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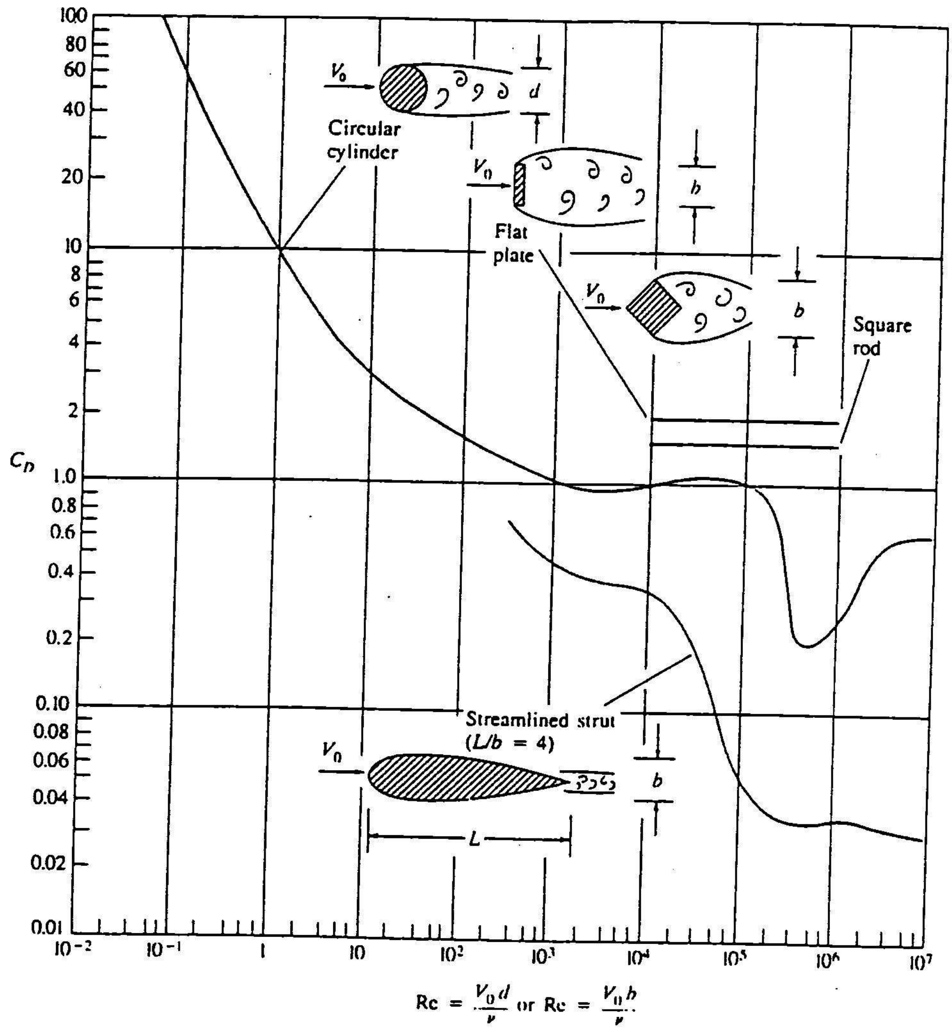
FIGURE 11.5

Coefficient of drag versus Reynolds number for two-dimensional bodies. [Data sources: Bullivant (5), Defoe (7), Goett and Bullivant (10), Jacobs (13), Jones (15), and Lindsey (19)]



Then, from Fig. 11.5, $C_D = 0.20$. Now we compute the total drag:

$$F_D = \frac{C_D A_p \rho V_0^2}{2}$$

$$= \frac{(0.2)(30\ \text{m})(0.3\ \text{m})(1.20\ \text{kg/m}^3)(35^2\ \text{m}^2/\text{s}^2)}{2} = 1323\ \text{N}$$

Assuming that the resultant drag force acts midway up the pole, the moment is

$$M = F_D\left(\frac{L}{2}\right) = (1323\ \text{N})\left(\frac{30}{2}\ \text{m}\right) = 19{,}845\ \text{N}\cdot\text{m}$$

11.5 Drag of Axisymmetric and Three-Dimensional Bodies

The same principles that apply to the drag of two-dimensional bodies also apply to that of axisymmetric and three-dimensional bodies. That is, at very low values of the Reynolds number, the coefficient of drag is given by exact equations relating C_D and Re. At high values of Re, the coefficient of drag becomes constant for angular bodies, whereas rather abrupt changes in C_D occur for rounded bodies. All of these characteristics can be seen in Fig. 11.11, where C_D is plotted against Re for several axisymmetric bodies.

