Chemical Engineering 374

Fluid Mechanics

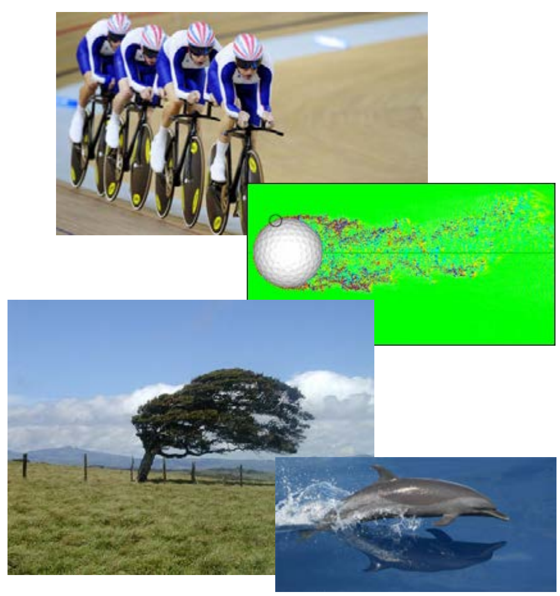
External Flows and Drag

1

2

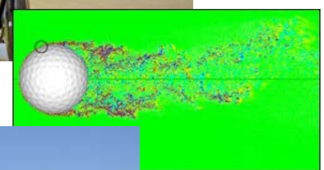
Introduction

- Previous
  - Internal flows:
  - Flows in pipes
  - Friction
- Last time
  - Boundary layers
- Today
  - Flow around objects
    - Separation
    - Streamlining
  - Drag
    - Coefficients
  - Calculations

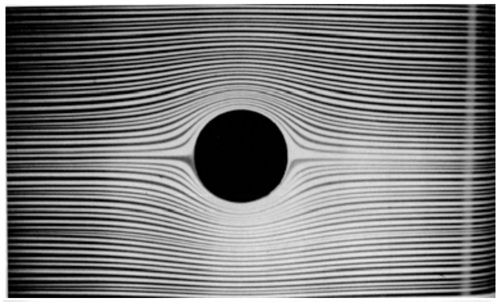


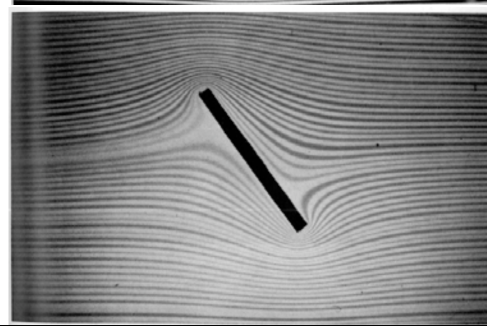
Some Questions

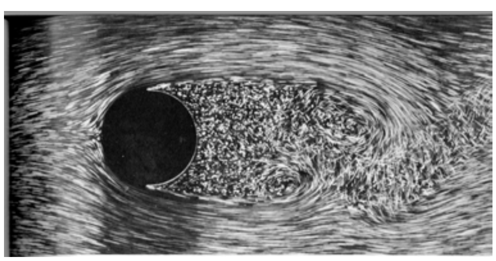
- Why are golf balls dimpled but ping pong balls are smooth?
- Why are cars streamlined?
- How and why does shape matter?
- What is separation and how does it form?
- What happens to the velocity of falling objects?

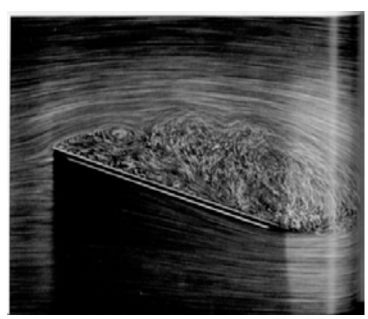



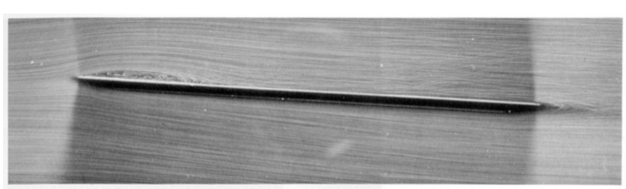
- What is drag
- Where does it come from?
- What affects it?
- …
- Some pictures…

