Chapter 2: Properties of Fluids

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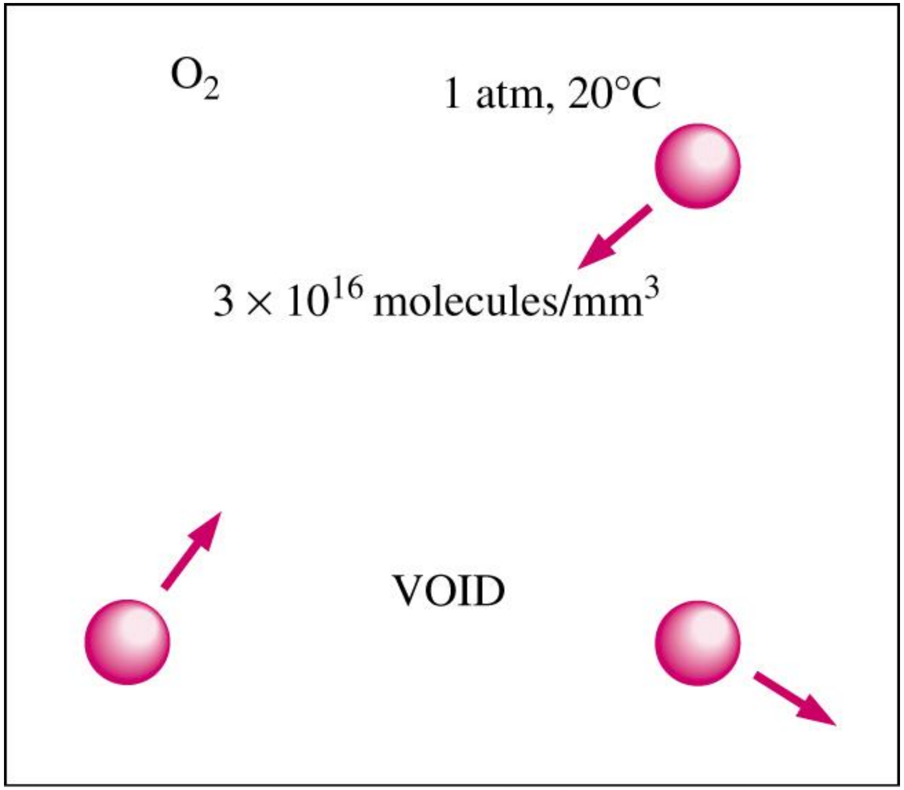
Introduction

- 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 or size 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 $e=E/m$.

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.

Fluid Properties

- **Properties Involving Mass and Weight**
- **Mass Density, ρ**
- *Mass density* is defined as the ratio of mass to volume at a point, given by
- $\rho = \lim_{\Delta V \to 0} \frac{\Delta m}{\Delta V}$ $\left(\frac{\mathrm{kg}}{\mathrm{m}^3} \right), \left(\frac{\mathrm{Ibm}}{\mathrm{ft}^3} \right)$
- $\rho_{waer} = 1000 \frac{\mathrm{kg}}{\mathrm{m}^3}$ @ 4°C
- $\rho_{air} = 1.2 \frac{\mathrm{kg}}{\mathrm{m}^3}$ @ 20°C

Fluid Properties

- **Variation in Liquid Density**
- In practice, engineers need to decide whether or not to model a fluid as

Incompressible Fluids
ρ = constant

compressible Fluids
ρ = varies

- Liquids Required High P to change ρ

→ **For most application Liquids can be considered Incompressible**

Exception:

An exception to this occurs when different solutions, such as saline and fresh water, are mixed.