For Reynolds numbers less than 0.5, the flow around the sphere is laminar and amenable to analytical solutions. An exact solution by Stokes yielded the following equation, which is called *Stokes' law*, for the drag of a sphere:

$$F_D = 3\pi\mu V_0 d \tag{11.8}$$

Note that the drag for this laminar-flow condition varies directly with the first power of V_0. This is characteristic of all laminar-flow processes. For com-

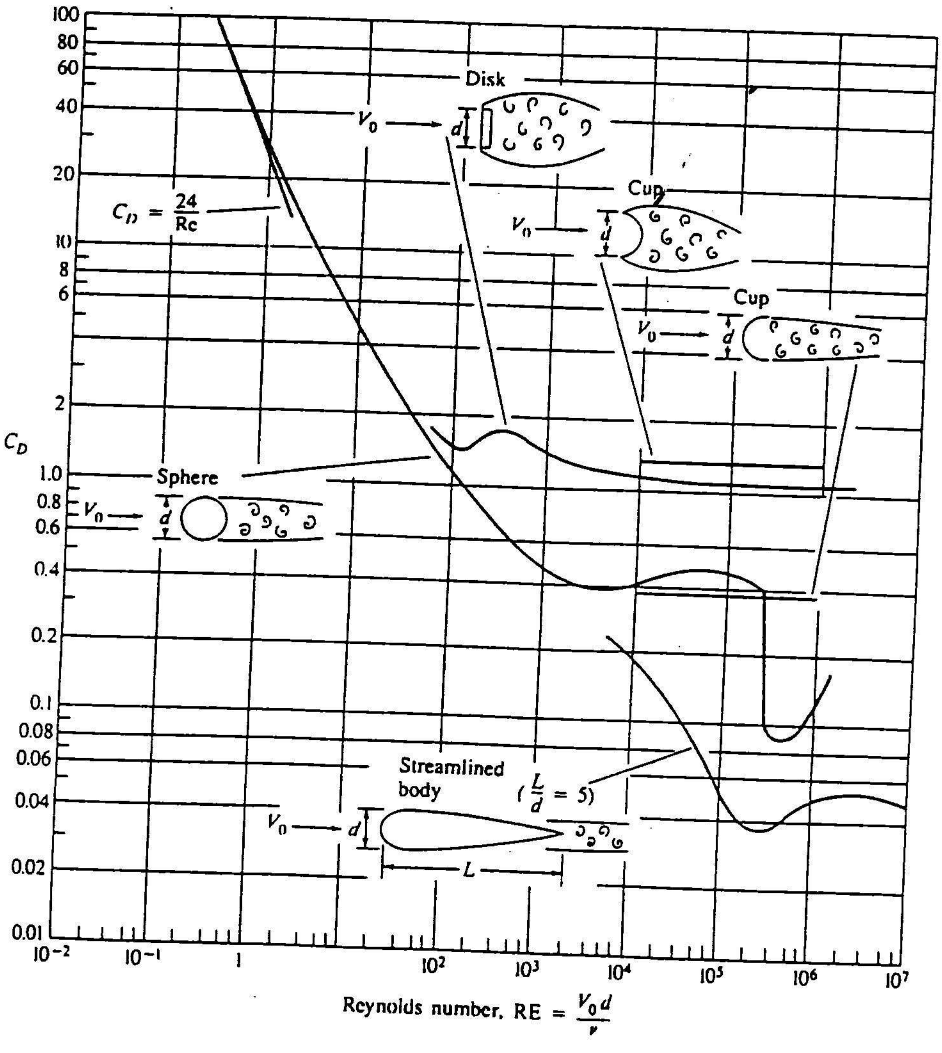
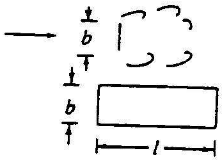
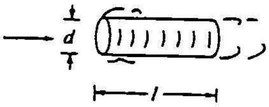
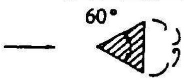
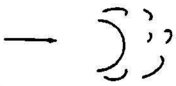
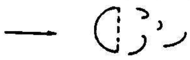
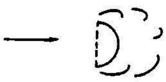
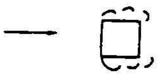
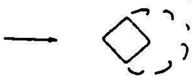
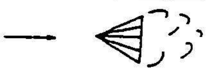


