Flow Past Objects (Denn Chapter 4)

LEARNING OBJECTIVES

1. Relate and calculate the Drag Coefficient (c_D) to fluid and object parameters for different Reynold's number regions.
2. Derive and apply terminal (settling) velocity as a function of fluid and object parameters.
3. Derive and apply a model for fluid flow through packed bed systems.

INTRODUCTION

Why do engineers care about flow past an object?

FLOW PAST A SPHERE

Consider flow past a sphere:

How does drag force F_D depend on...

Dimensional Analysis

Variable	Dimensions (Length, Time, Mass)
F_D	$\frac{ML}{T^2}$

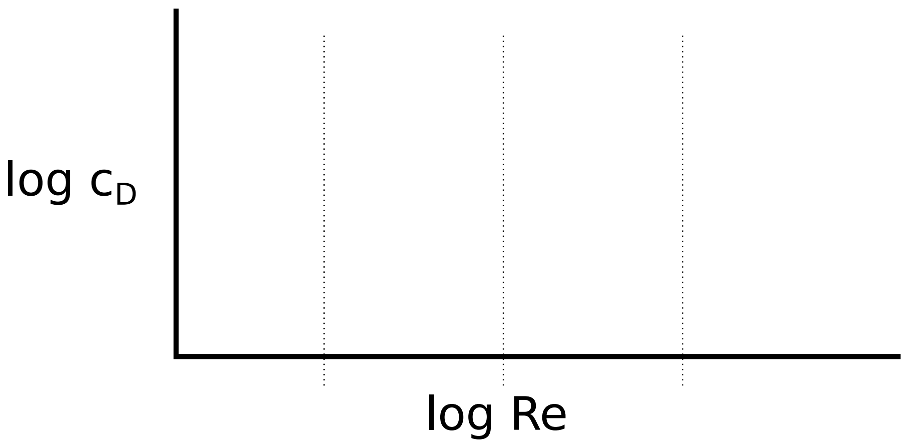
Many options; conventions dictate:

$\mathrm{Re} =$

$c_D =$

For the drag coefficient c_D, the general definition is

$c_D = f(\mathrm{Re})$



Representation of Data

Small Re (<1)

Find that $c_D \propto \frac{1}{\text{Re}}$. In fact, $c_D =$

Intermediate Region (1<Re<10^3)

$$c_D =$$

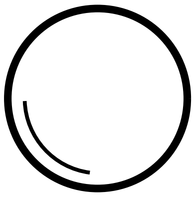
Large Re (10^3<Re<2×10^5)

$$c_D \approx$$

For $\text{Re} = 2 \times 10^5$, sharp drop...

TERMINAL VELOCITY

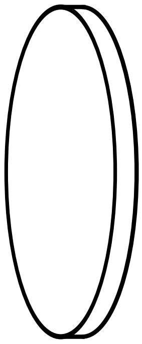
Sphere falling/rising in fluid by gravitational force.

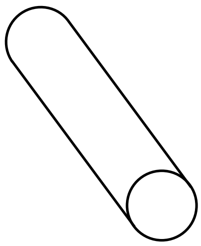


Stokes regime:

Newton regime:

Other Shapes





Handouts

Table 9.4 from Munson, Young, and Okiishi. Fundamentals of Fluid Mechanics, 5th edition.

Comments

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Flow Patterns/Discussion → DVD-ROM

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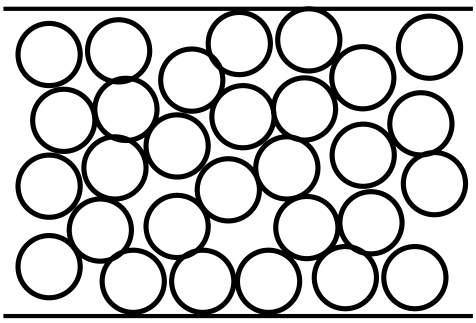
EXAMPLE

How much energy does the 1992 version of Professor Burghardt expend to overcome aerodynamic drag while running a complete marathon race on a day with no wind? Assume that he completed a marathon in 3 hours.

