DEPARTMENT OF MECHANICAL ENGINEERING TECHNIQUES OF POWER

Fluid Mechanics: Fundamentals of Fluid Mechanics, 7th Edition,
Bruce R. Munson. Theodore H. Okiishi. Alric P. Rothmayer
John Wiley & Sons, Inc.l, 2013

Lecture- 3
Fluid Properties
(Part B)

Dr. Dhafer Manea Hachim AL-HASNAWI
Assist Proof
Al-Furat Al-Awsat Technical University
Engineering Technical College / Najaf
email:coj.dfr@atu.edu.iq

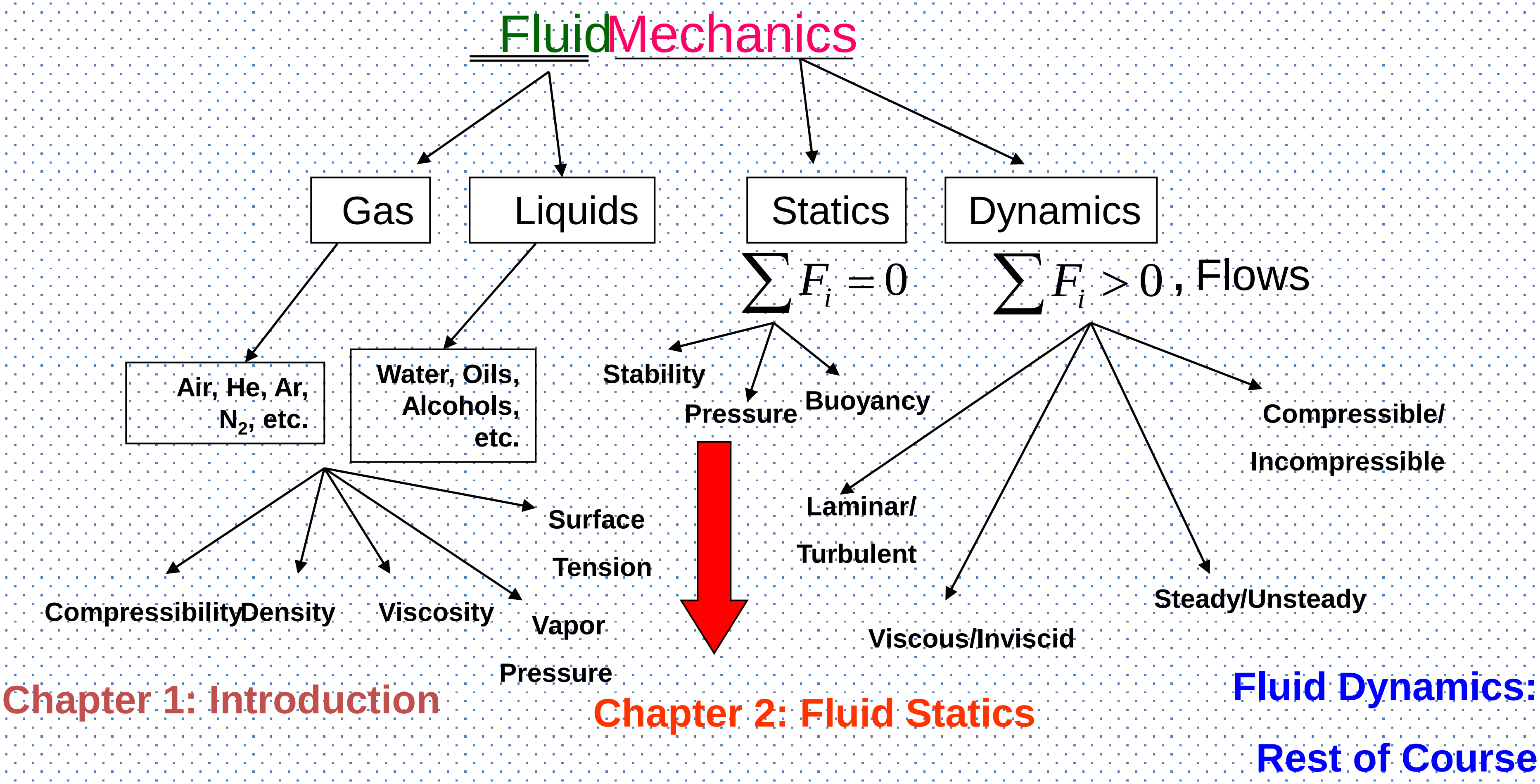
Learning Objectives

- After completing this Lecture, you should be able to:
- explain effects of fluid compressibility.
- use the concepts of viscosity, vapor pressure, and surface tension.

Outline

- Compressibility of Fluids
- Vapor Pressure
- Surface Tension

Fluid Mechanics Overview



Compressibility of Fluids: Bulk Modulus

$$E_\upsilon = -\frac{dp}{d\rho/\rho}$$

P is pressure, and ρ is the density.

- Measure of how pressure compresses the volume/density
- Units of the bulk modulus are N/m^2 (Pa) and lb/in.^{2} (psi).
- Large values of the bulk modulus indicate incompressibility
- Incompressibility indicates large pressures are needed to compress the volume slightly
- It takes 3120 psi to compress water 1% at atmospheric pressure and 60° F.
- Most liquids are incompressible for most practical engineering problems.

Compressibility of Fluids: Compression of Gases

Ideal Gas Law: $p = \rho RT$

P is pressure, ρ is the density, R is the gas constant, and T is Temperature

Isothermal Process (constant temperature):

$$\frac{p}{\rho} = constant \xrightarrow{\text{Math}} E_\upsilon = p$$

Isentropic Process (frictionless, no heat exchange):