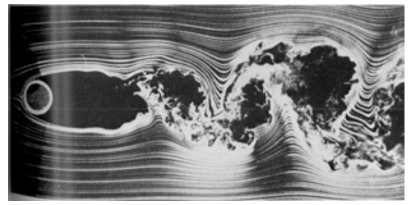


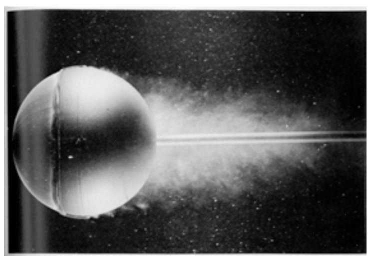


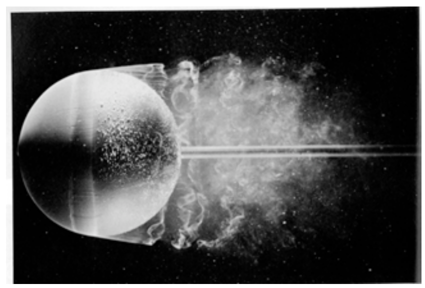








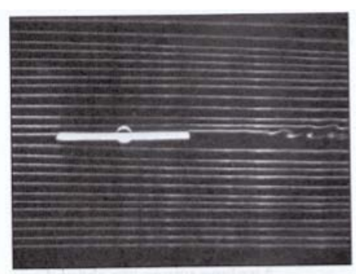


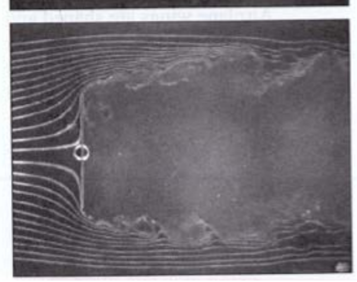


Drag

- What is drag
- Where does it come from?
- What affects it?

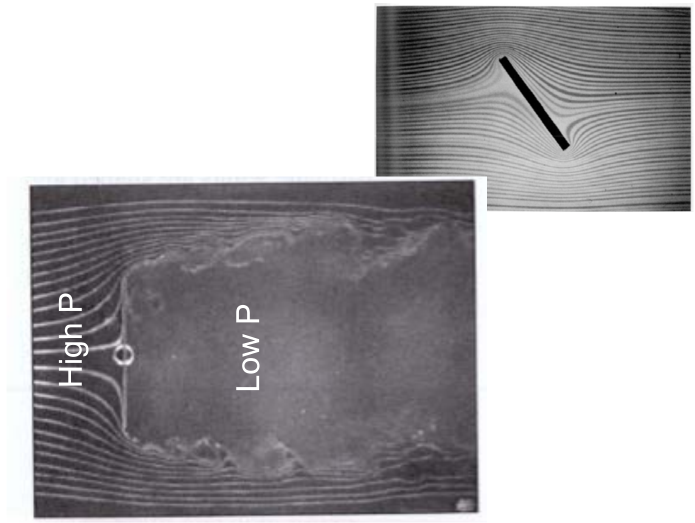
- "Drag is the net force a fluid exerts on a body in the flow direction"
- Two types:
  - Friction drag
    - Along the surface
    - Dominates at low speeds (lower Re)
  - Pressure drag
    - Normal to the surface
    - "Form drag"
    - Dominates at higher speeds (higher Re)
    - Primarily due to flow separation / wakes