Fluid Properties

- **Specific Weight,** γ (gamma)
- The gravitational force per unit volume of fluid, or simply the weight per unit volume
- $\gamma = \rho g$ N/m^3
- $\gamma_{waer=9790}\ N/\mathrm{m}^3$ @ 20℃

Fluid Properties

- **Specific Gravity, S**
- S= $\frac{\gamma_{fluid}}{\gamma_{water}} = \frac{\rho_{fluid}}{\rho_{water}}$
- **Example:**
- Calculate the specific gravity of Mercury Hg @ 20 C
- S= $\frac{\gamma_{fluid}}{\gamma_{water}}$
- $S_{Hg} = \frac{13300\ N/\mathrm{m}^3}{9790\ N/\mathrm{m}^3}$
- $S_{Hg} = 13.6$

Fluid Properties

- **Ideal Gas Law**
- The *ideal gas law* relates important thermodynamic properties, and is often used to calculate density

$$P = \rho RT$$

$$\rho = \frac{P}{RT}$$

Where:
P is the absolute pressure
T is absolute temperature
P is mass density
R is gas constant

Fluid Properties

- Example:
- Air at standard sea-level pressure (P= 101 kN/m^2) has a temperature of 4°C. What is the density of the air?

Solution

$P = \rho RT$ $\qquad\qquad$ $\rho = \frac{P}{RT}$

$$\rho = \frac{101\times10^3\ N/m^2}{287\ J/kgK(273+4)K} = 1.27\ kg/m^3$$

Fluid Properties

- **Properties Involving Thermal Energy:**
- **Specific Heat, *c***
- It is the property that describes the capacity of a substance to store thermal energy.
- The specific heat of a gas depends on the process accompanying the change in temperature
- If the *specific volume* constant it is identified C_v
- if the *Pressure* constant it is identified C_p
- $K=C_p/C_v$, K and Cp for various gases are given in Table A.2

Fluid Properties

- **Internal Energy, U:**
- It is the energy that a substance possesses because of the state of the molecular activity in the substance
- **Enthalpy, h:**
- The combination of $\underline{\mathbf{u} + p/\rho}$ is encountered frequently in equations for thermodynamics and compressible flow. It has given the name of specific enthalpy.

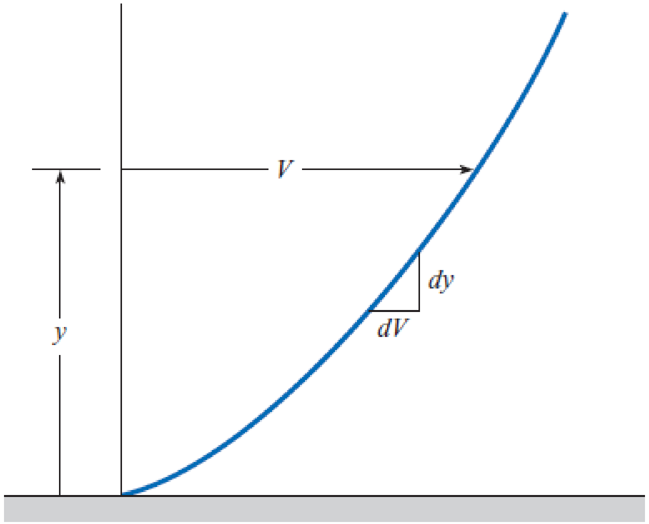
Fluid Properties

- **Viscosity, μ:**
- It is a measure of a fluid's resistance to deformation under shear stress.
- $\tau = \mu \frac{dV}{dy}$