$$\frac{p}{\rho^k} = constant \xrightarrow{\text{Math}} E_\upsilon = kp$$

k is the ratio of specific heats, c_p (constant pressure) to c_v (constant volume), and $R = c_p – c_v$.

If we consider air under at the same conditions as water, we can show that air is 15,000 times more compressible than water. However, many engineering applications allow air to be considered incompressible.

EXAMPLE 1.6 Isentropic Compression of a Gas

GIVEN A cubic foot of air at an absolute pressure of 14.7 psi is compressed isentropically to $\frac{1}{2}$ ft^3 by the tire pump shown in Fig. E1.6*a*.

FIND What is the final pressure?

SOLUTION

For an isentropic compression

$$\frac{p_i}{\rho_i^k} = \frac{p_f}{\rho_f^k}$$

where the subscripts i and f refer to initial and final states, respectively. Since we are interested in the final pressure, p_f, it follows that

$$p_f = \left(\frac{\rho_f}{\rho_i}\right)^k p_i$$

Figure E1.6*a*

As the volume, $\mathcal{V}$, is reduced by one-half, the density must double, since the mass, $m = \rho \mathcal{V}$, of the gas remains constant. Thus, with $k = 1.40$ for air

$$p_f = (2)^{1.40}(14.7 \text{ psi}) = 38.8 \text{ psi (abs)} \qquad \textbf{(Ans)}$$

COMMENT By repeating the calculations for various values of the ratio of the final volume to the initial volume, V_f/V_i, the results shown in Fig. E1.6*b* are obtained. Note that even though air is often considered to be easily compressed (at least compared to liquids), it takes considerable pressure to significantly reduce a given volume of air as is done in an automobile engine where the compression ratio is on the order of $\mathcal{V}_f/\mathcal{V}_i = 1/8 = 0.125$.

