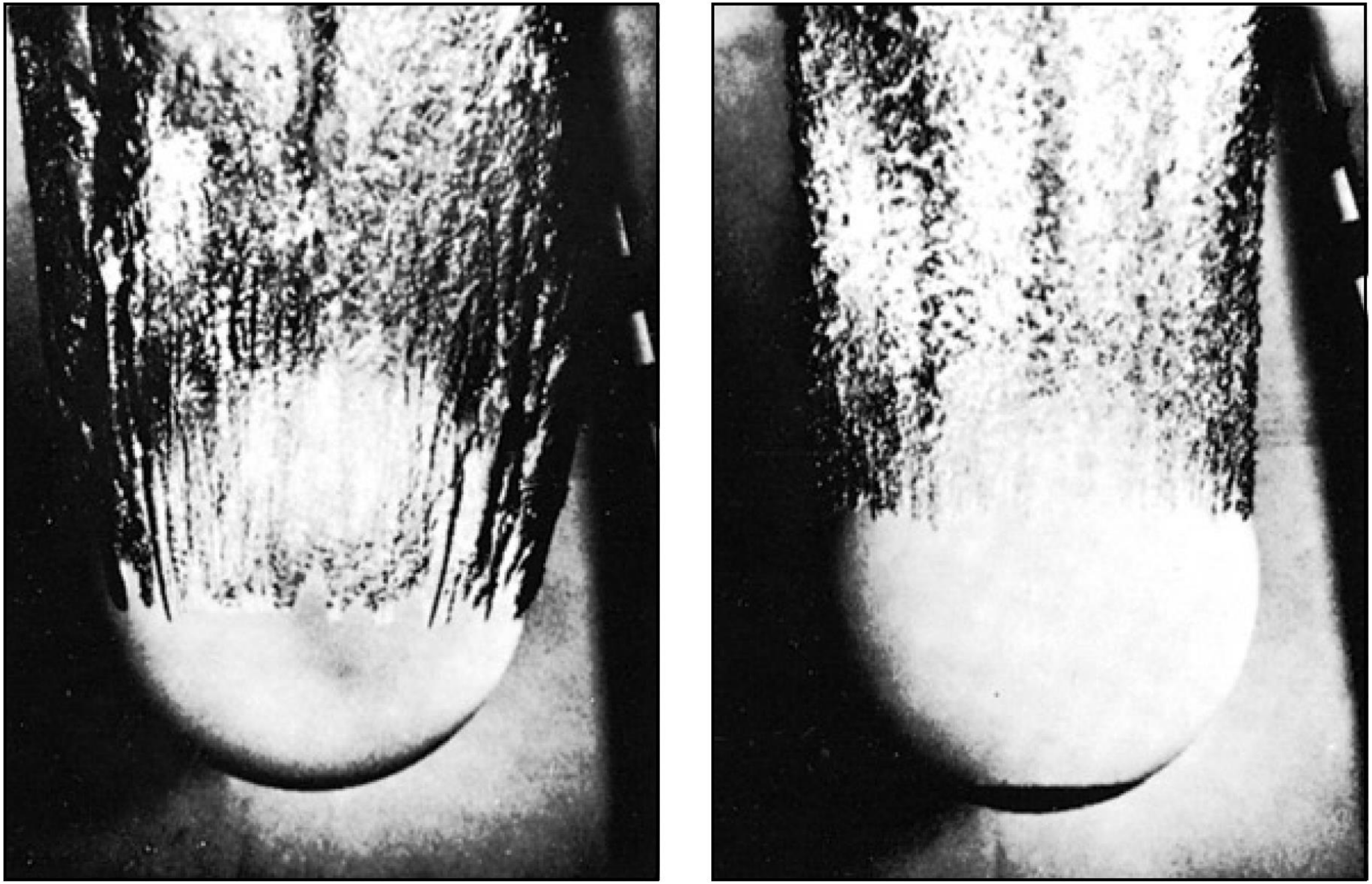


FIGURE 3.1 Drag coefficient versus Reynolds number for spheres.


