Flow over immerse bodies

Henryk Kudela

Contents

1 Lift and Drag Concepts

When any body moves through a fluid, an interaction between the body and the fluid occurs; this effect can be described in terms of the forces at the fluidbody interface. This can be described in terms of the stresseswall shear stresses, due to viscous effects and normal stresses due to the pressure, p. Typical shear stress and pressure distributions are shown in Figs. (**??**a) and (**??**b). Both τ_w and p vary in magnitude and direction along the surface. It is often useful to know the detailed distribution of shear stress and pressure over the surface of the body, although such information is difficult to obtain. Many times, however, only the integrated or resultant effects of these distributions are needed. The resultant force in the direction of the upstream velocity is termed the drag F_D, and the resultant force normal to the upstream velocity is termed the lift, F_L, as is indicated in Fig.(**??**c). The resultant of the shear stress and pressure distributions can be obtained by integrating the effect of these two quantities on the body surface as is indicated in Fig. The x and y components of the fluid force on the small area element dA are

$$dF_x = (p\, dA)\cos\Theta + (\tau_w\, dA)\sin\Theta \tag{1}$$

$$dF_y = -(p\, dA)\sin\Theta + (\tau_w\, dA)\cos\Theta \tag{2}$$

Thus, the net x and y components of the force on the object are

Without detailed information concerning the shear stress and pressure distributions on a body, Eqs. (3) cannot be used. The widely used alternative is to define dimensionless **lift** and **drag coefficients** and determine their approximate values by means of either a simplified analysis, some numerical technique, or an appropriate experiment. The *lift coefficient*, and *drag coefficient*, are defined as

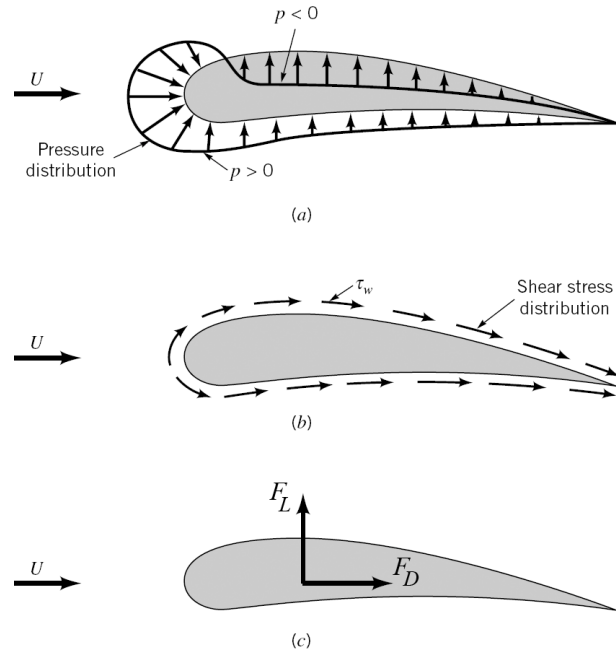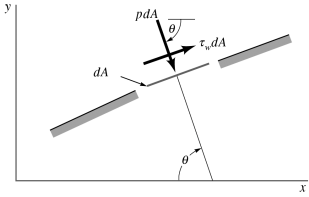$$\boxed{C_D = \frac{F_D}{\frac{1}{2}\rho U^2 A}, \qquad C_L = \frac{F_L}{\frac{1}{2}\rho U^2 A}} \tag{5}$$

1

Figure 1: Forces from surrounding fluid a) pressure force, b) viscous force, c)resultant force .

$$F_D = \int_A dF_x = \int_A p\cos\Theta\, dA + \int_A \tau_w \sin\Theta\, dA$$

$$(3)$$

$$F_L = \int_A dF_y = -\int_A p\sin\Theta\, dA + \int_A \tau_w \cos\Theta\, dA$$

$$(4)$$

Figure 2: Pressure and shear forces on a small element of the surface of a body .

where A is taken to be **frontal area**- projected are seen by a person looking toward the object from a direction parallel to the upstream velocity, U or as **planform area** - the projected area seen by an observer looking toward the object from a direction normal to the upstream velocity.

Classification of body shape can be made depending on whether the body is streamlined or blunt. In general, **streamlined bodies** (i.e., airfoils, racing cars, etc.) have little effect on the surrounding fluid, compared with the effect that **blunt bodies** (i.e., parachutes, buildings, etc.) have on the fluid.

1.1 Friction drag

Friction drag, F_F, is that part of the drag that is due directly to the shear stress, on the object. It is a function of not only the magnitude of the wall shear stress, but also of the orientation of the surface on which it acts. This is indicated by the factor $\tau_w \sin\Theta$ in Eq. (3). If the surface is parallel

2

to the upstream velocity, the entire shear force contributes directly to the drag. This is true for the flat plate parallel to the flow. If the surface is perpendicular to the upstream velocity, the shear stress contributes nothing to the drag.

The friction drag on a flat plate of width b and length l oriented parallel to the upstream flow can be calculated from

$$F_D = C_{D_f} \frac{1}{2} \rho U^2 b l$$

where C_{D_f} is the friction drag coefficient. The value of C_{D_f} is given as a function of Reynolds number, $Re_l = \rho U l / \mu$, and relative surface roughness, ε / l. The precise determination of the shear stress along the surface of a curved body is quite difficult to obtain.