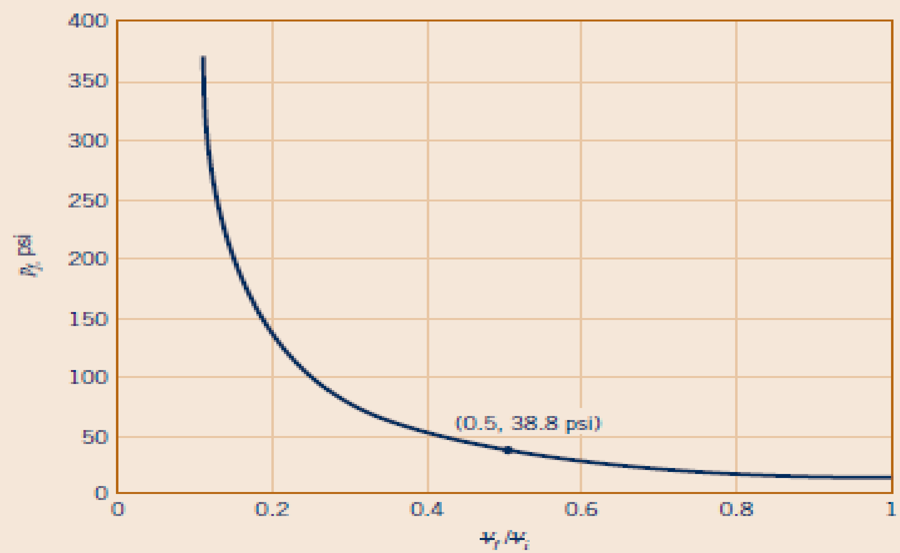


Figure E1.6*b*

Compressibility of Fluids: Speed of Sound

A consequence of the compressibility of fluids is that small disturbances introduced at a point propagate at a finite velocity. Pressure disturbances in the fluid propagate as sound, and their velocity is known as the speed of sound or the acoustic velocity, c.

$$c = \sqrt{\frac{dp}{d\rho}} \quad or \quad c = \sqrt{\frac{E_v}{\rho}}$$

Isentropic Process (frictionless, no heat exchange because):

$$c = \sqrt{\frac{kp}{\rho}}$$

Ideal Gas and Isentropic Process:

$$c = \sqrt{kRT}$$

Compressibility of Fluids: Speed of Sound

- Speed of Sound in Air at (33.3 degC) 60 °F ≈ 1117 ft/s or 300 m/s
- Speed of Sound in Water at 60 °F ≈ 4860 ft/s or 1450 m/s
- If a fluid is truly incompressible, the speed of sound is infinite, however, all fluids compress slightly.

Example: A jet aircraft flies at a speed of 250 m/s at an altitude of 10,700 m, where the temperature is -54 °C. Determine the ratio of the speed of the aircraft, V, to the speed of sound, c at the specified altitude. Assume k = 1.40

Ideal Gas and Isentropic Process:

$$c = \sqrt{kRT}$$

$$c = \sqrt{1.40 * (286.9\ \ J/kgK) * 219\ \ K}$$

$$c = 296.6\ \ m/s$$

Compressibility of Fluids: Speed of Sound

Example (Continued):

$$Ratio = \frac{V}{c}$$

$$Ratio = \frac{250\ m/s}{296.6\ m/s}$$

$$Ratio = 0.84$$

- The above ratio is known as the Mach Number, Ma
- For Ma < 1 ***Subsonic Flow***
- For Ma > 1 ***Supersonic Flow***

For Ma > 1 we see shock waves and "sonic booms":

1) Wind Tunnel Visualization known as Schlieren method
2) Condensation instigated from jet speed allowing us to see a shock wave