FIGURE 11.11

Coefficient of drag versus Reynolds number for axisymmetric bodies. [Data sources: *Abbott (1), Brevoort and Joyner (4), Freeman (9), and Rouse (26)*]

[illegible]

Type of Body		Length Ratio	Re	C_D
	Rectangular plate	$l/b = 1$	$>10^4$	1.18
		$l/b = 5$	$>10^4$	1.20
		$l/b = 10$	$>10^4$	1.30
		$l/b = 20$	$>10^4$	1.50
		$l/b = \infty$	$>10^4$	1.98
	Circular cylinder—axis // to flow	$l/d = 0$ (disk)	$>10^4$	1.17
		$l/d = 0.5$	$>10^4$	1.15
		$l/d = 1$	$>10^4$	0.90
		$l/d = 2$	$>10^4$	0.85
		$l/d = 4$	$>10^4$	0.87
		$l/d = 8$	$>10^4$	0.99
	Square rod	∞	$>10^4$	2.00
	Square rod	∞	$>10^4$	1.50
	Triangular cylinder	∞	$>10^4$	1.39
	Semicircular shell	∞	$>10^4$	1.20
	Semicircular shell	∞	$>10^4$	2.30
	Hemispherical shell		$>10^4$	0.39
	Hemispherical shell		$>10^4$	1.40
	Cube		$>10^4$	1.10
	Cube		$>10^4$	0.81
	Cone—60° vertex		$>10^4$	0.49
	Parachute		$\approx 3 \times 10^7$	1.20

SOURCES: Brevoort and Joyner (4), Lindsey (19), Morrison (22), Roberson et al. (24), Rouse (26), and Scher and Gale (28).

Table 1.2 Models relating τ_{yx} to du/dy for fluids without a yield stress

Equation	Model	Form	Empirical Constants (See Nomenclature)	References	Some Published Applications
1.15	1. Power law or Ostwald-deWaele	$\tau_{yx} = \frac{K}{g_c}\left(\frac{du}{dy}\right)^n$	K lb mass $\sec^{n-2}$ ft^{-1}; n dimensionless	60, 65	Flow in various ducts (Chaps. 4 and 6), around spheres (Chap. 4), in boundary layers (Chap. 8), mixing (Chap. 9), heat transfer (Chap. 10)
1.16	2. Ellis	$\tau_{yx} = \frac{1}{A + B\tau_{yx}^{\alpha-1}}\left(\frac{du}{dy}\right)$	A ft^2 sec^{-1} lb $force^{-1}$; B $ft^{2\alpha}$ sec^{-1} lb $force^{-\alpha}$; α dimensionless	66	Flow around spheres (Chap. 4), tube flow (76), heat transfer (26)
1.17	3. DeHaven	$\tau_{yx} = \frac{\mu_0/g_c}{1 + C\tau_{yx}^n}\left(\frac{du}{dy}\right)$	μ_0 lb mass/ft sec; C (lb $force/ft^2)^{-n}$; n dimensionless	17, 18	Control valve design (17), extruder design (18)
1.18	4. Prandtl-Eyring	$\tau_{yx} = A \sinh^{-1}\left[\frac{1}{B}\left(\frac{du}{dy}\right)\right]$	A lb $force/ft^2$; B sec^{-1}	21, 64	Mixing (Chap. 9), tube flow-heat transfer (Chap. 10)
1.19	5. Powell-Eyring	$\tau_{yx} = C\left(\frac{du}{dy}\right) + \frac{1}{B}\sinh^{-1}\left[\frac{1}{A}\left(\frac{du}{dy}\right)\right]$	A sec^{-1}; B ft^2/lb force; C lb force sec/ft^2	11	Flow in tubes (11), heat transfer (Chap. 10)
1.20	6. Reiner-Philippoff	$\tau_{yx} = \frac{1}{g_c}\left[\mu_\infty + \frac{\mu_0 - \mu_\infty}{1 + (\tau_{yx}/A)^2}\right]\left(\frac{du}{dy}\right)$	μ_0, μ_∞ lb mass/ft sec; A lb $force/ft^2$	63	Fitting flow curves (63)
1.21	7. Sisko	$\tau_{yx} = A\left(\frac{du}{dy}\right) + B\left(\frac{du}{dy}\right)^n$	A lb force sec/ft^2; B lb force sec^n/ft^2; n dimensionless	74	Flow around spheres (75), flow in tubes (74)