Chapter 2: Properties of Fluids

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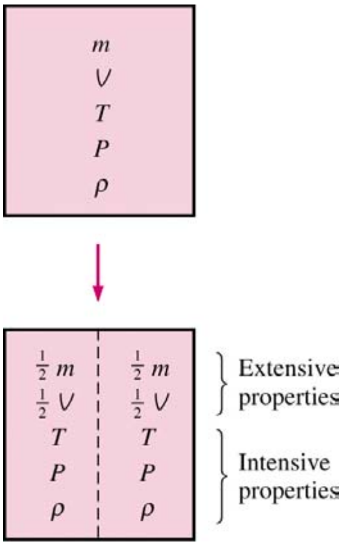
Introduction

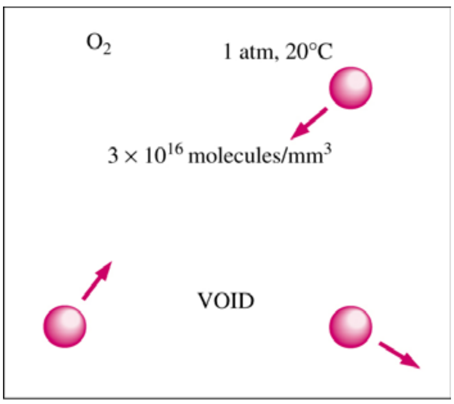
- Any characteristic of a system is called a **property.**
  - Familiar: pressure *P*, temperature *T,* volume *V*, and mass *m*.
  - Less familiar: viscosity, thermal conductivity, modulus of elasticity, thermal expansion coefficient, vapor pressure, surface tension.
- *Intensive* properties are independent of the mass of the system. Examples: temperature, pressure, and density.
- *Extensive* properties are those whose value depends on the size of the system. Examples: Total mass, total volume, and total momentum.
- Extensive properties per unit mass are called **specific properties**. Examples include specific volume $v = V/m$ and specific total energy $e=E/m$.

Properties



Criteria to differentiate intensive and extensive properties

Continuum



- Atoms are widely spaced in the gas phase.
- However, we can disregard the atomic nature of a substance.
- View it as a continuous, homogeneous matter with no holes, that is, a **continuum**.
- This allows us to treat properties as smoothly varying quantities.
- Continuum is valid as long as size of the system is large in comparison to distance between molecules.

Density and Specific Gravity

- Density is defined as the *mass per unit volume* $\rho = m/V$. Density has units of kg/m^3
- Specific volume is defined as $v = 1/\rho = V/m$.
- For a gas, density depends on temperature and pressure.
- **Specific gravity**, or relative density is defined as *the ratio of the density of a substance to the density of some standard substance at a specified temperature* (usually water at 4°C), i.e., $SG=\rho/\rho_{H_2O}$. SG is a dimensionless quantity.
- The **specific weight** is defined as the weight per unit volume, i.e., $\gamma_s = \rho g$ where g is the gravitational acceleration. γ_s has units of N/m^3.

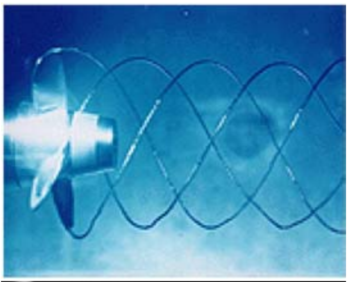
Density of Ideal Gases

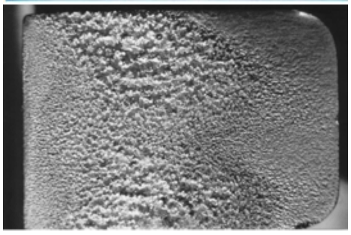
- **Equation of State**: equation for the relationship between pressure, temperature, and density.
- The simplest and best-known equation of state is the ideal-gas equation.

$$P\,v = R\,T \qquad \text{or} \qquad P = \rho\,R\,T$$

- Ideal-gas equation holds for most gases.
- However, dense gases such as water vapor and refrigerant vapor should not be treated as ideal gases. Tables should be consulted for their properties, e.g., Tables A-3E through A-6E in textbook.