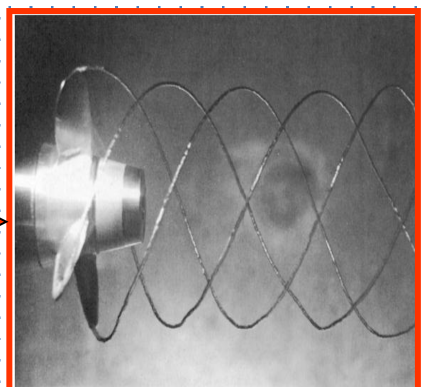
Vapor Pressure: Evaporation and Boiling

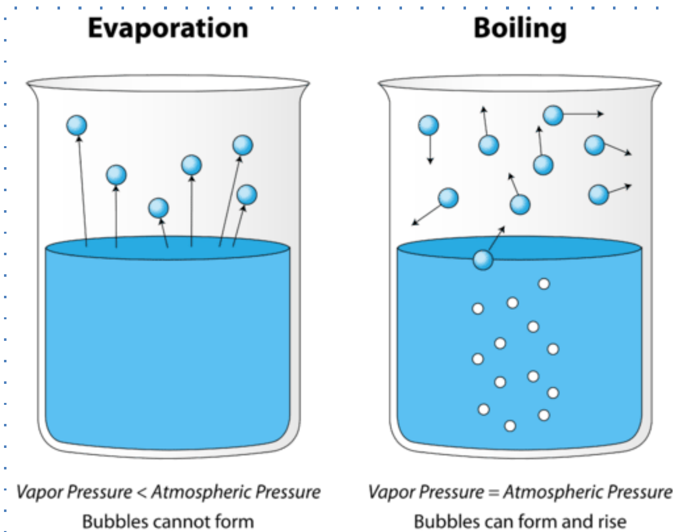
Evaporation occurs in a fluid when liquid molecules at the surface have sufficient momentum to overcome the intermolecular cohesive forces and escape to the atmosphere.

Vapor Pressure is that pressure exerted on the fluid by the vapor in a closed saturated system where the number of molecules entering the liquid are the same as those escaping. Vapor pressure depends on temperature and type of fluid.

Boiling occurs when the absolute pressure in the fluid reaches the vapor pressure. Boiling occurs at approximately 100 °C, but it is not only a function of temperature, but also of pressure. For example, in Colorado Spring, water boils at temperatures less than 100 °C.

Cavitation is a form of Boiling due to low pressure locally in a flow.





Surface Tension

At the interface between a liquid and a gas or two immiscible liquids, forces develop forming an analogous "skin" or "membrane" stretched over the fluid mass which can support weight.

This "skin" is due to an imbalance of cohesive forces. The interior of the fluid is in balance as molecules of the like fluid are attracting each other while on the interface there is a net inward pulling force.

Surface tension is the intensity of the molecular attraction per unit length along any line in the surface.

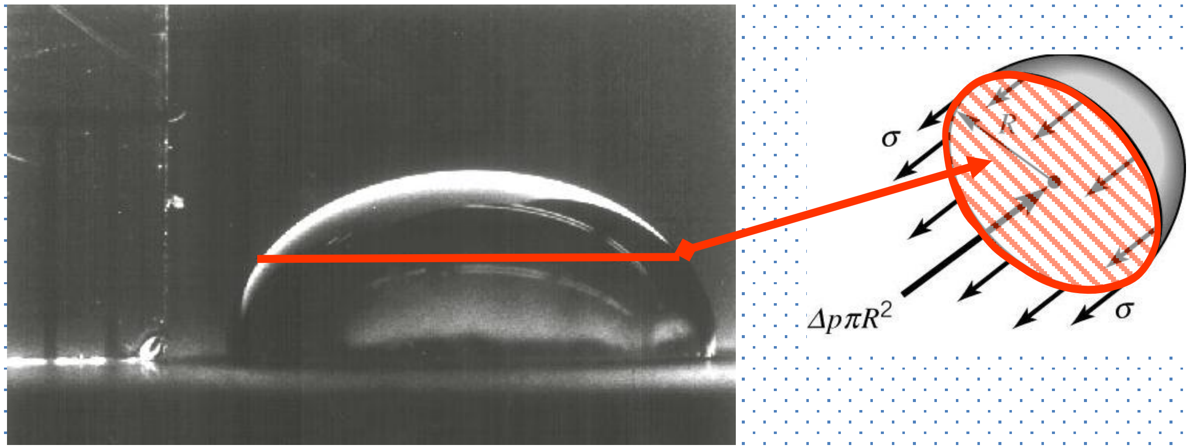
Surface tension is a property of the liquid type, the temperature, and the other fluid at the interface.