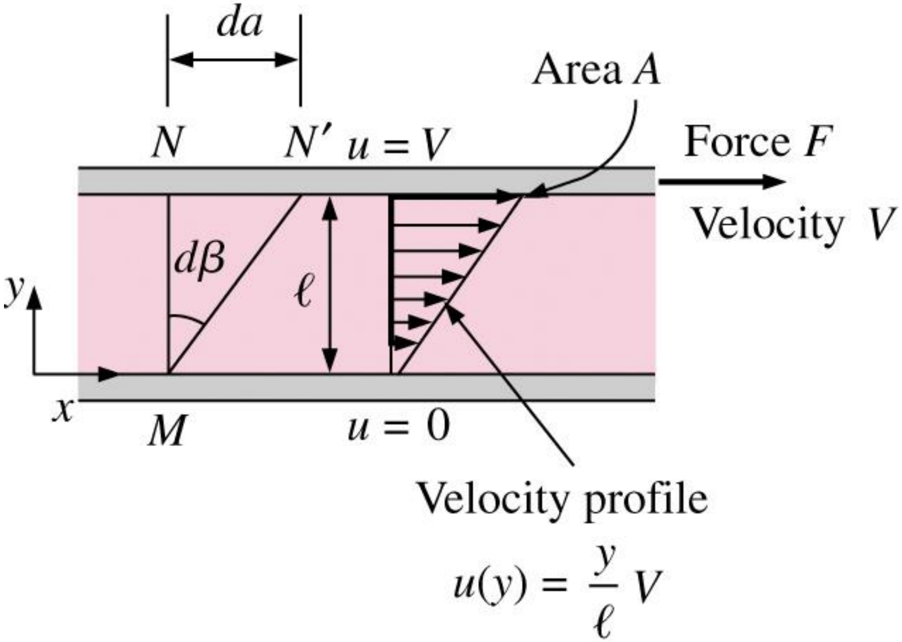
$$\mu = \frac{\tau}{dV/dy}$$

Where:
τ is the shear stress =F/A
μ is viscosity
$\frac{dV}{dy}$ the velocity gradient

The unit is:
$N.s/m^2$



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**.

Fluid Properties

- **Kinematic Viscosity,** υ (nu):
- **It is the ratio of viscosity to the mass density**
- $\upsilon = \frac{\mu}{\rho}$
- the units is → m^2/s or ft^2/s

Temperature Dependency

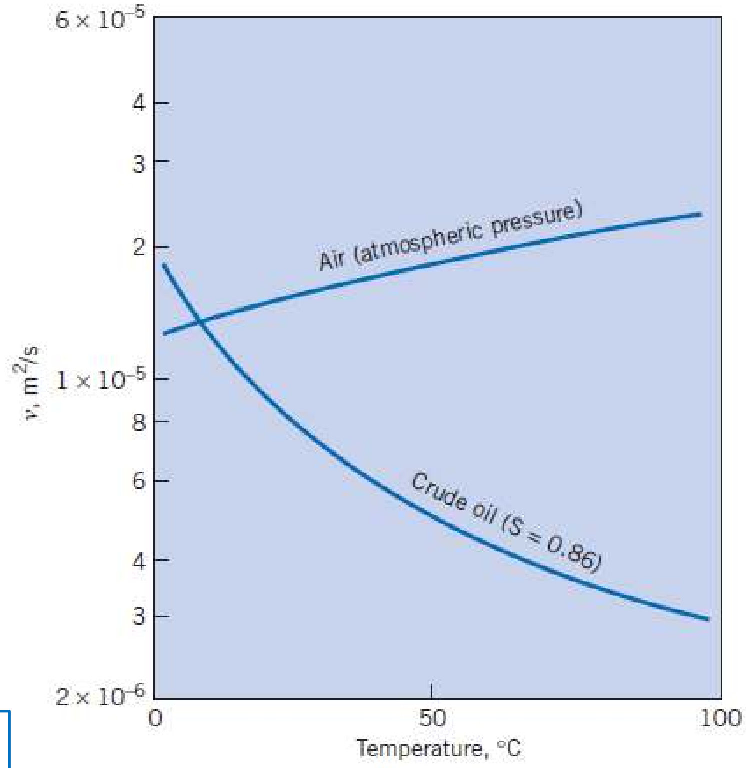
The viscosity of liquids decreases as the temperature increases.