Forces, Separation

Net Force →



Drag Coefficients

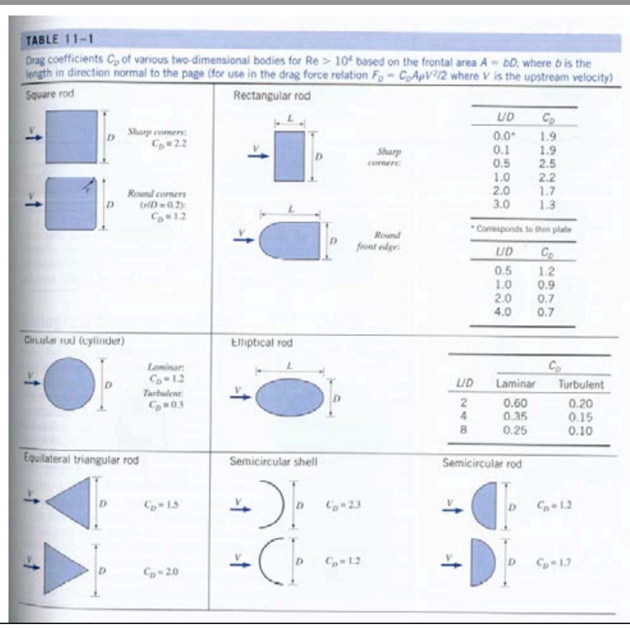


TABLE 11–1

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

$C_D = 2.3$

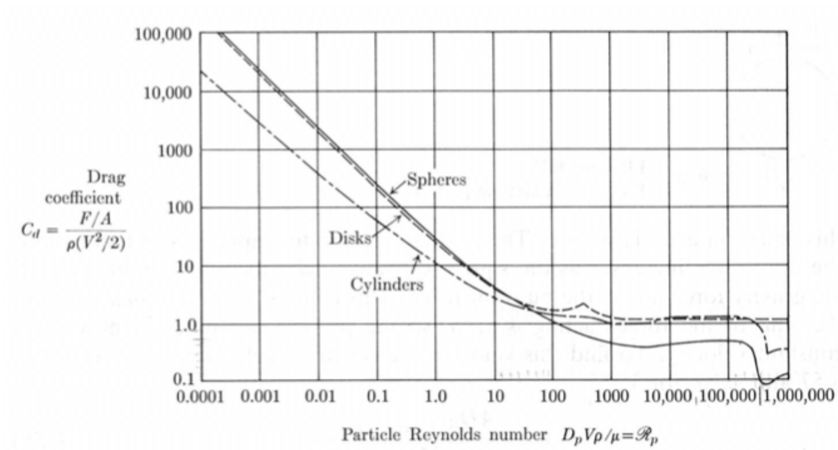
$C_D = 1.2$

Semicircular rod

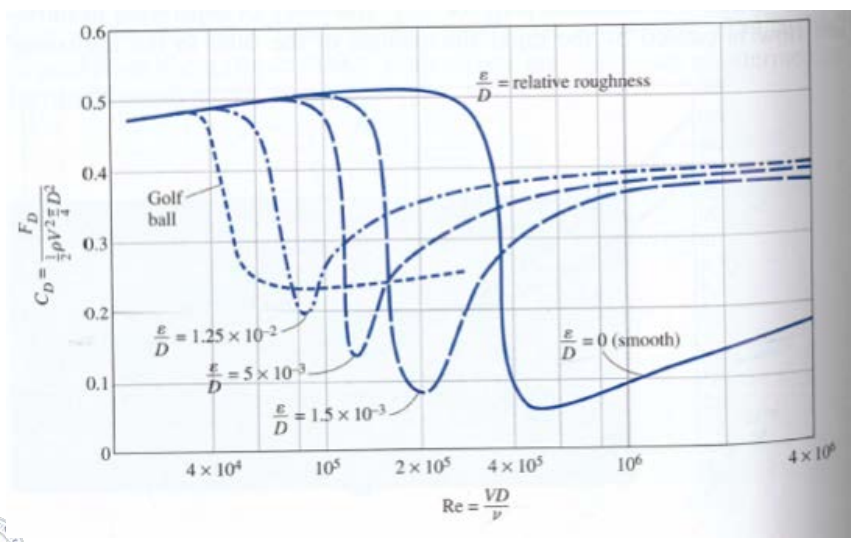
$C_D = 1.2$

$C_D = 1.7$

Drag vs. Re



Drag on Spheres with Roughness



Example

- Question:
- If you drop a droplet of water in air, what happens to its velocity?
  - Starts at 0.
  - Gravity accelerates it: v increases
  - As v increases, drag increases until gravity matches drag.
  - → $v = v_{term}$
- Problem
  - Find v_{term} of a water droplet in air
  - D = 1 mm
  - ρ_f=1.2 kg/m^3
  - $\nu=\mu/\rho$ = 1.5E-5 m^2/s
  - C_d = 0.5
- Q: What if $C_d = C_d(Re)$ instead?

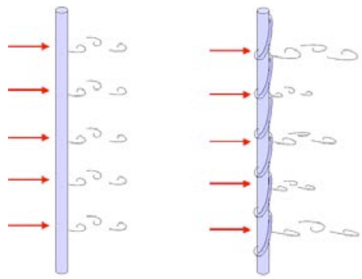
$$C_d = \frac{F}{A\rho_f v^2/2}$$

⬇

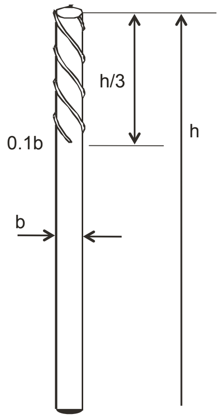
$$F = \frac{1}{2}\rho_f A v^2$$

For mitigation of vortex-shedding induced vibration :

