Today, we will:

- Finish talking about boundary layers with pressure gradients (finish Chapter 10)
- Begin Chapter 11 – Flow over Bodies: Drag and Lift
- Do example problems – drag and lift on bodies (cars, bicycles, airplane wings, etc.)

7. BLs w/ pressure gradient (continued)

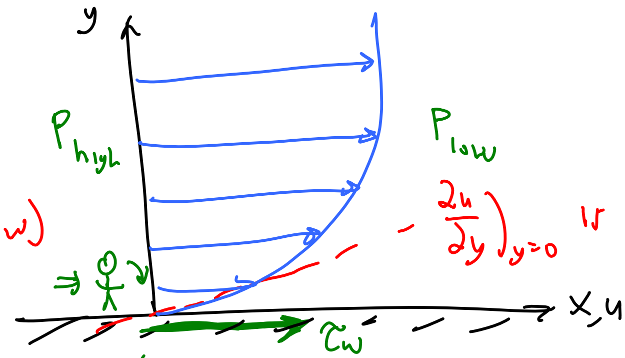
a. Definitions

b. Physical Explanation of Flow Separation

Favorable p.g. $\frac{dP}{dx} < 0$

$P \downarrow$ with x (accelerating flow)

$U \uparrow$ " "



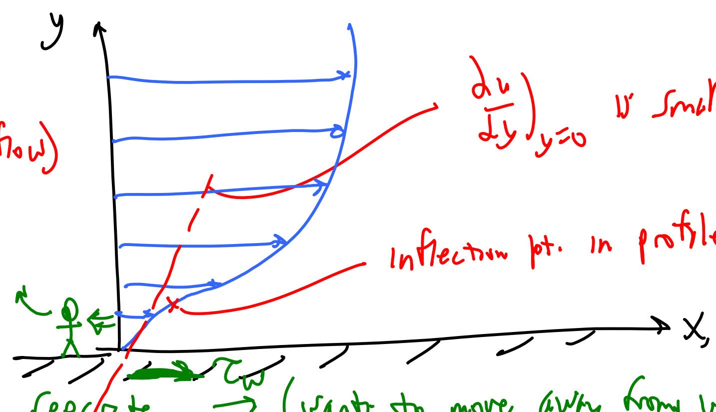
$\left.\frac{\partial u}{\partial y}\right)_{y=0}$ is larger

This flow is not likely to separate (wants to cling to the wall)

Adverse p.g. $\frac{dP}{dx} > 0$

$P \uparrow$ with x (decelerating flow)

$U \downarrow$ " "

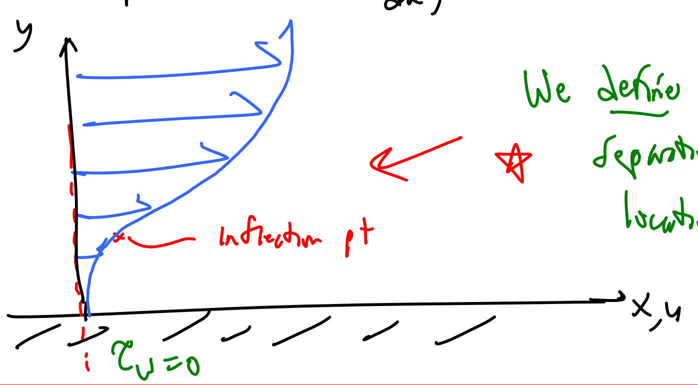


$\left.\frac{du}{dy}\right)_{y=0}$ is smaller

inflection pt. in profile

This flow is more likely to separate → (wants to move away from wall)