The viscosity of Air increases as the temperature increases.

the variation of liquid viscosity with temperature is

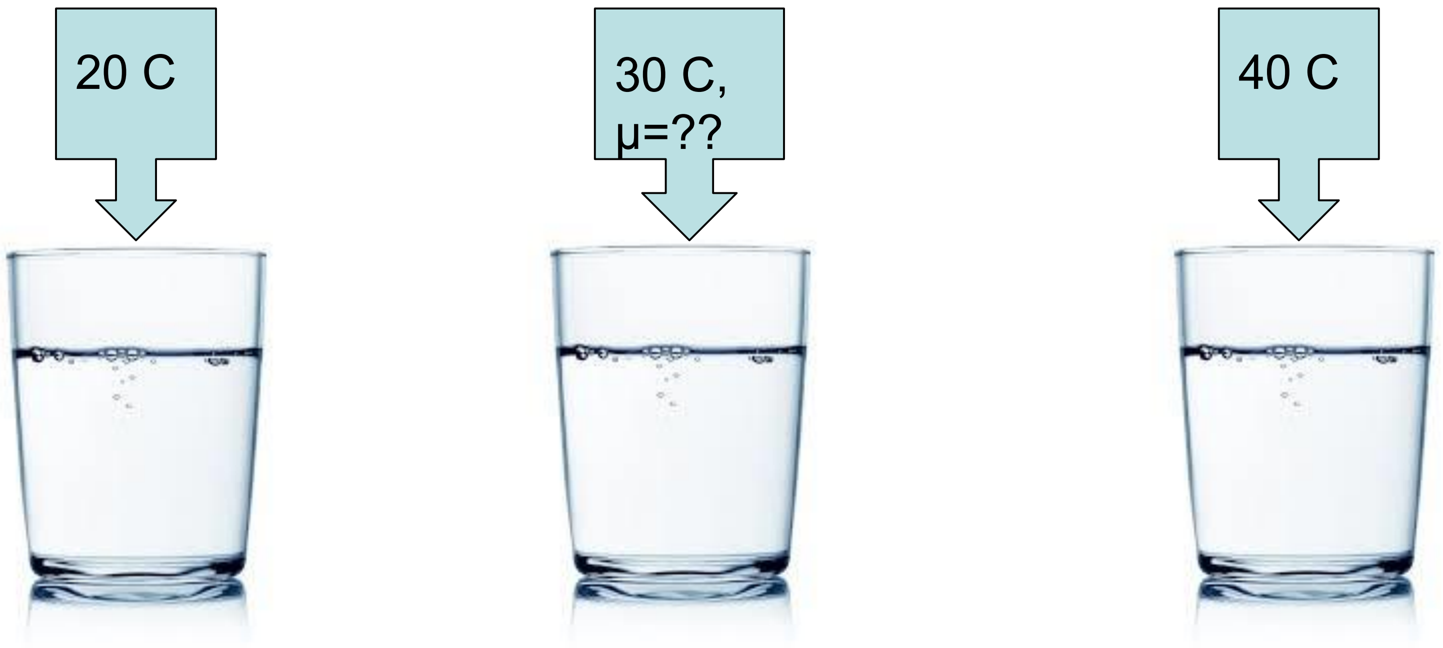
$$\mu = Ce^{b/T}$$

(*C* and *b* are empirical constants that require viscosity data at two temperatures for evaluation)



Fluid Properties

- Example:
  - The dynamic viscosity of water at 20°C is $1 \times 10^{-3}\ N.s/m^2$ and the viscosity at 40°C is $6.53 \times 10^{-4}\ N.s/m^2$ Using Eq. (2.9), estimate the viscosity at 30°C.



Fluid Properties

- Solution:

Find: The viscosity at 30°C by interpolation.

Properties:
a) Water at 20°C, $\mu = 1.00 \times 10^{-3}\ \mathrm{N \cdot s/m^2}$.
b) Water at 40°C, $\mu = 6.53 \times 10^{-4}\ \mathrm{N \cdot s/m^2}$.