This membrane can be "broken" with a surfactant which reduces the surface tension.

Surface Tension: Liquid Drop

The pressure inside a drop of fluid can be calculated using a free-body diagram:

Real Fluid Drops | Mathematical Model



R is the radius of the droplet, σ is the surface tension, Δp is the pressure difference between the inside and outside pressure.

The force developed around the edge due to surface tension along the line:

$$F_{surface} = 2\pi R\sigma$$

Applied to Circumference

This force is balanced by the pressure difference Δp:

$$F_{pressure} = \Delta p \pi R^2$$

Applied to Area

Surface Tension: Liquid Drop

Now, equating the Surface Tension Force to the Pressure Force, we can estimate $\Delta p = p_i - p_e$:

$$\Delta p = \frac{2\sigma}{R}$$

This indicates that the internal pressure in the droplet is greater that the external pressure since the right hand side is entirely positive.

Is the pressure inside a bubble of water greater or less than that of a droplet of water?

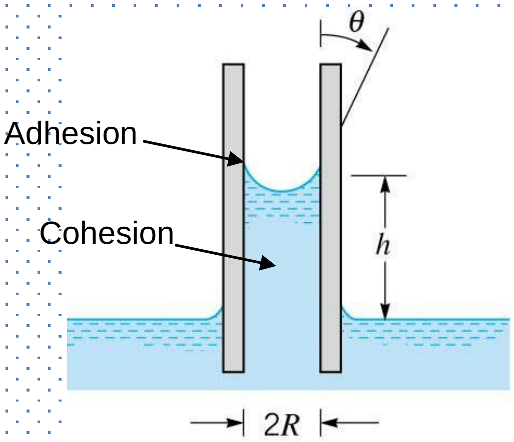
Prove to yourself the following result: $\Delta p = \frac{4\sigma}{R}$

Example: A soap of bubble 62.5 mm diameter has an internal pressure in excess of the outside pressure of 20 N/m^2. What is surface tension in the soap film?

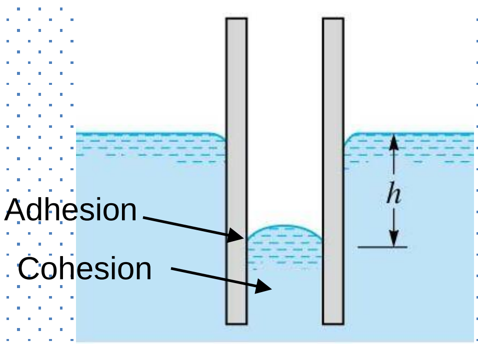
Surface Tension: Capillary Action

Capillary action in small tubes which involve a liquid-gas-solid interface is caused by surface tension. The fluid is either drawn up the tube or pushed down.

“Wetted”



“Non-Wetted”



Adhesion > Cohesion

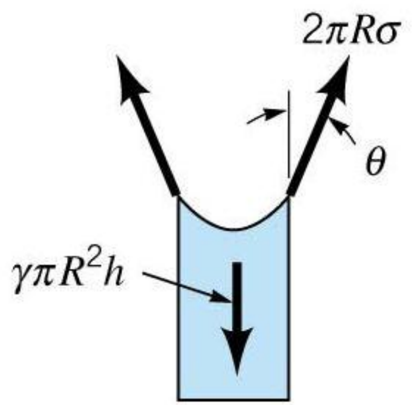
Cohesion > Adhesion

h is the height, R is the radius of the tube, θ is the angle of contact.

The weight of the fluid is balanced with the vertical force caused by surface tension.