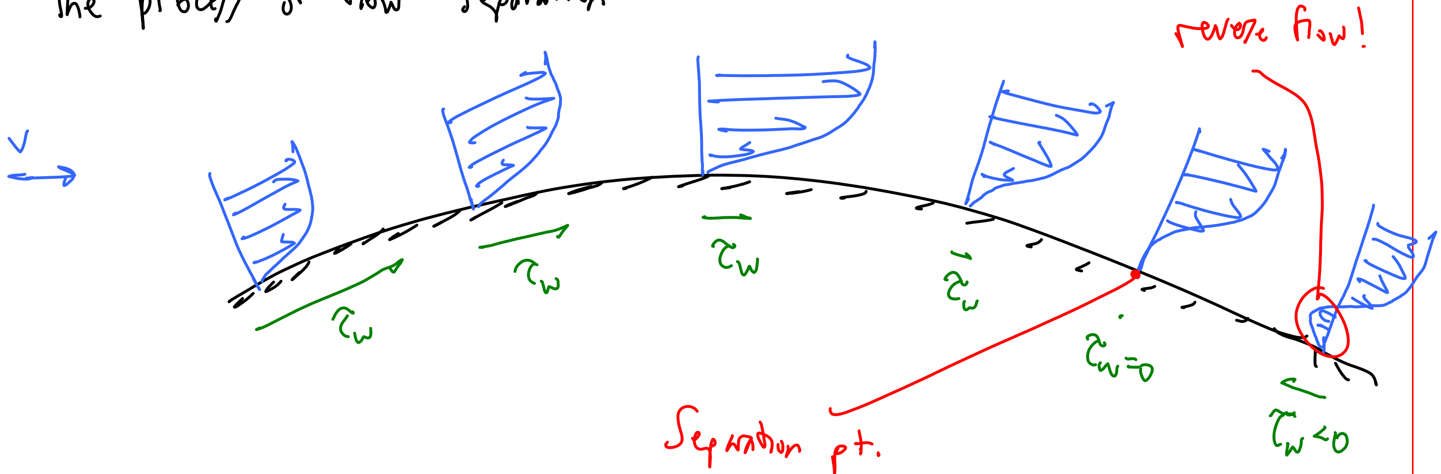
At high enough adverse p.g. (large $\frac{dP}{dx}$) the flow separates



We define the separation pt. as the location where $\left.\frac{du}{dy}\right)_w = 0$

$(\tau_w = 0)$

The process of flow separation



downstream of separation pt.

- Skin friction drag goes <u>down</u>
- Pressure drag goes <u>up</u>

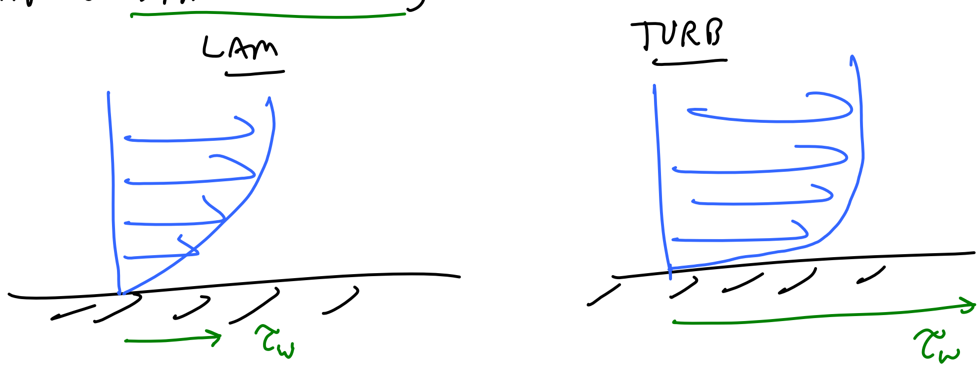
} Pressure usually wins

Separation is bad → leads to <u>more</u> overall drag, on airfoils leads to stall, etc.

C. Which is better – laminar BL or turbulent BL?

Ans – it depends on application!

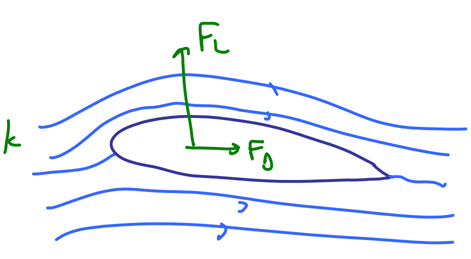
- In terms of <u>skin friction drag</u>



Laminar is better → less skin friction

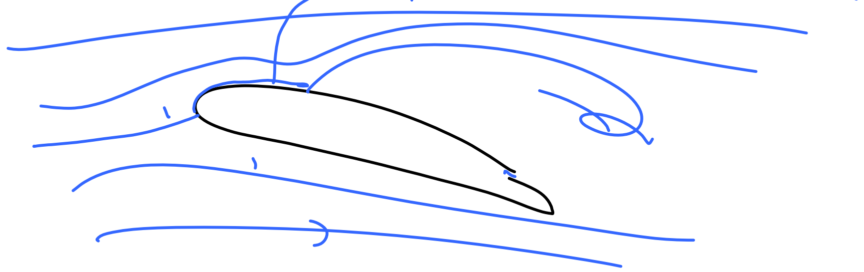
Application: Airfoil/wing at low ∠ of attack