1. Logarithm of Eq. (2.9)

$$\mu = Ce^{b/T}$$

$$\ln \mu = \ln C + b/T \quad \text{——— } 1$$

بالتعويض في 1 مرة عند 20 درجة ومرة عند 40 درجة

$$-6.908 = \ln C + 0.00341 b \quad \text{——— } 2$$

$$-7.334 = \ln C + 0.00319 b \quad \text{——— } 3$$

0.426 = 0.00022 b

b = 0.426/0.00022 =1936 K

بالتعويض في 2 أو 3

-6.908= lnC+ 0.0034 (1936)

lnC=-6.908 – (0.0034 * 1936)
ln C= -13.51

$$C = e^{-13.51} = 1.357 \times 10^{-6}$$

4. Substitution back in exponential equation

$$\mu = Ce^{b/T} \Rightarrow \mu = 1.357 \times 10^{-6} e^{1936/T}$$

At 30°C

$$\mu = \boxed{8.08 \times 10^{-4}\ \mathrm{N \cdot s/m^2}}$$

Fluid Properties

- An estimate of the variation of gas viscosity with temperature is *Sutherland's equation:*
- $\frac{\mu}{\mu_0} = (\frac{T}{T_0})^{3/2} \frac{T_0+S}{T+S}$

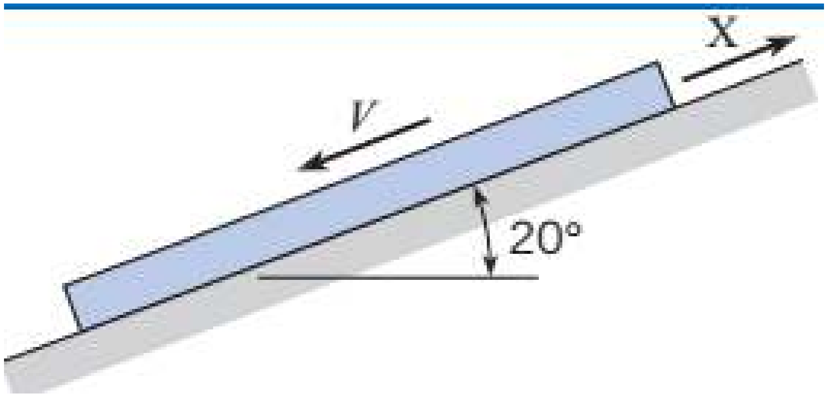
Where:

- μ_0 the viscosity at temperature T_0
- *S* is Sutherland's constant
- Sutherland's constant for air is 111 K
- All temperatures are absolute.

Note: Sutherland's equation for air yields viscosities with an accuracy of 2% for temperatures between 170 K and 1900 K.

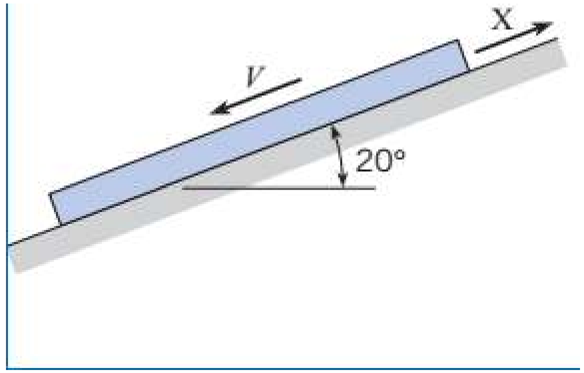
Example 2:

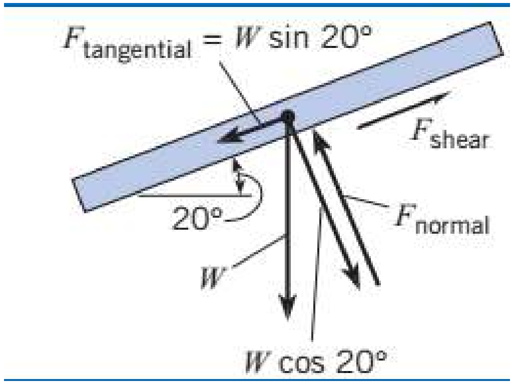
- A board 1 m by 1 m that weighs 25 N slides down an inclined ramp (slope 20°) with a velocity of 2.0 m/s The board is separated from the ramp by a thin film of oil with a viscosity of 0.05 $N.s/m^2$ Neglecting edge effects, calculate the space between the board and the ramp.