Separation
θ
82°
V
p_∞
Broad wake
$C_D = 1.2$
Separation
θ
120°
V
p_∞
Narrow wake
$C_D = 0.3$
1.0
0.0
−1.0
−2.0
−3.0
$C_p = \frac{p - p_\infty}{\rho V^2/2}$
Turbulent
Laminar
Inviscid theory
$C_p = 1 - 4\sin^2\theta$
0°
45°
90°
135°
180°
θ

(a) (b)

(c)



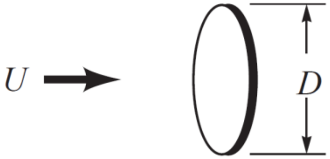
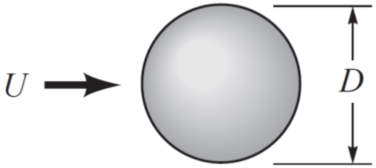
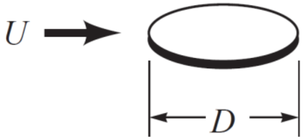
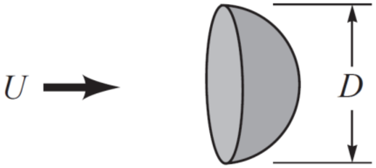
(*a*)

(*b*)

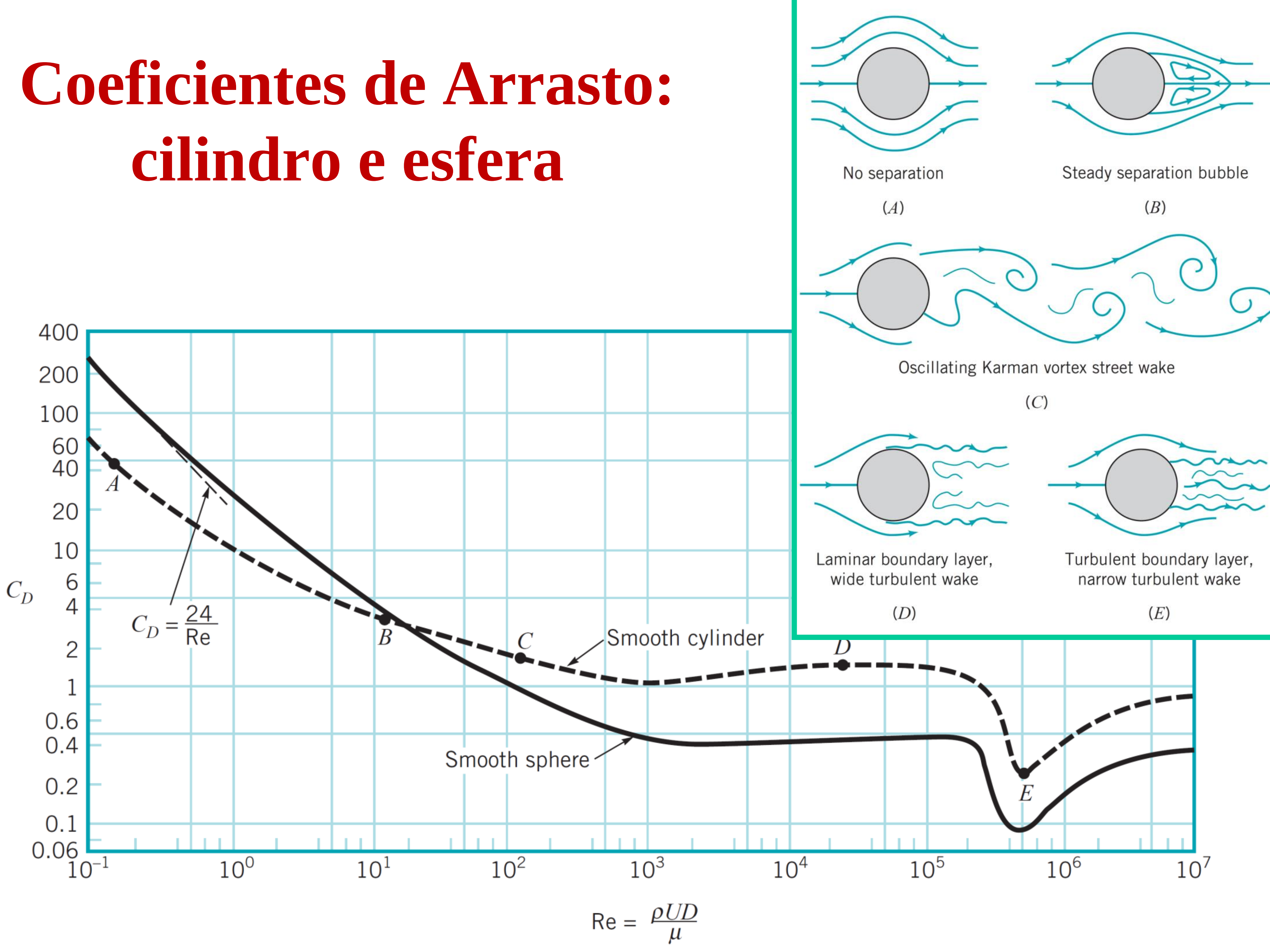
Strong differences in laminar and turbulent separation on an 8.5-in bowling ball entering water at 25 ft/s: (*a*) smooth ball, laminar boundary layer; (*b*) same entry, turbulent flow induced by patch of nose-sand roughness.