No flow separation

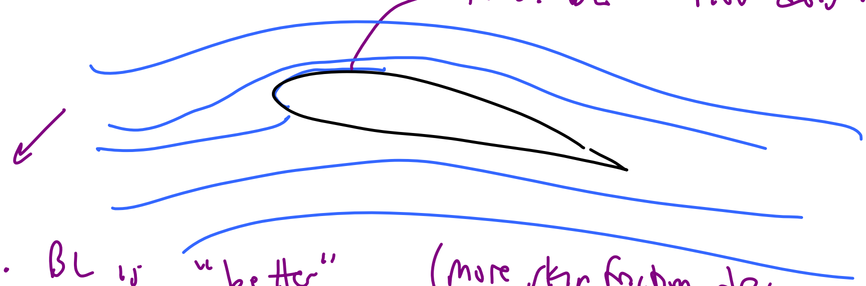


· Airfoil @ high $\angle$ of attack:

Laminar BL → Flow separates



turb. BL → Flow does not separate

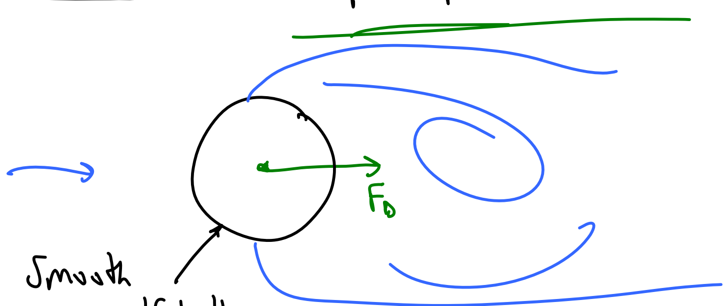


Turb. BL is "better" (more skin friction drag, compare lam vs. turb)

But less pressure drag

E.g. Golf balls → dimples promote turbulence

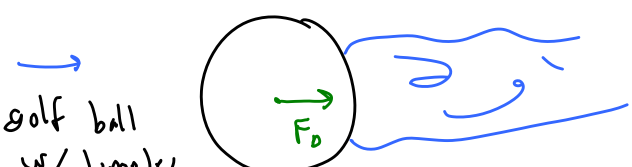
lam



Smooth golf ball

turb

golf ball w/ dimples

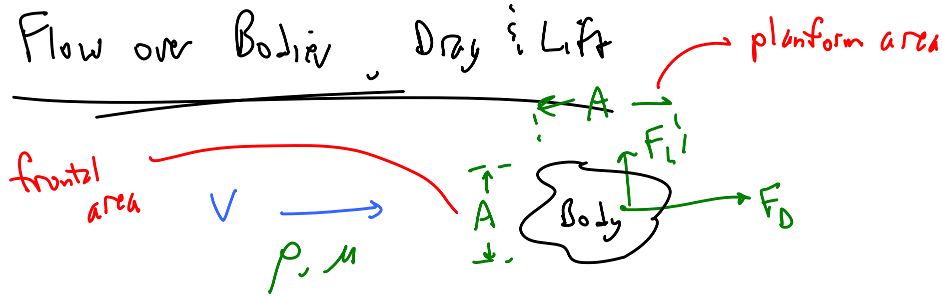


less overall drag

IX Ch. 11 → Flow over Bodies, Drag & Lift

A. Intro

1. Definitions



F_D = drag force is // to $\vec{V}$ (upstream velocity)

