**Distinction between a solid and a fluid (1)**

- Molecules of solid closer together than those of fluid
- Solid: intermolecular forces larger than in fluid
  - Elastic solid
    - deforms under load
    - recovers original state when unloaded
  - Plastic solid
    - deforms under sufficient load
    - continues deforming as long as load is applied
    - does not return to original state

**Distinction between a solid and a fluid (2)**

- Intermolecular forces in fluid not large enough to hold elements together
- Fluid flows under slightest stress and continues flowing as long as stress is present

**Distinction between a gas and a liquid (1)**

- Fluids: gases or liquids
- GAS:
  - Molecules farther apart
  - Very compressible
  - Tends to expand indefinitely
- LIQUID:
  - Relatively incompressible
  - If external pressure removed, does not expand
  - May have a free surface (subject to its own vapor pressure)

**Distinction between a gas and a liquid (2)**

- VAPOR:
  - Gas whose \( T \) and \( P \) very near the liquid phase
  - Steam is a vapor, state near that of water
- GAS:
  - Super-heated vapor, far away from liquid phase
  - Volume of gas or vapor greatly affected by \( \Delta T \) and \( \Delta P \)
- Thermodynamics
  - Study of heat phenomena
  - Important if significant \( \Delta T \) or phase changes involved
**Density, Specific Weight**

- Density, or mass density, \( \rho \) = mass per unit volume (kg/m\(^3\), slug/ft\(^3\))
  \[ \rho = \frac{m}{V} \]

- Specific weight, \( \gamma \) = weight per unit volume (N/m\(^3\), lb/ft\(^3\) = pcf)
  \[ \gamma = \frac{W}{V} \]

- Related by
  \[ \rho = \frac{\gamma}{g} \text{ or } \gamma = \rho \cdot g \]

**Specific Volume, Specific Gravity**

- Specific volume, \( v \): volume per unit mass (ft\(^3\)/slug, m\(^3\)/kg)

- Specific gravity for a liquid is the dimensionless ratio
  \[ \varepsilon = \frac{\rho_L}{\rho_W} \]

  where \( \rho_L \) = density of liquid, \( \rho_W \) = density of water at a standard temperature (either 4°C, or 60°F)

- For gases, the reference density is not standard. It must be specified.

See Sample problems 2.1, 2.2, pp. 15-16

**Compressible and incompressible fluids**

- Compressible: variable density
- Incompressible: constant density

- No real incompressible fluid exists, assumed so if \( \Delta \rho \) is small as \( P \) changes, e.g.,
  - Liquids usually
  - Gases if \( \Delta P \) small relative to absolute pressure

- Liquid compressibility important in pressure waves
- Air:
  - Incompressible: ventilating system, fly < 250 mph
  - Compressible: high-velocity pipe, fly > 760 mph (speed of sound)

**Compressibility of liquids (1)**

- Bulk (volume) modulus of elasticity, \( E_v \) (kPa-abs, psia)
  \[ E_v = -\rho_v \left( \frac{dP}{dv} \right) = -\left( \frac{v}{dv} \right) \cdot dp \]

- \( E_v \) represents the \( \Delta P \) required to produce a unit change in specific volume (\( \Delta v/v \))

- \( E_v = f(T,p) \) for liquids (e.g., see Table 2.1, p. 17)

- Use absolute pressures, thus, units: psia, kPa abs

**Compressibility of liquids (2)**

- For a fixed mass of liquid at constant temperature, the bulk modulus does not change much on a moderate range of temperature (e.g., see Table 2.1, p. 17, for water).

- In this case (refer to figure in previous slide), we can write:
  \[ \frac{\Delta v}{v} = -\frac{dP}{E_v} \text{ or } \frac{v_2 - v_1}{v_1} = \frac{P_2 - P_1}{E_v} \]

- See Sample Problem 2.3, p. 18.
Specific weight of liquids

- See Table 2.2, p. 20, for \( \gamma \) for common liquids at 68°F (20°C) and standard sea-level pressure with \( g = 32.2 \) ft/sec\(^2\) (9.81 m/s\(^2\))

- Specific weight of liquids:
  - Varies only slightly with pressure
  - May vary considerably with temperature

- See Figure 2.1, p. 20, \( \gamma = f(p, T) \)

- For water at atmospheric pressure conditions at sea level, see Table A.1, Appendix A, p. 732

Property relations for perfect gases (1)

- Perfect gases: gases with constant specific heats that obey the perfect-gas law:

\[
\frac{p}{\rho} = \frac{p \cdot v}{R \cdot T} \quad \text{or} \quad \gamma = \frac{\rho \cdot p}{RT}
\]

\( p = \) abs pres., \( \rho = \) density, \( v = 1/\rho, T = \) abs temp., \( R = \) gas constant

- For air, \( R = 1715 \) ft/(sec\(^2\)oR) = 287 m\(^2\)/(s\(^2\)K)

- Equations: equations of state, or property relations

Property relations for perfect gases (2)

- Avogadro's law: all gases under same \( p, T, g \) have the same number of molecules per unit of volume. Thus, \( \gamma \sim M \) (molar mass, or molecular weight).