(*U.S. Navy photograph, Ordnance Test Station,Pasadena Annex.*)

Coeficientes de Arrasto

Object	$C_D = \mathscr{D}/(\rho U^2 A/2)$ **(for Re $\lesssim$ 1)**	**Object**	C_D
a. Circular disk normal to flow  	20.4/Re	c. Sphere  	24.0/Re
b. Circular disk parallel to flow  	13.6/Re	d. Hemisphere  	22.2/Re

Coeficientes de Arrasto: cilindro e esfera



Coeficientes de Arrasto

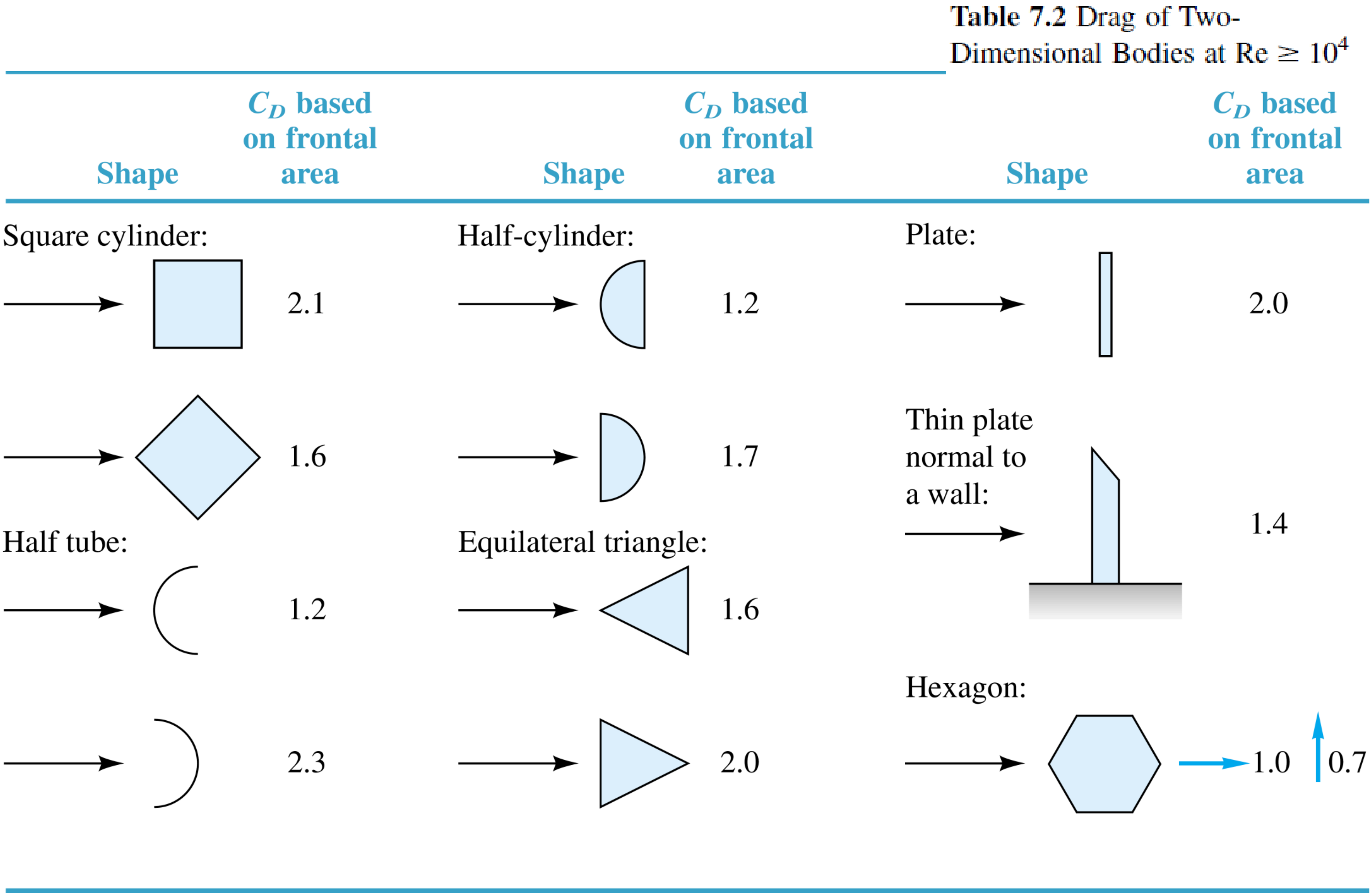


Table 7.2 Drag of Two-Dimensional Bodies at Re $\geq 10^4$

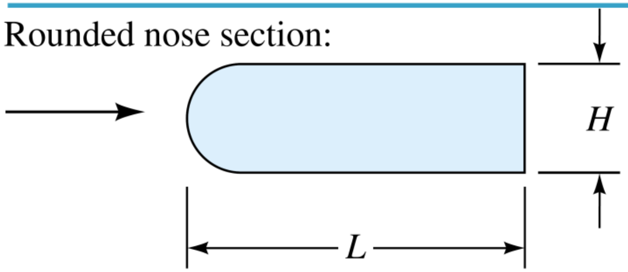
Shape	C_D based on frontal area	Shape	C_D based on frontal area	Shape	C_D based on frontal area