Surface Tension: Capillary Action

Free Body Diagram for Capillary Action for a Wetted Surface:



$$F_{surface} = 2\pi R\sigma\cos\theta$$

$$W = \gamma\pi R^2 h$$

Equating the two and solving for h:

$$h = \frac{2\sigma\cos\theta}{\gamma R}$$

For clean glass in contact with water, $\theta \approx 0°$, and thus as R decreases, h increases, giving a higher rise.

For a clean glass in contact with Mercury, $\theta \approx 130°$, and thus h is negative or there is a push down of the fluid.

Surface Tension: Capillary Action

At what value of contact angle θ does the liquid-solid interface become "non-wetted"?

$\theta > 90°$

Capillary Action:

Surface tension is apparent in many practical problems such as movement of liquid through soil and other porous media, flow of thin films, formation of drops and bubbles, and the breakup of liquid jets.

EXAMPLE 1.8 Capillary Rise in a Tube

GIVEN Pressures are sometimes determined by measuring the height of a column of liquid in a vertical tube.

FIND What diameter of clean glass tubing is required so that the rise of water at 20 °C in a tube due to capillary action (as opposed to pressure in the tube) is less than $h = 1.0$ mm?

SOLUTION

From Eq. 1.22

$$h = \frac{2\sigma \cos\theta}{\gamma R}$$

so that

$$R = \frac{2\sigma \cos\theta}{\gamma h}$$

For water at 20 °C (from Table B.2), $\sigma = 0.0728$ N/m and $\gamma = 9.789$ kN/m^3. Since $\theta \approx 0°$ it follows that for $h = 1.0$ mm,

$$R = \frac{2(0.0728 \text{ N/m})(1)}{(9.789 \times 10^3 \text{ N/m}^3)(1.0 \text{ mm})(10^{-3} \text{ m/mm})} = 0.0149 \text{ m}$$

and the minimum required tube diameter, D, is

$$D = 2R = 0.0298 \text{ m} = 29.8 \text{ mm} \qquad \text{(Ans)}$$

COMMENT By repeating the calculations for various values of the capillary rise, h, the results shown in Fig. E1.8 are obtained.

Note that as the allowable capillary rise is decreased, the diameter of the tube must be significantly increased. There is always some capillarity effect, but it can be minimized by using a large enough diameter tube.

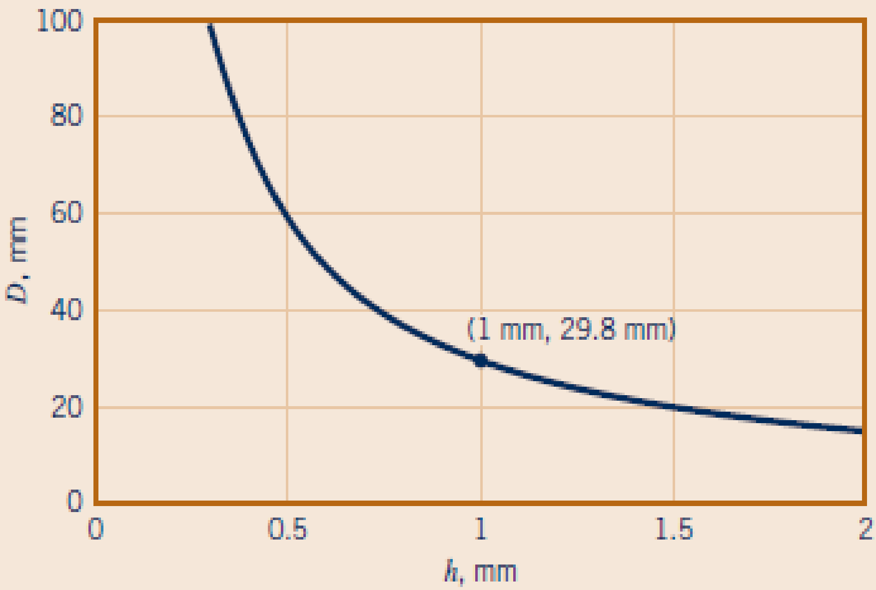


Figure E1.8