- Universal gas constant, \( R_0 = M \cdot R \)

\[
R_0 = 49,709 \text{ ft} \cdot \text{lb}/(\text{slug} \cdot \text{mol} \cdot \text{oR})
\]

\[
R_0 = 8,312 \text{ N} \cdot \text{m}/(\text{kg} \cdot \text{mol} \cdot \text{K})
\]

- For real (nonperfect) gases, \( R_0 = M \cdot z \cdot R \), where \( z = \) compressibility factor, \( z = f(p, T) \), and the equation of state is now

\[
\frac{p}{\rho} = p \cdot v = z \cdot R \cdot T
\]

Property relations for perfect gases (3)

- Dalton's law of partial pressures: each gas in a mixture exerts its own pressure as if the other were not present. Thus, each gas' pressure is governed by its own equation of state.

- Water vapor as naturally occurring in the atmosphere has a low vapor pressure. Treat it as an ideal gas with

\[
R = 2760 \text{ ft/(sec}^2\text{)oR} = 462 \text{ m}^2/(\text{s}^2\text{K})
\]

- For vapors reaching the liquid phase, obtain properties from specific tables (e.g., steam tables)

Property relations for perfect gases (4)

- Process equation: another important relationship for perfect gases:

\[
p \cdot v^n = p_i \cdot v_i^n = \text{const.}, \text{or } (p/p_i) = (\rho/\rho_i)^n = \text{const.}
\]

where \( n > 0 \), and its value depends on the process.

- Isothermal (constant temperature) process, \( n = 1 \)

- Adiabatic (no heat transfer) process.

- Isentropic (frictionless, reversible, adiabatic) process, \( n = k = c_p/c_v \), the \( c's \) are the heat capacities at constant \( p \) and at constant \( v \)
Property relations for perfect gases (5)

- See Table A.5 for values of $k$. For air at usual temps., $k = 1.4$.
- Other useful relations:

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{n-1} = \left(\frac{\rho_2}{\rho_1}\right)^{n-1} = \left(\frac{p_2}{p_1}\right)^{(n-1)/n}$$

- See Sample Problem 2.5, p. 24.

Compressibility of perfect gases (5)

- Differentiate $p\cdot v^n = \text{const.}$, for variable $v$ and $p$:

$$n\cdot p\cdot v^{n-1} \, dv + v^n \, dp = 0$$

then use definition of $E_v$:

$$E_v = n \cdot p$$

- For an isothermal process, $n = 1$, and $E_v = p$
- For an isentropic process, $n = k$, and $E_v = k \cdot p$
- See discussion in p. 25, and Sample Problem 2.6, pp. 26-27

Standard atmosphere (1)

- Need to standardize aircraft instruments.
- ICAO Standard Atmosphere (1964), extends up to 32 km (105 000 ft)
- ISO Standard Atmosphere (1973), extends up to 50 km (164 000 ft)
- U.S. Standard Atmosphere (1976), extends up to 86 km (282 000 ft or 53.4 mi)
- See Figure 2.2, p. 28

U.S. Standard atmosphere - temperature

- Troposphere: 0-11.02 km (36 200 ft)
  - $T$ decreases linearly at a rate of -6.5°C/km
- Stratosphere: 9 km (30 000 ft) thick
  - $T$ remains constant at -56.5°C (-69.7°F)
- Mesosphere:
  - $T$ increases to a max. of -2.5°C (27.5°F) at about 50 km (165 000 ft or 31 mi)
- Ionosphere:
  - $T$ again decreases

U.S. Standard atmosphere - pressure

- $P$ decreases quite rapidly and smoothly to almost zero at an altitude of 30 km (98 000 ft)
- Temperature, pressure, and other parameters of the ICAO Standard Atmosphere in Table A.3, Appendix A
- Outside of an airplane flying at 30,000 ft, the ICAO Standard Atmosphere indicates:
  - $T = -47.832°F$
  - $P = 4.372$ psia (32% of sea-level pressure)

Figure 2.2 The U.S. Standard Atmosphere, temperature, and pressure distributions.