Vapor Pressure and Cavitation



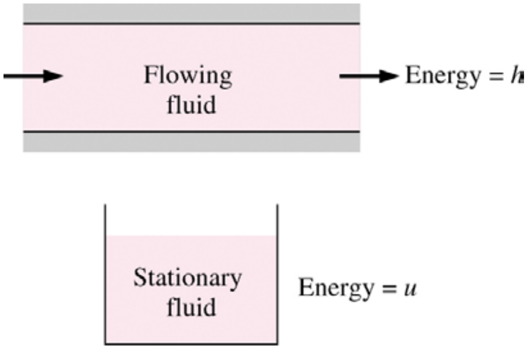


- **Vapor Pressure** P_v is defined as *the pressure exerted by its vapor in phase equilibrium with its liquid at a given temperature*
- If P drops below P_v, liquid is locally vaporized, creating cavities of vapor.
- Vapor cavities collapse when local P rises above P_v.
- Collapse of cavities is a violent process which can damage machinery.
- Cavitation is noisy, and can cause structural vibrations.

Energy and Specific Heats

- Total energy E is comprised of numerous forms: thermal, mechanical, kinetic, potential, electrical, magnetic, chemical, and nuclear.
- Units of energy are *joule* (J) or *British thermal unit* (BTU).
- Microscopic energy
  - Internal energy u is for a non-flowing fluid and is due to molecular activity.
  - Enthalpy $h=u+Pv$ is for a flowing fluid and includes flow energy (Pv).
- Macroscopic energy
  - Kinetic energy $ke=V^2/2$
  - Potential energy $pe=gz$
- In the absence of electrical, magnetic, chemical, and nuclear energy, the total energy is $e_{flowing}=h+V^2/2+gz$.

Energy



The internal energy u represents the microscopic energy of a nonflowing fluid per unit mass, whereas enthalpy h represents the microscopic energy of a flowing mass.

Specific heats

- For an ideal gas

$$du = c_v dT \quad \text{and} \quad dh = c_p dT$$

c_v, c_p: constant volume and constant pressure specific heats

- For incompressible substances:

$$c_p \approx c_v \approx c$$

$$\Delta h = \Delta u + \Delta p / \rho \approx c_{ave} \Delta T + \Delta P / \rho$$

Coefficient of Compressibility

- How does fluid volume change with *P* and *T*?
- Fluids expand as $T\uparrow$ or $P\downarrow$
- Fluids contract as $T\downarrow$ or $P\uparrow$
- Need fluid properties that relate volume changes to changes in *P* and *T*.
  - Coefficient of compressibility

$$\kappa = -v\left(\frac{\partial P}{\partial v}\right)_T = \rho\left(\frac{\partial P}{\partial \rho}\right)_T$$

  - Coefficient of volume expansion

$$\beta = \frac{1}{v}\left(\frac{\partial v}{\partial T}\right)_P = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_P$$

- Combined effects of *P* and *T* can be written as

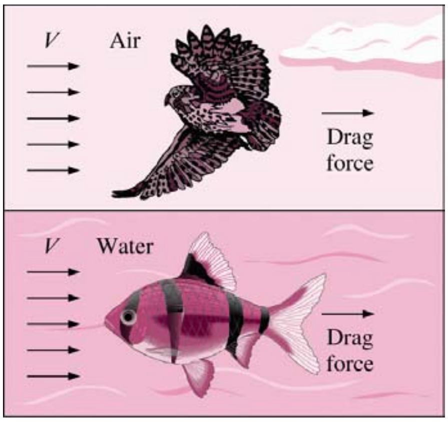
$$dv = \left(\frac{\partial v}{\partial T}\right)_P dT + \left(\frac{\partial v}{\partial P}\right)_T dP$$

Coefficient of Compressibility

- Fractional change in volume or density:

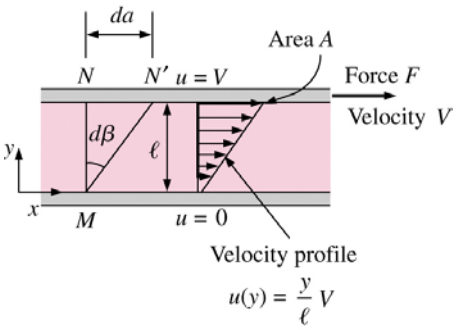
$$\frac{\Delta\upsilon}{\upsilon} = -\frac{\Delta\rho}{\rho} \cong \beta\Delta T - \alpha\Delta P$$

Viscosity



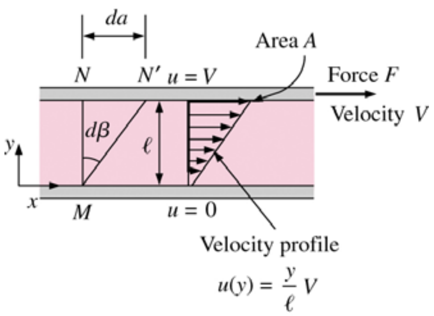
- **Viscosity** is a property that represents the internal resistance of a fluid to motion.
- The force a flowing fluid exerts on a body in the flow direction is called the **drag force**, and the magnitude of this force depends, in part, on viscosity.