Fluid Properties

- Solution:





Find: Space (in m) between the board and the ramp.

Properties: Oil, $\mu = 0.05 \ \text{N} \cdot \text{s/m}^2$.

1. Freebody analysis

$$F_{\text{tangential}} = F_{\text{shear}}$$

$$W \sin 20° = \tau A$$

$$W \sin 20° = \mu \frac{dV}{dy} A$$

2. Substitution of dV/dy as $\Delta V/\Delta y$

$$W \sin 20° = \mu \frac{\Delta V}{\Delta y} A$$

3. Solution for Δy

$$\Delta y = \frac{\mu \Delta V A}{W \sin 20°}$$

$$\Delta y = \frac{0.05 \ \text{N} \cdot \text{s/m}^2 \times 0.020 \ \text{m/s} \times 1 \ \text{m}^2}{25 \ \text{N} \times \sin 20°}$$

$$\Delta y = 0.000117 \ \text{m}$$

$$\Delta y = \boxed{0.117 \ \text{mm}}$$

Fluid Properties

■ Newtonian versus Non-Newtonian Fluids

❑ Fluids for which the shear stress is directly proportional to the rate of strain is **called Newtonian**

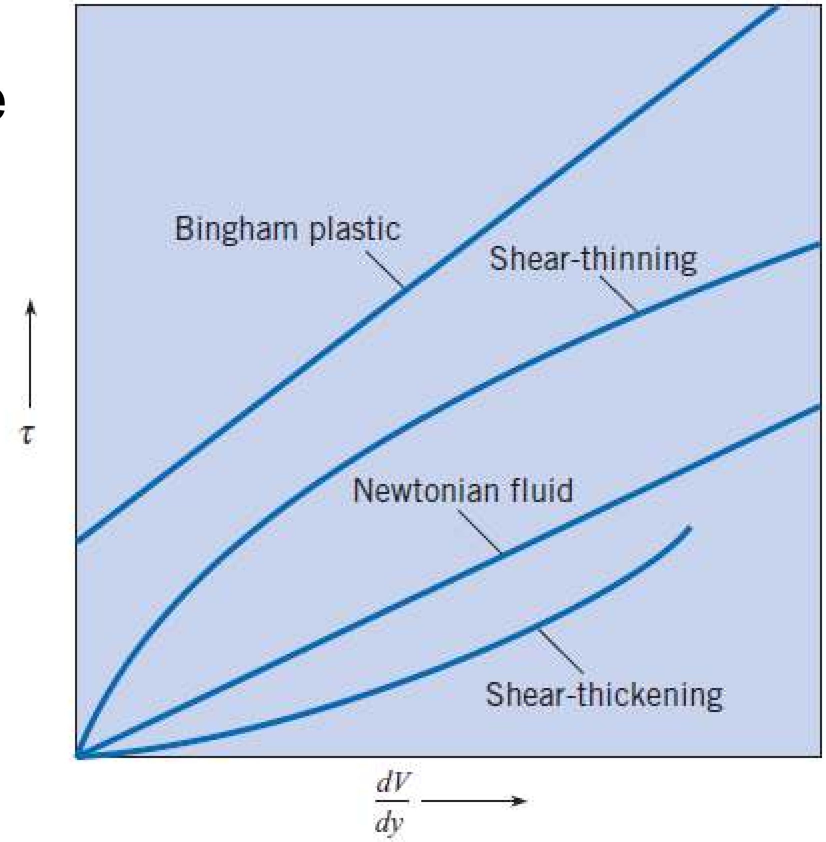
❑ **non-Newtonian Fluid**

❑ The shear stress is no directly proportional to the rate of strain.