1.2 Pressure drag

Pressure drag, is that part of the drag that is due directly to the pressure, p, on an object. It is often referred to as *form drag* because of its strong dependency on the shape or form of the object. Pressure drag is a function of the magnitude of the pressure and the orientation of the surface element on which the pressure force acts. For example, the pressure force on either side of a flat plate parallel to the flow may be very large, but it does not contribute to the drag because it acts in the direction normal to the upstream velocity. On the other hand, the pressure force on a flat plate normal to the flow provides the entire drag.

If the viscosity were zero, the pressure drag on any shaped object (symmetrical or not) in a steady flow would be zero. There perhaps would be large pressure forces on the front portion of the object, but there would be equally large (and oppositely directed) pressure forces on the rear portion. If the viscosity is not zero, the net pressure drag may be nonzero because of boundary layer separation.

1.3 Drag coefficient data

During this course I will be used the following books:

References

[1] F. M. White, 1999. *Fluid Mechanics*, McGraw-Hill.

[2] B. R. Munson, D.F Young and T. H. Okiisshi, 1998. *Fundamentals of Fluid Mechanics*, John Wiley and Sons, Inc. .
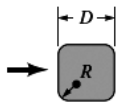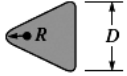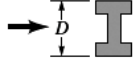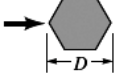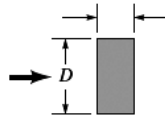
Shape	Reference area A (b = length)	Drag coefficient $C_D = \dfrac{1}{\frac{1}{2}\rho U^2 A}$	Reynolds number $Re = \rho U D / \mu$
Square rod with rounded corners	$A = bD$	$\begin{array}{c\|c} R/D & C_D \\ \hline 0 & 2.2 \\ 0.02 & 2.0 \\ 0.17 & 1.2 \\ 0.33 & 1.0 \end{array}$	$Re = 10^5$
Rounded equilateral triangle	$A = bD$	$\begin{array}{c\|cc} R/D & C_D (\rightarrow) & C_D (\leftarrow) \\ \hline 0 & 1.4 & 2.1 \\ 0.02 & 1.2 & 2.0 \\ 0.08 & 1.3 & 1.9 \\ 0.25 & 1.1 & 1.3 \end{array}$	$Re = 10^5$
Semicircular shell	$A = bD$	$\rightarrow$ 2.3 $\leftarrow$ 1.1	$Re = 2 \times 10^4$
Semicircular cylinder	$A = bD$	$\rightarrow$ 2.15 $\leftarrow$ 1.15	$Re > 10^4$
T-beam	$A = bD$	$\rightarrow$ 1.80 $\leftarrow$ 1.65	$Re > 10^4$
I-beam	$A = bD$	2.05	$Re > 10^4$
Angle	$A = bD$	$\rightarrow$ 1.98 $\leftarrow$ 1.82	$Re > 10^4$
Hexagon	$A = bD$	1.0	$Re > 10^4$
Rectangle	$A = bD$	$\begin{array}{c\|c} l/D & C_D \\ \hline \leq 0.1 & 1.9 \\ 0.5 & 2.5 \\ 0.65 & 2.9 \\ 1.0 & 2.2 \\ 2.0 & 1.6 \\ 3.0 & 1.3 \end{array}$	$Re = 10^5$

Figure 3: Typical drag coefficient for regular two-dimensional objects
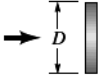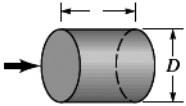
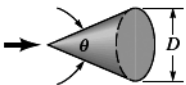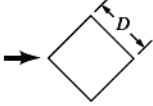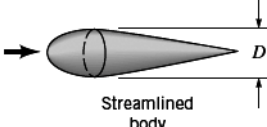| Shape		Reference area A	Drag coefficient C_D	Reynolds number $Re = \rho U D/\mu$
	Solid hemisphere	$A = \dfrac{\pi}{4}D^2$	1.17 0.42	$Re > 10^4$
	Hollow hemisphere	$A = \dfrac{\pi}{4}D^2$	1.42 0.38	$Re > 10^4$
	Thin disk	$A = \dfrac{\pi}{4}D^2$	1.1	$Re > 10^3$
	Circular rod parallel to flow	$A = \dfrac{\pi}{4}D^2$	l/D — C_D: 0.5 — 1.1; 1.0 — 0.93; 2.0 — 0.83; 4.0 — 0.85	$Re > 10^5$
	Cone	$A = \dfrac{\pi}{4}D^2$	θ, degrees — C_D: 10 — 0.30; 30 — 0.55; 60 — 0.80; 90 — 1.15	$Re > 10^4$
	Cube	$A = D^2$	1.05	$Re > 10^4$
	Cube	$A = D^2$	0.80	$Re > 10^4$
	Streamlined body	$A = \dfrac{\pi}{4}D^2$	0.04	$Re > 10^5$

Figure 4: Typical drag coefficient for regular three-dimensional objects

5