Square cylinder:		Half-cylinder:		Plate:	
	2.1		1.2		2.0
	1.6		1.7	Thin plate normal to a wall:	1.4
Half tube:		Equilateral triangle:			
	1.2		1.6		
	2.3		2.0	Hexagon:	→ 1.0 ↑ 0.7

Coeficientes de Arrasto

Table 7.2 Drag of Two-Dimensional Bodies at Re $\geq 10^4$

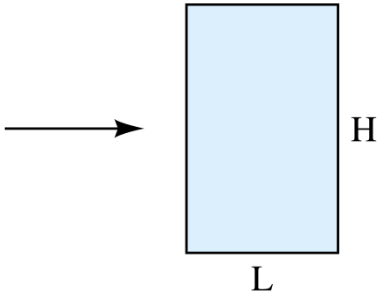
Shape	C_D based on frontal area

Rounded nose section:



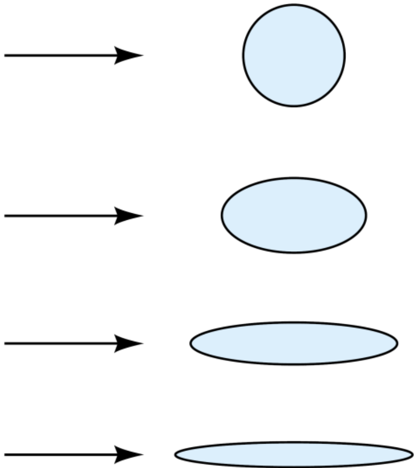
L/H:	0.5	1.0	2.0	4.0	6.0
C_D:	1.16	0.90	0.70	0.68	0.64

Flat nose section



L/H:	0.1	0.4	0.7	1.2	2.0	2.5	3.0	6.0
C_D:	1.9	2.3	2.7	2.1	1.8	1.4	1.3	0.9

Elliptical cylinder:



	Laminar	Turbulent
1:1	1.2	0.3
2:1	0.6	0.2
4:1	0.35	0.15
8:1	0.25	0.1

Coeficientes de Arrasto

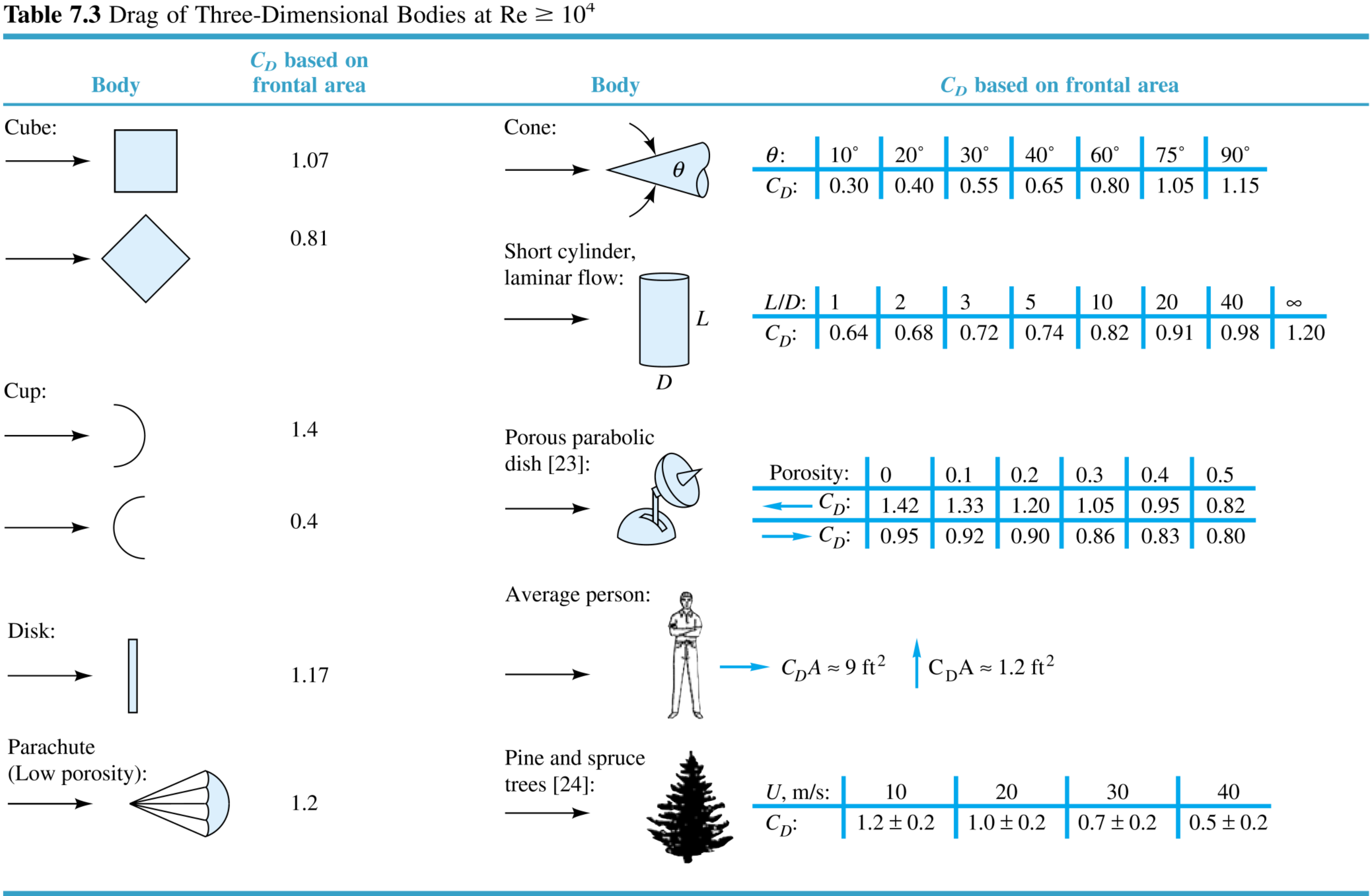


Table 7.3 Drag of Three-Dimensional Bodies at Re $\geq 10^4$

Body	C_D based on frontal area
Cube: → (face)	1.07
→ (edge)	0.81
Cup: → (convex side)	1.4
→ (concave side)	0.4
Disk:	1.17
Parachute (Low porosity):	1.2

Body	C_D based on frontal area
Cone:	see below
Short cylinder, laminar flow:	see below
Porous parabolic dish [23]:	see below
Average person:	→ $C_DA \approx 9$ ft^2 ↑ $C_DA \approx 1.2$ ft^2
Pine and spruce trees [24]:	see below

Cone:

θ:	10°	20°	30°	40°	60°	75°	90°
C_D:	0.30	0.40	0.55	0.65	0.80	1.05	1.15

Short cylinder, laminar flow:

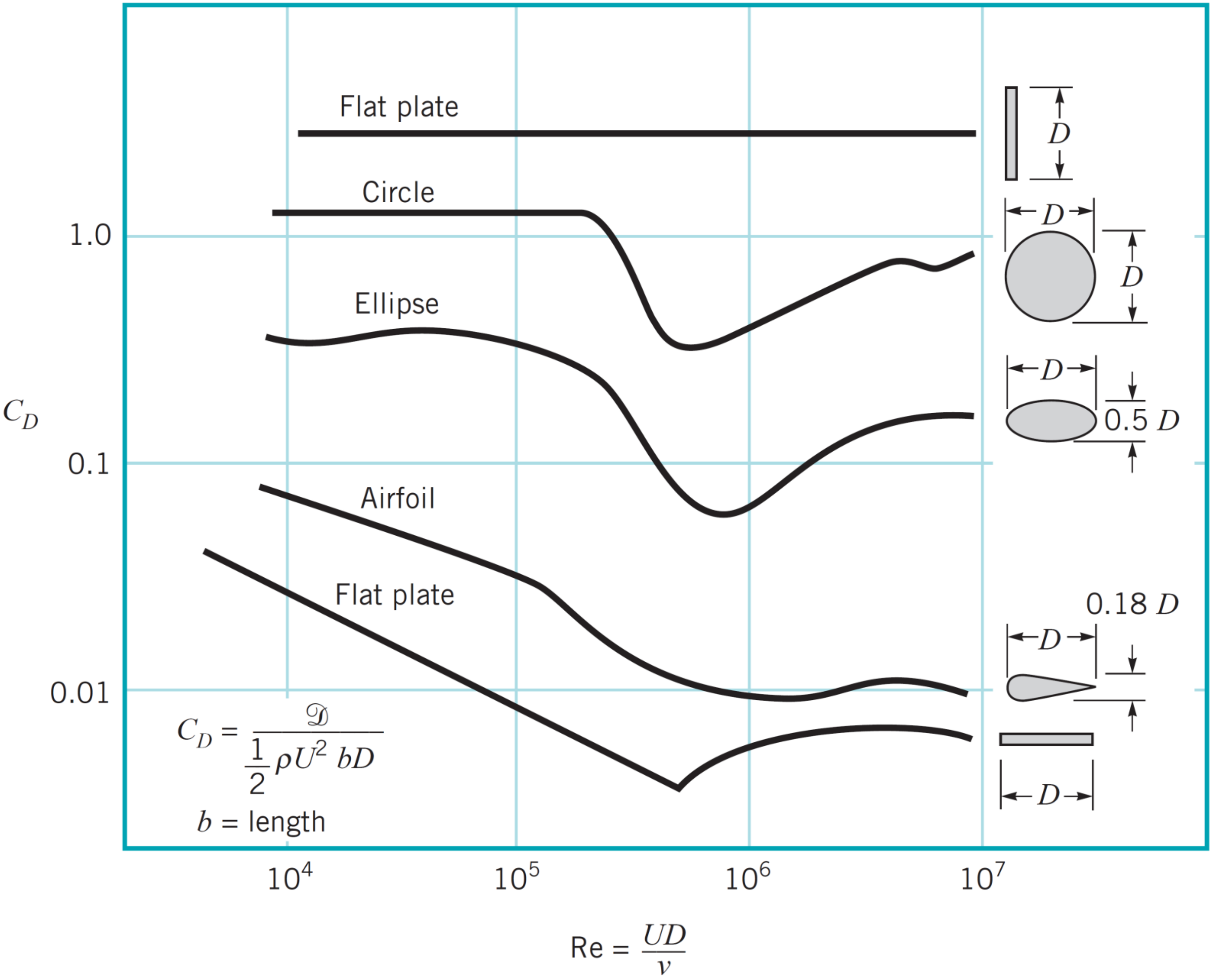
L/D:	1	2	3	5	10	20	40	∞
C_D:	0.64	0.68	0.72	0.74	0.82	0.91	0.98	1.20

Porous parabolic dish [23]:

Porosity:	0	0.1	0.2	0.3	0.4	0.5
← C_D:	1.42	1.33	1.20	1.05	0.95	0.82
→ C_D:	0.95	0.92	0.90	0.86	0.83	0.80

Pine and spruce trees [24]:

U, m/s:	10	20	30	40
C_D:	1.2 ± 0.2	1.0 ± 0.2	0.7 ± 0.2	0.5 ± 0.2


Flat plate
Circle
Ellipse
Airfoil
Flat plate
C_D
1.0
0.1
0.01
10^4
10^5
10^6
10^7
$\mathrm{Re} = \frac{UD}{\nu}$
$C_D = \frac{\mathscr{D}}{\frac{1}{2}\rho U^2\, bD}$
b = length
D
0.5 D
0.18 D