Now suppose that Professor Burghardt had used that energy instead to power a light bulb (100 watts). How long could he generate light for a family in India who doesn't have access to electricity?

PACKED BEDS



Uses:

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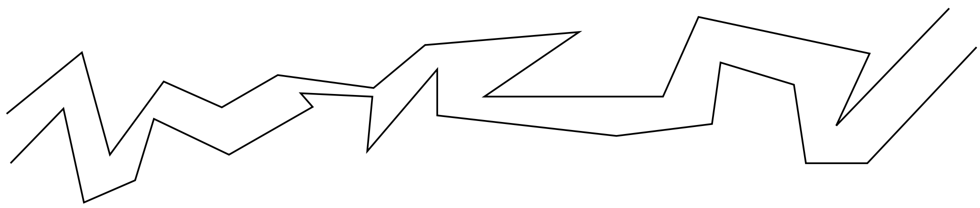
"Void Fraction" = ε =

"Superficial velocity" = v_∞ =

How does Δp depend on...

Approach: Think of fluid's path through packing as a complicated "pipe"



For pipe flow, correlate data:

Problem: How do D_{eff} and v_{eff} relate to measurable variables?

1.

2. Set $D_{\text{eff}} = D_H$ (hydraulic diameter)

V_{fluid} - Volume of the fluid V_{solids} - Volume of the solid particles

V_{bed} - Volume of the bed ($V_{\text{bed}} = V_{\text{fluid}} + V_{\text{solids}}$)

Let N_p be the number of particles in the bed

$D_{\text{eff}} =$

Plug back into the correlation:

Normally drop numerical factors, and represent data according to:

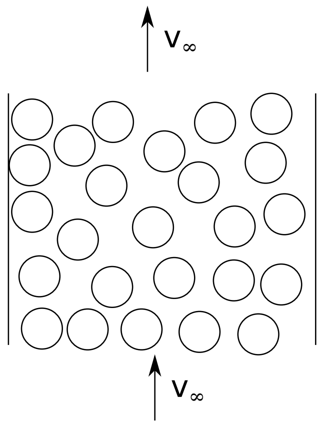
$$f_p = f_p(Re_p)$$

Experimental Data

Data correlation. Ergun Equation: $f_p =$

For low Re_p, we can neglect the constant term

Fluidized beds



Chapter Summary

In this chapter we consider flow past objects in technically relevant areas for engineers

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We developed a model to relate drag force F_D to fluid and object parameters. In particular, we use the dimensionless group c_D against Reynold's number (Re).

APPENDIX A

TABLE 9.4
Low Reynolds Number Drag Coefficients (Ref. 7) ($Re = \rho UD/\mu, A = \pi D^2/4$)

Object	$C_D = \mathfrak{D}/(\rho U^2 A/2)$ (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

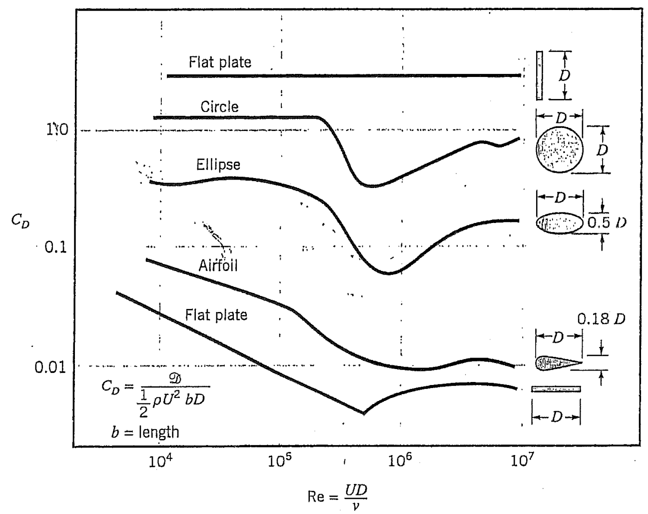

FIGURE 9.22 Character of the drag coefficient as a function of Reynolds number for objects with various degrees of streamlining, from a flat plate normal to the upstream flow to a flat plate parallel to the flow (two-dimensional flow) (Ref. 5).

