Ideal Fluids

- Ideal fluid: a fluid with no friction
- Also referred to as an *inviscid* (zero viscosity) fluid
- Internal forces at any section within are normal (pressure forces)
- Practical applications: many flows approximate frictionless flow away from solid boundaries.
- Do not confuse ideal fluid with a perfect (ideal) gas.

Real Fluids

- Tangential or shearing forces always develop where there is motion relative to solid body
- Thus, fluid friction is created
- Shear forces oppose motion of one particle past another
- Friction forces gives rise to a fluid property called *viscosity*

Viscosity (1)

- A measure of a fluid's resistance to angular deformation, e.g.,
  - Motor oil: high viscosity, feels sticky
  - Gasoline: low viscosity, flows “faster”
- Friction forces result from cohesion and momentum interchange between molecules.

Viscosity (2)

- Mechanisms of viscous action:
  - Liquids: cohesion forces (diminish with temperature)
  - Gases: molecular interchange between moving layers
- Molecular interchange in gases:
  - Molecular interchange ➔ shear/friction between layers
  - As T increases, so does molecular activity ➔ increasing viscosity in gases as T increases
**Viscosity (4)**

- Rapidly-moving molecule into slowly-moving layer ➞ speeds up the layer.
- Slow-moving molecule into faster-moving layer ➞ slows down the layer.

**Viscosity (5) - Moving & stationary parallel plates**

- Fluid particles adhere to walls: no-slip condition
- Velocities: zero at (1), U at (2) ➞ velocity profile
- For small U, Y, and no net flow ➞ linear velocity profile
- Experiments show that  \( F \sim A \cdot U / Y \)

**Viscosity (6) – Newton's equation**

- From previous slide:  \( F \sim A \cdot U / Y \)
- \( \tau = F / A \) = shear stress between layers
- Newton's equation of viscosity (for the linear velocity profile)

\[
\tau = \frac{F}{A} = \mu \frac{U}{Y} = \mu \frac{du}{dy}
\]

- \( \mu = \text{coefficient of viscosity, absolute viscosity, dynamic viscosity, or simply viscosity} \)

**Viscosity (7) - Moving parallel plate with net flow**

- Velocity profile when small bulk flow present:
  - Combination of linear + parabolic profile
  - Non-linear profile
  - adds zero velocities at the walls
  - Shows maximum velocity at center line

**Viscosity (8) – Newton's equation**

- For non-linear profile, use the slope of the velocity profile at position \( y \), i.e., \( du/dy \), to calculate the shear stress between layers

\[
\tau = \mu \frac{du}{dy}
\]

- \( \mu = \text{coefficient of viscosity, absolute viscosity, dynamic viscosity, or simply viscosity} \)

1 - For solids, shear stress depends on magnitude of angular deformation (\( \tau \sim \text{angular deformation} \))
2 – For many fluids shear stress is proportional to the time rate of angular deformation (\( \tau \sim du/dy \))
**Viscosity (9) – \( \tau \)- vs.- (du/dy) behavior**

- Elastic solid
- Ideal plastic
- Non-Newtonian fluid
- Newtonian fluid
- Ideal fluid

**Viscosity (10) – Different materials**

- Newtonian fluid: \( \mu \) is constant
  - Air, water are Newtonian fluids
- Ideal fluid has \( \mu = 0 \)
- Ideal plastic: requires a threshold stress \( \tau_0 \) before it flows
- Non-Newtonian fluids: \( \mu \) varies with velocity gradient (du/dy)
  - Paints, printer's ink, gels, emulsions are Non-Newtonian fluids.

**Viscosity (11) – Journal bearing**

- See Figure 2.6, p. 32, for sketch of journal bearing
- Lubricating fluid fills small annular space between a shaft and its surrounding support
- For coaxial cylinders with constant angular velocity \( (\omega) \), resisting torque = driving torque
- Because radii at inner and outer walls are different \( \Rightarrow \) shear stresses at the walls must be different
- Shear stresses vary continuously and velocity profile in gap must be curve
- For very small gaps, velocity is linear \( \tau = \mu \cdot \frac{U}{Y} \)

**Viscosity (12) – Kinematic viscosity**

- Ratio of absolute viscosity to density
  \[ \nu = \frac{\mu}{\rho} \]
- Appears in many problems in fluids
- Called *kinematic viscosity* because it involves no force (dynamic) dimensions
- B.G. Units = \( ft^2/sec \), S.I. Units = \( m^2/s \)
- The *stoke* (St)
  - Metric unit of kinematic viscosity
  - Named after Sir George Stokes (1819-1903)
  - The centistoke: \( 1 \text{ cSt} = 0.01 \text{ St} = 10^{-6} \text{ m}^2/\text{s} \)
  - For water at 68.4°F (20.22°C), \( \mu = 1 \text{ cP} \)
Viscosity (13) – Kinematic vs. dynamic

- $\mu$ for most fluids is virtually independent of pressure for the range of interest to engineers

- $\nu$ for gases varies strongly with pressure because of changes in density ($\rho$)

- To determine $\nu$ at non-standard pressures, look up the pressure-independent value of $\mu$ and calculate $\nu = \frac{\mu}{\rho}$.