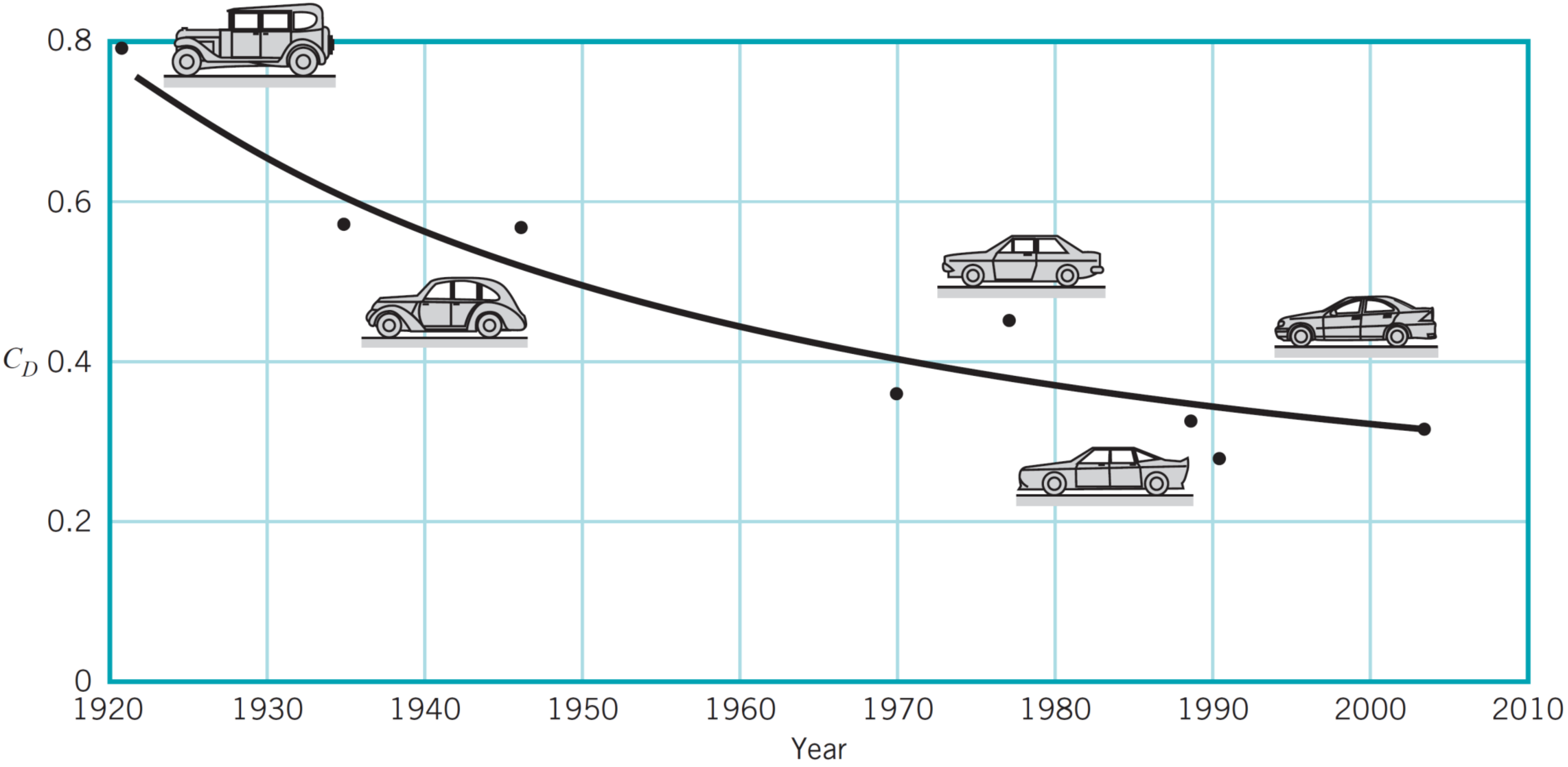


FIGURE 9.27 The historical trend of streamlining automobiles to reduce their aerodynamic drag and increase their miles per gallon (adapted from Ref. 5).