Shape	Reference area A (b = length)	Drag coefficient $C_D = \dfrac{\mathfrak{D}}{\frac{1}{2}\rho U^2 A}$	Reynolds number $Re = \rho UD/\mu$
Square rod with rounded corners	$A = bD$	R/D: 0, 0.02, 0.17, 0.33; C_D: 2.2, 2.0, 1.2, 1.0	$Re = 10^5$
Rounded equilateral triangle	$A = bD$	R/D: 0, 0.02, 0.08, 0.25; C_D (→): 1.4, 1.2, 1.3, 1.1; C_D (←): 2.1, 2.0, 1.9, 1.3	$Re = 10^5$
Semicircular shell	$A = bD$	→ 2.3; ← 1.1	$Re \doteq 2 \times 10^4$
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: ≤0.1, 0.5, 0.65, 1.0, 2.0, 3.0; C_D: 1.9, 2.5, 2.9, 2.2, 1.6, 1.3	$Re = 10^5$

FIGURE 9.28 Typical drag coefficients for regular two-dimensional objects (Refs. 5, 6).

Source: Munson, Young + Okiishi
Fundamentals of Fluid Mechanics, 5th Ed.

Shape	Reference area A	Drag coefficient C_D	Reynolds number $Re = \rho UD/\mu$
Solid hemisphere	$A = \frac{\pi}{4}D^2$	→ 1.17 ← 0.42	$Re > 10^4$
Hollow hemisphere	$A = \frac{\pi}{4}D^2$	→ 1.42 ← 0.38	$Re > 10^4$
Thin disk	$A = \frac{\pi}{4}D^2$	1.1	$Re > 10^3$
Circular rod parallel to flow	$A = \frac{\pi}{4}D^2$	ℓ/D | C_D 0.5 | 1.1 1.0 | 0.93 2.0 | 0.83 4.0 | 0.85	$Re > 10^5$
Cone	$A = \frac{\pi}{4}D^2$	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	$A = \frac{\pi}{4}D^2$	0.04	$Re > 10^5$

FIGURE 9.29 Typical drag coefficients for regular three-dimensional objects (Ref. 5).

Shape	Reference area	Drag coefficient C_D
Parachute	Frontal area $A = \frac{\pi}{4}D^2$	1.4
Porous parabolic dish	Frontal area $A = \frac{\pi}{4}D^2$	Porosity: 0 | 0.2 | 0.5 → 1.42 | 1.20 | 0.82 ← 0.95 | 0.90 | 0.80 Porosity = open area/total area
Average person	Standing Sitting Crouching	$C_DA = 9\ ft^2$ $C_DA = 6\ ft^2$ $C_DA = 2.5\ ft^2$
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
Six-car passenger train	Frontal area	1.8
Bikes		
Upright commuter	$A = 5.5\ ft^2$	1.1
Racing	$A = 3.9\ ft^2$	0.88
Drafting	$A = 3.9\ ft^2$	0.50
Streamlined	$A = 5.0\ ft^2$	0.12
Tractor-trailer tucks		
Standard	Frontal area	0.96
With fairing (Fairing)	Frontal area	0.76
With fairing and gap seal (Gap seal)	Frontal area	0.70
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 $Re = 6 \times 10^6$ (flat plate has $C_{Df} = 0.0031$)
Large birds	Frontal area	0.40

FIGURE 9.30 Typical drag coefficients for objects of interest (Refs. 5, 6, 15, 20).

Packed Bed Example

Suppose cylindrically shaped particles with diameters of 0.5 mm and lengths of 1 mm are packed into a space with a diameter of 50 mm and length of 15 mm. The mass flow rate is 4×10^{-4} kg/s. The liquid density and viscosity are 1200 kg/m^3 and 700 Pa s respectively. What's the pressure drop if the void fraction ε is 0.4?