F_L = lift force is $\perp$ to $\vec{V}$

Drag coeff

$$\boxed{C_D = \frac{F_D}{\frac{1}{2}\rho V^2 A}}$$

dynamic pressure

$$\boxed{C_L = \frac{F_L}{\frac{1}{2}\rho V^2 A}}$$

Use appropriate area

2. Power required to overcome aerodynamic drag

$$\boxed{\dot{W}_{aero} = F_D \cdot V}$$

$$\left\{\frac{F \cdot L}{t}\right\} = \{F\} \cdot \left\{\frac{L}{t}\right\}$$

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3. Drag on Automobiles

$$\boxed{F_{D_{total}} = F_{D_{rolling\ resistance}} + F_{D_{aerodynamic}}}$$

typically constant

frontal area

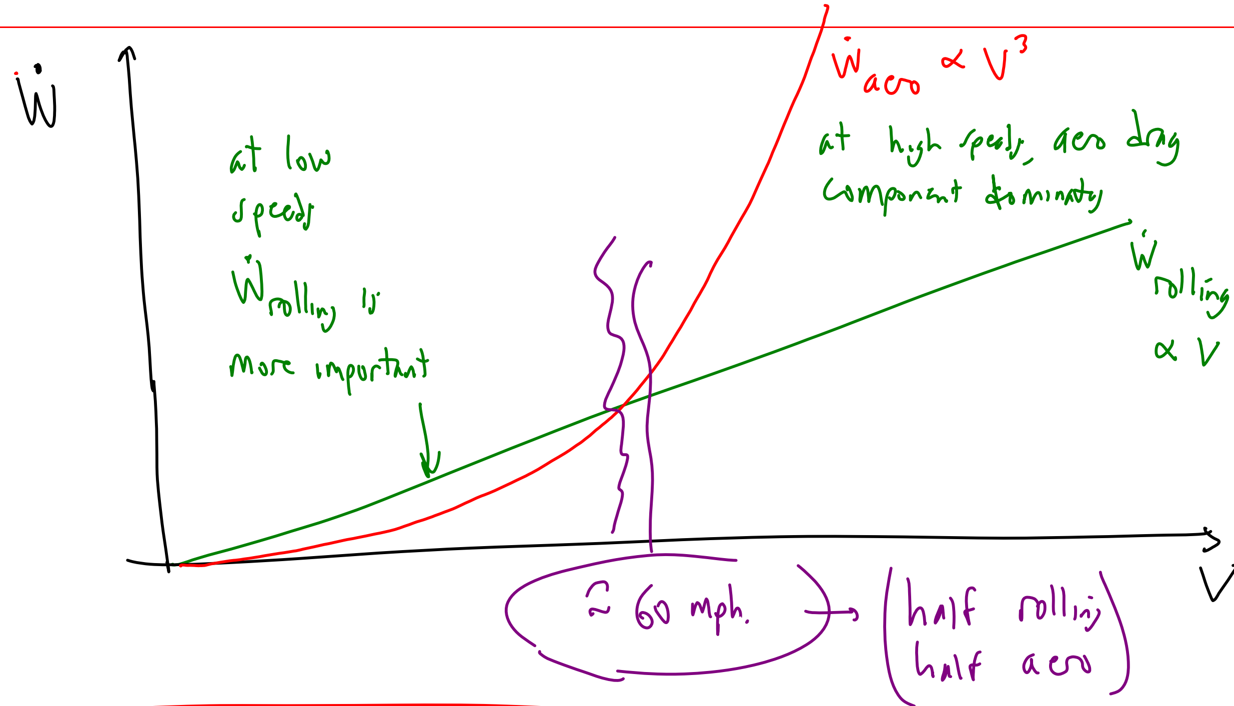
$$F_{D_{total}} = \mu_{rolling} \cdot W + C_D \frac{1}{2}\rho V^2 A$$

total power requirement:

$$\boxed{\dot{W} = F_D V = \mu_{rolling} \cdot W \cdot V + C_D \frac{1}{2}\rho V^3 A}$$

increases linearly with V

increases like V^3



Rule of thumb: For a typical car or truck @ highway speeds

$\approx$ half the power is aerodynamic & half is rolling resistance

e.g. if I improve C_D by 20%, I increase my mpg by $\approx$ 10% for highway driving

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C_D of cars: Boxy $C_D \simeq 0.5$

very streamlined (corvette) $C_D \simeq 0.3$

Ford Model T $C_D \simeq 0.8$

See Tables 11.1 & 11.2 for C_D on various body shapes

"Drag Area"

$$F_D = \frac{1}{2}\rho V^2 C_D A$$

"Drag area"

Typical:

Pickup truck	$C_D A = 1.5\ m^2$
van	$1.0\ m^2$
sedan	$0.6 - 0.9\ m^2$
sports car	$0.4 - 0.7\ m^2$

Comparison of two cars with identical engines, transmissions, frontal area, etc., but different aerodynamics

2005 Scion XA

$C_D = 0.31$

$C_D A = 7.0 \text{ ft}^2$

EPA Mileage estimate with manual transmission: **32 City, 37 Highway**.

2005 Scion XB

$C_D = 0.35$

$C_D A = 8.5 \text{ ft}^2$

EPA Mileage estimate with manual transmission: **30 City, 33 Highway**.

Conclusions:

- Mileage estimates in the city do not differ very much, since aerodynamic drag is a small percentage of total drag at low speeds.
- Mileage estimates on the highway differ more significantly, since aerodynamic drag is much more significant at highway speeds.

Quick Prediction → Q: How much will the mpg improve at highway speeds from an XB to an XA, all else being equal?

A: $C_D A_{XA}$ = 17.6% better than $C_D A_{XB}$ → ∴ we predict 17.6/2 = 8.8% improvement in mpg. → $mpg_{XB} = mpg_{XA}(1.088) = 33 \times 1.088 = \boxed{36 \text{ mpg}}$ — pretty close!