Viscosity



- To obtain a relation for viscosity, consider a fluid layer between two very large parallel plates separated by a distance ℓ
- Definition of shear stress is $\tau = F/A$.
- Using the no-slip condition, $u(0) = 0$ and $u(\ell) = V$, the velocity profile and gradient are $u(y) = Vy/\ell$ and $du/dy = V/\ell$
- Shear stress for Newtonian fluid: $\tau = \mu du/dy$
- μ is the **dynamic viscosity** and has units of *kg/m·s*, *Pa·s*, or **poise**.

Viscosity



The angular displacement or deformation (or shear strain) is

$$d\beta \approx \tan\beta = \frac{da}{\ell} = \frac{Vdt}{\ell} = \frac{du}{dy}dt$$

$$\frac{d\beta}{dt} = \frac{du}{dy}$$

From experiments:

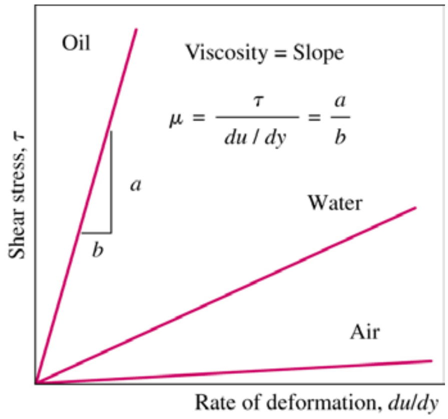
$$\tau \propto \frac{d\beta}{dt} \quad or \quad \tau \propto \frac{du}{dy}$$

Viscosity

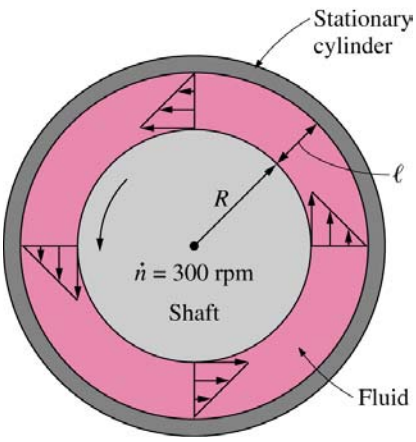
For 1-D Newtonian fluids

$$Shear\ stress: \ \tau = \mu \frac{du}{dy} \quad (N/m^2)$$

μ = coef. of viscosity



Viscometry

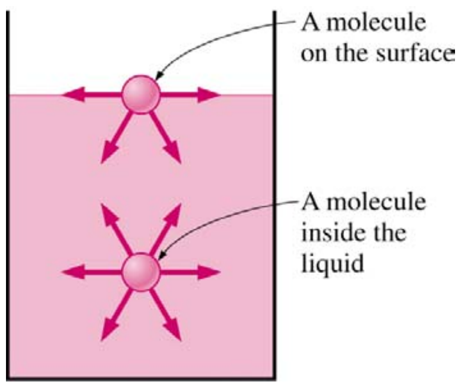


- How is viscosity measured? A rotating viscometer.
  - Two concentric cylinders with a fluid in the small gap ℓ.
  - Inner cylinder is rotating, outer one is fixed.
- Use definition of shear force:

$$F = \tau A = \mu A \frac{du}{dy}$$

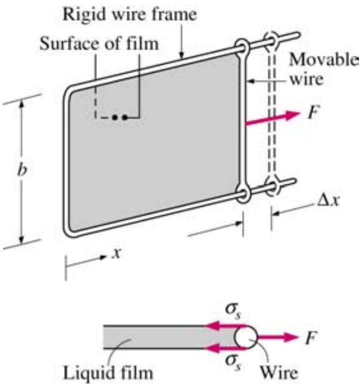
- If $\ell/R << 1$, then cylinders can be modeled as flat plates.
- Torque $T = FR$, and tangential velocity $V=\omega R$
- Wetted surface area $A=2\pi RL$.
- Measure T and ω to compute μ

Surface Tension



- Liquid droplets behave like small spherical balloons filled with liquid, and the surface of the liquid acts like a stretched elastic membrane under tension.
- The pulling force that causes this is
  - due to the attractive forces between molecules
  - called **surface tension** σ_s.
- Attractive force on surface molecule is not symmetric.
- Repulsive forces from interior molecules causes the liquid to minimize its surface area and attain a spherical shape.