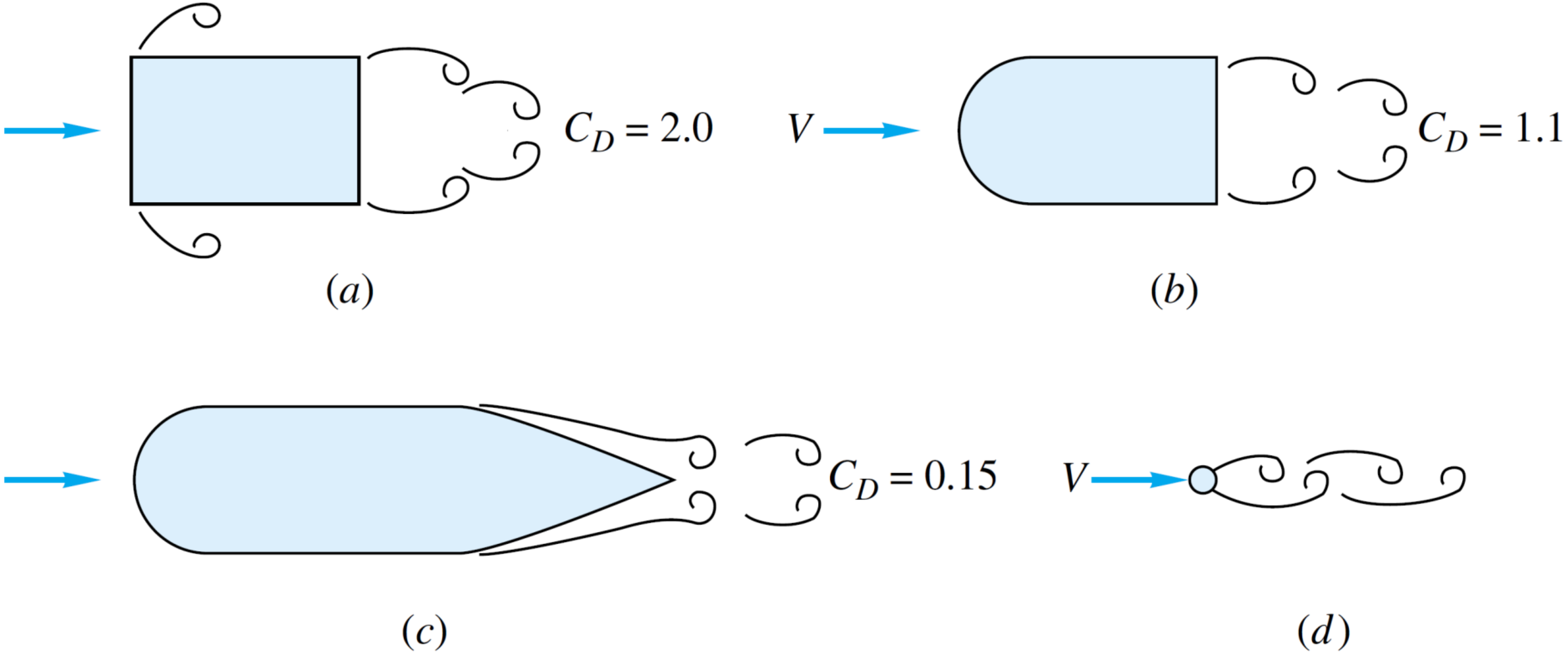
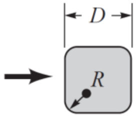
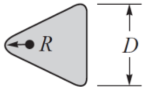
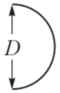
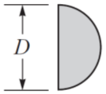
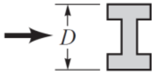
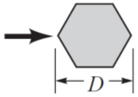
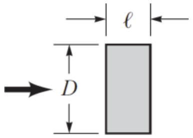


Fig. 7.15 The importance of streamlining in reducing drag of a body (C_D based on frontal area): (*a*) rectangular cylinder; (*b*) rounded nose; (*c*) rounded nose and streamlined sharp trailing edge; (*d*) circular cylinder with the same drag as case (*c*).

Fluid Mechanics – 4th ed. -Frank M. White

Shape	Reference area A (b = length)	Drag coefficient $C_D = \frac{\mathcal{D}}{\frac{1}{2}\rho U^2 A}$	Reynolds number Re = $\rho UD/\mu$
 Square rod with rounded corners	$A = bD$	R/D C_D 0 2.2 0.02 2.0 0.17 1.2 0.33 1.0	Re = 10^5
 Rounded equilateral triangle	$A = bD$	R/D C_D → ← 0 1.4 2.1 0.02 1.2 2.0 0.08 1.3 1.9 0.25 1.1 1.3	Re = 10^5
 Semicircular shell	$A = bD$	→ 2.3 ← 1.1	Re = 2×10^4
 Semicircular cylinder	$A = bD$	→ 2.15 ← 1.15	Re > 10^4
 T-beam	$A = bD$	→ 1.80 ← 1.65	Re > 10^4
 I-beam	$A = bD$	2.05	Re > 10^4
 Angle	$A = bD$	→ 1.98 ← 1.82	Re > 10^4
 Hexagon	$A = bD$	1.0	Re > 10^4
 Rectangle	$A = bD$	ℓ/D C_D ≤0.1 1.9 0.5 2.5 0.65 2.9 1.0 2.2 2.0 1.6 3.0 1.3	Re = 10^5

■ **FIGURE 9.28** **Typical drag coefficients for regular two-dimensional**