Eliminates cross-wind vibration, but increases drag coefficient and along-wind vibration

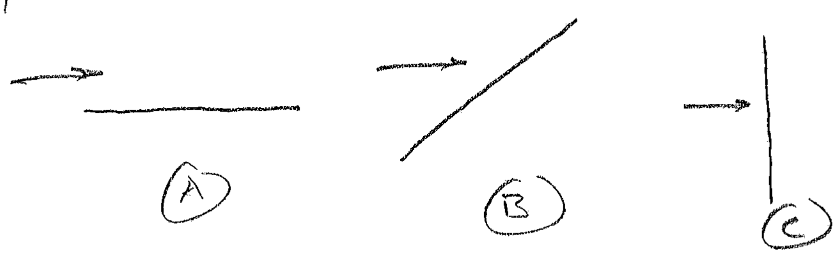


- Helical strakes



Lecture 29 – External Flows

- Chp 11
- Slides 1-8
  - Intro
    - Previous
    - Today
  - Questions to motivate.
- Pictures with properties / observations
  - Potential Flow
    - B. E
    - Pressure / Velocity Changes
    - Speed? High or low?
  - Flow w/ Separation
    - Speed? High or low
    - P/V Changes
  - Turbulent vs laminar Boundary Layer Separation.
    $Re = 15k$ vs $30k$
- Recap:



	A	B	C
D_p	0	✓	✓
D_f	✓	✓	0

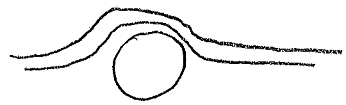
- Slides – 9
- Forces / Separation

Separation

- Flow → streamlines around object
- Flow Separation → Streamlines detach from the object

  - Car around bend too fast : Restraing force Not enough → fly off road.
  - Fluid similar.

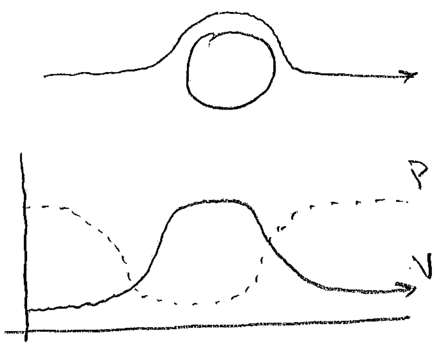
- Flow Separation : Consider effect of friction
  - Slide 1



