Introduction to Fluid Dynamics

Outline: units, dimensions
types of fluids
viscous fluids
surface tension

- hand out mud cards
- HW tomorrow
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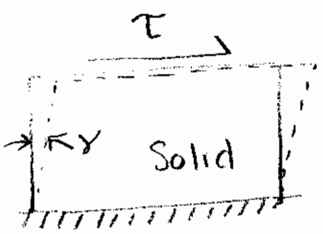
Fluid Dynamics:
- study of fluids in motion or at rest
- effects of fluid on boundaries
- compromise between theory and experiment

What is the difference between a fluid and a solid?

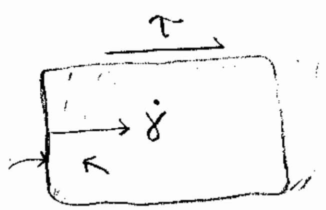
Solid: does not continuously deform under a shear stress (only very small initial deformation)



$\gamma \sim \tau$

- densely spaced molecules
- large intermolecular cohesive forces

Fluid: continuously deforms under shear stress



$\dot{\gamma} \sim \tau$

- less densely spaced molecules
- smaller intermolecular forces

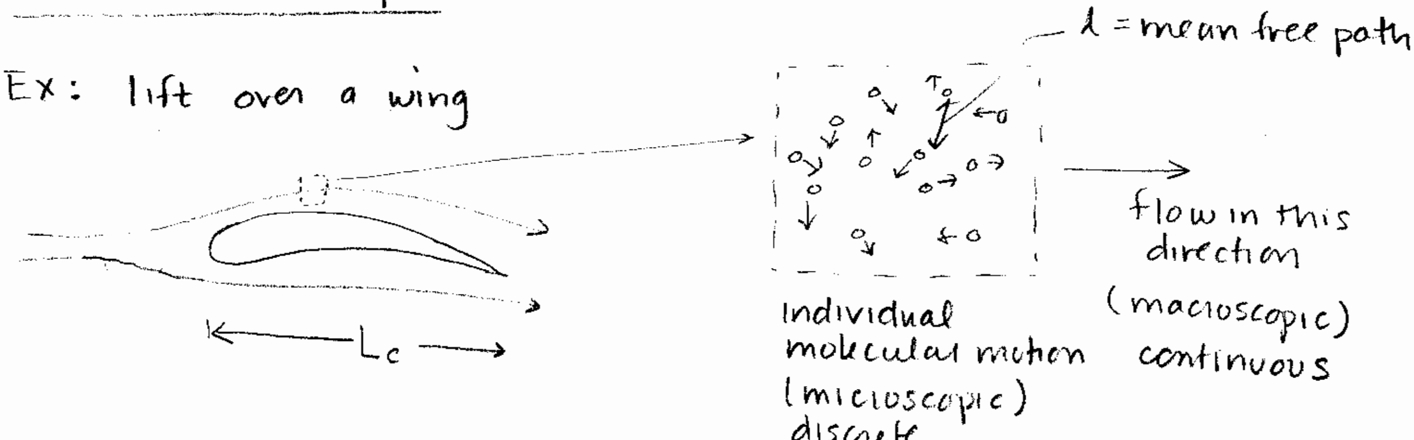
Subset: Gases
- always expands to fill container

Exceptions: Rheology - "inbetween" substances
mayonaise, toothpaste, slurries, jelly

Non-Newtonian fluids (later)

Continuum Concept

Ex: lift over a wing



L_c = characteristic length (size of body around which flow is taking place)

If $L_c >> \lambda$, then continuum (macroscopic) approach is valid

Continuum approach: Pressure, velocity, etc. vary continuously throughout fluid

[Liquid: 1 mm³ volume contains 10^{21} molecules spaced 10^{-7} mm apart]

Units + Dimensions

English units: mass (slugs) (lbm)

1 slug = 32.174 lbm

Force or weight (lbf)

dimensionally homogeneous

$$W = \frac{mg}{g_c} \qquad \frac{[\text{lbm}][\text{ft}/\text{s}^2]}{[\text{lbm ft}/\text{lbf s}^2]}$$

g_c → 32.174 lbm ft/lbf s²

SI units: mass (kg)

force (N) = (kg m/s²)

Common Properties of a Fluid:

Density $[kg/m^3]$, $[slugs/ft^3]$

- specific volume $v = 1/\rho$
- specific weight $\gamma = \rho g$
- specific gravity $SG = \dfrac{\rho}{\rho_{H_2O}\ @\ 4°C}$

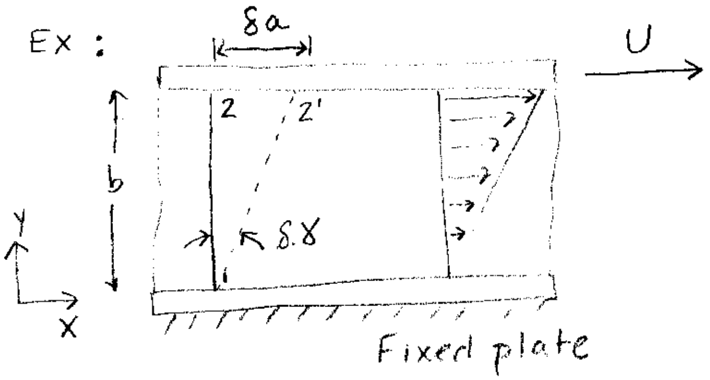
liquids $\rho = f(T)$

gases $\rho = f(T, P) \rightarrow \rho = \dfrac{P}{RT}$

Viscosity

describes "fluidity" of fluid

Ex:



$u = u(y) \rightarrow u = \dfrac{Uy}{b}$

(no-slip condition)

At time δt, fluid has moved through angle $\delta\gamma$

$\tan\delta\gamma = \dfrac{\delta a}{b} \approx \delta\gamma$ (small angle approximation)

$\left\{ \begin{array}{l} \sin\alpha = \alpha \\ \cos\alpha = 1 \\ \tan\alpha = \alpha \end{array} \right\}$

$\dfrac{U\delta t}{b} = \delta\gamma \rightarrow$ shear angle is a function of velocity and time

$$\dot{\gamma} = \lim_{\delta t \to 0} \frac{\delta\gamma}{\delta t} = \frac{U}{b} = \frac{du}{dy}$$

But we also know that $\dot{\gamma} \sim \tau$

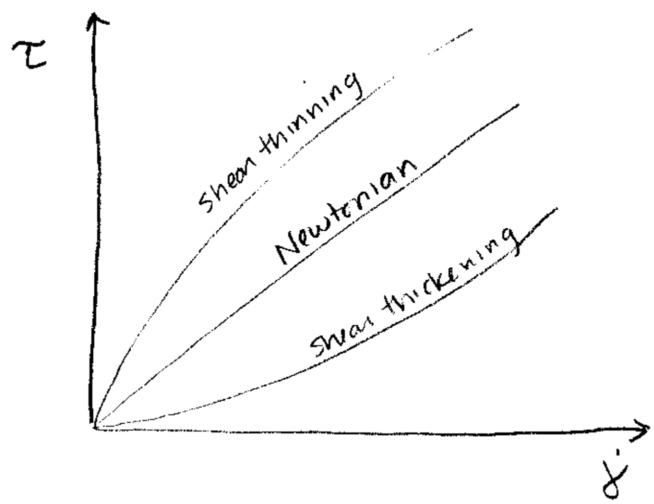
Therefore $\tau \sim \dfrac{du}{dy}$

and viscosity is the proportionality constant

$$\tau = \mu \frac{du}{dy} \quad \text{(Newtonian fluid)}$$

μ dynamic viscosity [kg/ms], [Ns/m²], [dyne·s/cm²] (poise)

ν Kinematic viscosity, $\nu = \frac{\mu}{\rho}$ [m²/s], [ft²/s]



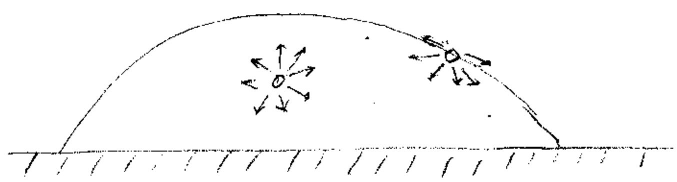
Shear thinning – latex paint, milk, blood

Shear thickening – cornstarch + water, Silly putty

Cornstarch video

Surface tension

Bead of water on a surface



"stretched membrane" behavior

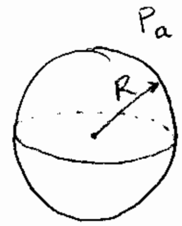
Molecules inside bead attracted to each other equally

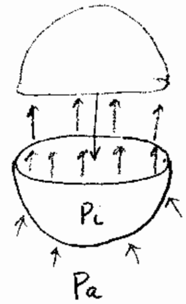
Molecules on surface subjected to net force inwards

Surface tension: intensity of molecular attraction per unit length along any line on the surface

σ [N/m] $= f(T)$ (dependent on molecular interaction)

Spherical drop





Surface tension force

$\sigma(2\pi R)$

Pressure force

$p_i(\pi R^2) - p_a(\pi R^2)$

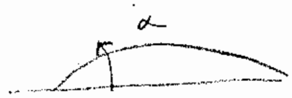
$$(p_i - p_a)\pi R^2 = \sigma 2\pi R$$

$$p_i - p_a = \Delta p = \frac{2\sigma}{R}$$

Pressure "jump" across interface

Capillary effects

Wetting fluid

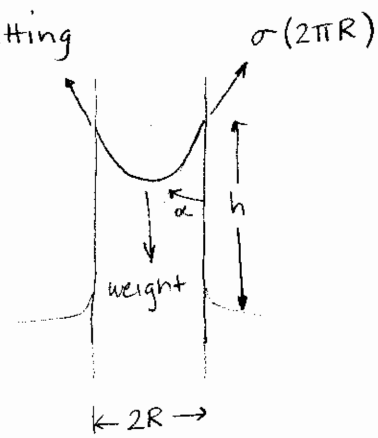


$\alpha < 90°$

Non-wetting fluid

$\alpha > 90°$

Wetting



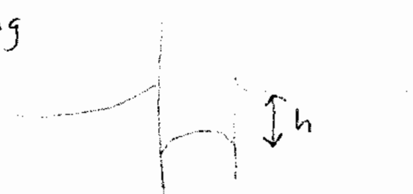
Attraction between wall and fluid that draws fluid up the tube

Weight of fluid in column = surface tension force

$$\rho g h \pi R^2 = 2\pi R \sigma \cos\alpha$$

$$h = \frac{2\sigma\cos\alpha}{\rho g R}$$

Non-wetting



[End Lecture 2]