- To calculate $\rho$ use the perfect gas law.

Viscosity (14) - Examples

See Sample Problems 2.8 and 2.9 in pages 34 and 35

Surface Tension (1)

- Molecular attraction forces in liquids:
  - Cohesion: enables liquid to resist tensile stress
  - Adhesion: enables liquid to adhere to another body

- Liquid-fluid interfaces:
  - Liquid-gas interface: free surface
  - Liquid-liquid (immiscible) interface

- At these interfaces, out-of-balance attraction forces forms imaginary surface film that exerts a tension force in the surface $\Rightarrow$ surface tension

- Computed as a force per unit length

Surface tension (2)

- Surface tension of various liquids
  - Cover a wide range
  - Decrease slightly with increasing temperature

- Values of surface tension for water between freezing and boiling points
  - 0.00518 to 0.00404 lb/ft or 0.0756 to 0.0589 N/m
  - See Table A.1, Appendix A

- Surface tension for other liquids
  - See Table A.4, Appendix A

Surface tension (3)

- Surface tension is responsible for the curved shapes of liquid drops and liquid sheets as in this example

Herring-bone jets
Surface Tension (4) - Capillarity

- Property of exerting forces on fluids by fine tubes and porous media, due to both cohesion and adhesion
- Cohesion < adhesion, liquid wets solid, rises at point of contact
- Cohesion > adhesion, liquid surface depresses at point of contact
- Meniscus: curved liquid surface that develops in a tube
- See Figure 2.7, p. 38

Surface Tension (5) - Meniscus

Mercury – non wetting liquid
Water – wetting liquid

In next slide:
- $\sigma =$ surface tension,
- $\theta =$ wetting angle,
- $\gamma =$ specific weight of liquid,
- $r =$ radius of tube,
- $h =$ capillary rise

Surface Tension (6) - Capillary Rise

Equilibrium of surface tension force and gravitational pull on the water cylinder of height $h$ produces:

$$2\pi r \sigma \cos \theta = \pi^2 h \gamma$$

$$h = 2\sigma \cos \theta / (\gamma)$$

Surface Tension (7)

- Expression in previous slide calculates the approximate capillary rise in a small tube
- The meniscus lifts a small amount of liquid near the tube walls, as $r$ increases this amount may become significant
- Thus, the equation developed overestimates the amount of capillary rise or depression, particularly for large $r$.
- For a clean tube, $\theta = 0^\circ$ for water, $\theta = 140^\circ$ for mercury
- For $r > \frac{1}{4}$ in (6 mm), capillarity is negligible

Surface Tension (8) - Applications

- Its effects are negligible in most engineering situations.
- Important in problems involving capillary rise, e.g., soil water zone, water supply to plants
- When small tubes are used for measuring properties, e.g., pressure, account must be made for capillarity
- Surface tension important in:
  - Small models in hydraulic model studies
  - Break up of liquid jets
  - Formation of drops and bubbles
Vapor Pressure of Liquids (1)

- Liquids tend to evaporate or vaporize by projecting molecules across the free surface.
- If enclosed space above free surface, partial pressure exerted by molecules increases.
- Saturation pressure (vapor pressure) reached when same number of molecules enter as leave the free surface.
- Molecular activity increases with increasing $T$ and decreasing $p$, so does the saturation pressure.

Vapor Pressure of Liquids (2)

- At any given $T$, if $p < \text{saturation pressure}$ $\rightarrow$ rapid rate of evaporation (boiling).
- Thus, saturation pressure is also known as boiling pressure for a given temperature.
- In flowing fluids, cavitation occurs when the fluid undergoes rapid vaporization and recondensation while passing through regions of low absolute pressure [see Section 5.10].
- Saturation vapor pressure data available in Table 2.3, p. 40, and Table A.4, Appendix A.4. For water, in Table A.1.

Cavitation in propellers

Cavitation damage in Karun Dam, Iran

Data on fluid properties – Appendix A

- Figure A.1 – $\mu$ vs. $T$ for various fluids
- Figure A.2 – $\nu$ vs. $T$ for various fluids
- Table A.1 – Physical properties of water at standard conditions ($\gamma$, $\rho$, $\mu$, $\nu$, $\sigma$, $p$, $p_v$, $\gamma_E$)
- Table A.2 – Physical properties of air at standard conditions ($\gamma$, $\rho$, $\mu$, $\nu$)
- Table A.3 – The ICAO standard atmosphere
- Table A.4 – Physical properties of common liquids
- Table A.5 – Physical properties of common gases