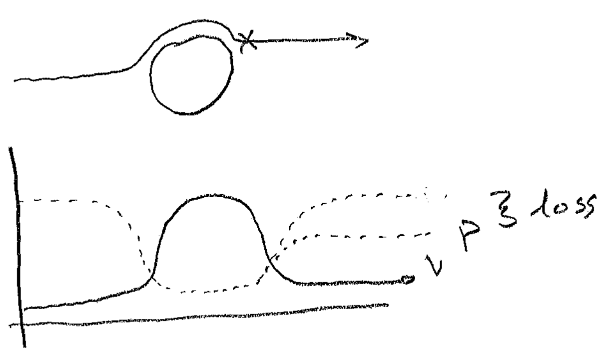
- As flow over sphere, streamlines get closer together, V increases
  - Fluid squeezed between smaller area channels

- Bernoulli Eq. $\frac{P}{\rho} + \frac{V^2}{2} = C$

No friction.

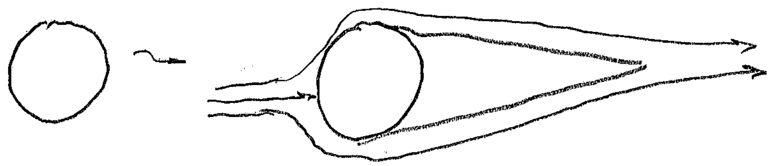


Friction



- $\frac{\Delta P}{\rho} + \frac{\Delta V^2}{2} = -F$
- losses → P can't increase back to old level
- P not high enough to "push" fluid around the bend
- Flow separates with a low pressure, turbulent wake.

"Fix" Separation by Streamlining.



Reduces form drag by minimizing the low pressure wake.

Measure Drag Forces with a Drag Coefficient.

Q: Key Parameters?

$F_D, \rho, \mu, V, L, \epsilon$ (A)

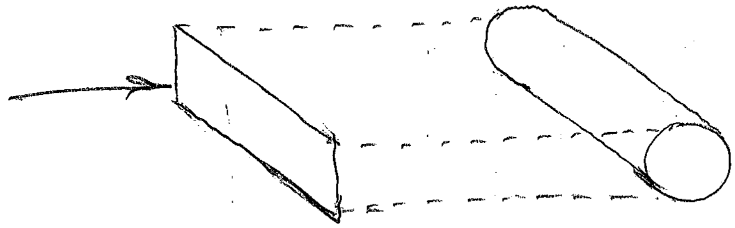
6 params
− 3 Dims
3 Π's

Pipes: $f = f(Re, \frac{\epsilon}{D})$ $\quad f \sim \frac{\Delta P}{\rho V^2} \cdot \frac{D}{L}$

Here: $C_d = C_d(Re, \frac{\epsilon}{L})$ $\quad \sim \frac{F/A}{\rho V^2}$

$\ldots \longrightarrow C_d = \frac{F}{A \rho V^2/2}$

A is the projected frontal Area

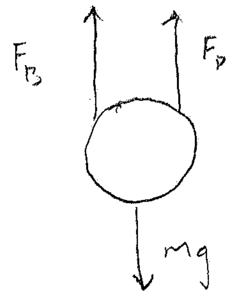


Slides

- C_d Table, Plots for Spheres

Example

Terminal Velocity



$$(\rho_p - \rho_f) V_p \cdot g = F_D = \frac{1}{2}\rho_f V^2 A C_D$$

- 1mm Diameter water Drop in air

$$V = \sqrt{\frac{2(\rho_p - \rho_f) V g}{\rho_f A C_D}} = \left(\frac{2(1000 - 1.2)\frac{\pi}{6}(0.001)^3(9.81)}{(1.2)(\frac{\pi}{4})(0.001)^2 \cdot C_D} \right)^{1/2}$$

$$V = \frac{3.3}{\sqrt{C_D}}$$

$$Re = \frac{\rho D V}{\mu} = 54794\ V$$

Guess $C_D = 2$

→ $V = 2.33$

→ $Re = 1.3 \times 10^5$

→ $C_D = 0.5$

→ $V = 4.667$

→ $Re = 2.6 \times 10^5$

→ $C_D = 0.5$

→ $V = 4.667$ m/s