Surface Tension



Consider the film of a soap bubble

Force balance: $F = 2b\sigma_s$

$\sigma_s = F/2b$

Work done in stretching the film:

W = Force × distance

$W = F\Delta x = 2b\,\sigma_s\Delta x = \sigma_s\Delta A$

$\Delta A = 2b\Delta x$

Surface tension = work done per unit surface area of the liquid

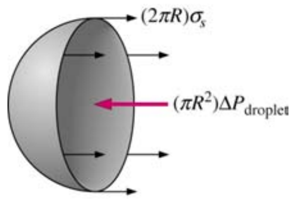
Surface tension

Consider a droplet and a bubble.

Horizontal force balance:

Droplet:

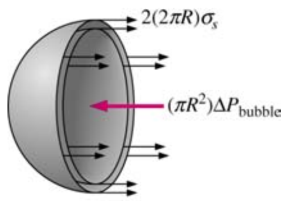
$$(2\pi R)\sigma_s = (\pi R^2)\Delta P_{droplet} \rightarrow \Delta P_{droplet} = P_i - P_o = \frac{2\sigma_s}{R}$$



(*a*) Half a droplet

Bubble:

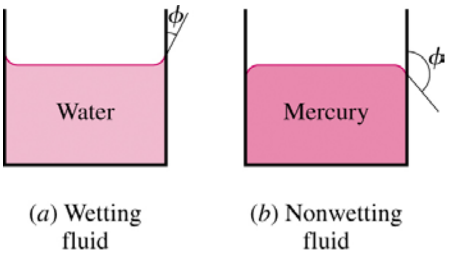
$$2(2\pi R)\sigma_s = (\pi R^2)\Delta P_{bubble} \rightarrow \Delta P_{bubble} = P_i - P_o = \frac{4\sigma_s}{R}$$



(*b*) Half a bubble

P_i, P_o : pressures inside and outside the bubble

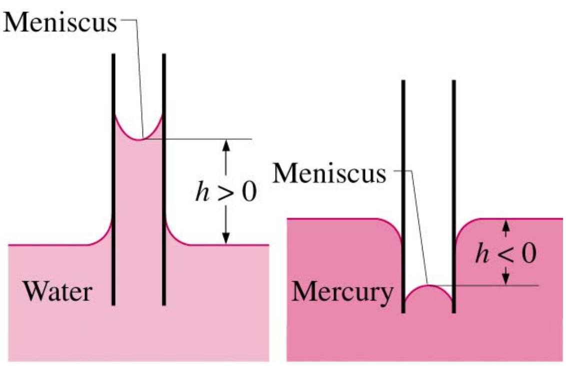
Capillary Effect



Contact angle for wetting and nonwetting fluids

- **Capillary effect** is the rise or fall of a liquid in a small-diameter tube.
- The curved free surface in the tube is call the **meniscus**.
- Water meniscus curves up because water is a *wetting fluid* (ø < 90º).
- Mercury meniscus curves down because mercury is a *nonwetting fluid* (ø > 90º).
- Force balance can describe magnitude of capillary rise.

Capillary Effect



The capillary rise of water and the capillary fall of mercury in a small-diameter glass tube.

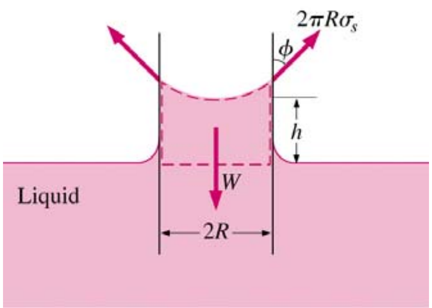
Capillary Rise

Force balance can describe magnitude of capillary rise

Weight of liquid column is:

$$W = mg = \rho V g = \rho g(\pi R^2 h)$$

Force balance in vertical direction



$$W = F_{surface}$$

$$\rho g(\pi R^2 h) = 2\pi R\sigma_s \cos \phi \quad \rightarrow h = \frac{2\sigma_s}{\rho g R}\cos\phi$$

h = capillary rise