❑ **Sher-thinning Fluids**

❑ **Sher-thickening Fluids**

❑ **Bingham plastic**



Fluid Properties

- **Bulk Modulus of Elasticity**
- *It* is a property that relates changes in pressure to changes in volume

$$E_v = -\frac{dp}{dV/V} = \frac{Change\ in\ Pressure}{Fraction\ a\ change\ in\ volume}$$

- $M = \rho V$, $dM = \rho dV + vdp = 0$
  $\mathrm{Vd\rho} = -dV$, $\mathrm{d\rho/\rho} = -dV/V$
- $E_v = \frac{dp}{\mathrm{d\rho/\rho}} = \frac{Change\ in\ Pressure}{Fraction\ a\ change\ in\ density}$

Fluid Properties

- ## Bulk Modulus of Elasticity
- The elasticity of an ideal gas is proportional to the pressure, according to the ideal gas law. For an isothermal (constant-temperature) process.
- $\frac{dp}{\rho} = \mathrm{RT}$
- $E_v = \rho\frac{dp}{d\rho} = \rho RT = P$
- For an adiabatic Process
- $E_v = kP$

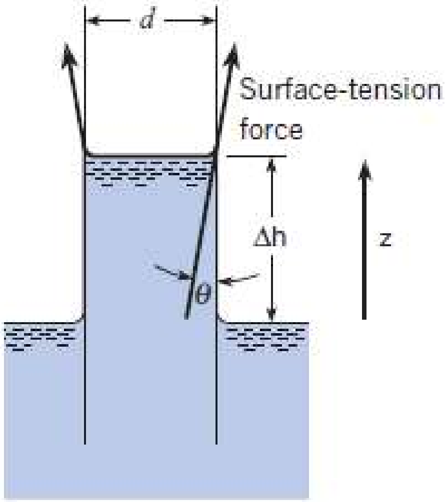
Fluid Properties

■ Surface Tension

- ■ is a material property whereby a liquid at a material interface exerts a force per unit length along the surface.
- ■ $F_\sigma = \sigma L$ where L=surface tension act

❑ Capillary action:

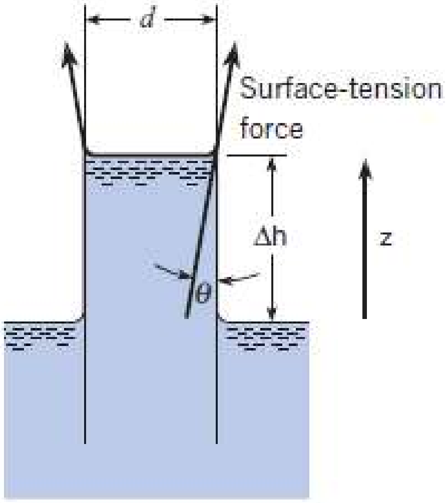
rise above a static water level at atmospheric pressure in a small tube



Capillary action

- Example :
- To what height above the reservoir level will water (at 20°C) rise in a glass tube, such as that shown in Fig. 2.7, if the inside diameter of the tube is 1.6 mm?

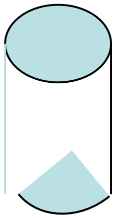
  Solution:

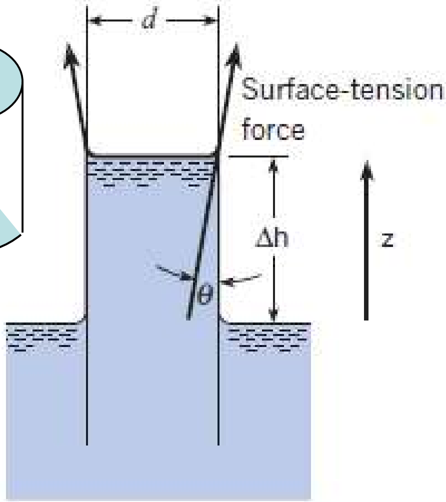


Solution:

From Table A5. Foe Water at 20 C

W= m * g
= V * ρ * g
= A* Δh * ρ *g
= (πd²/4) Δh *γ





$\sigma = 0.073\ \mathrm{N/m}$

$\gamma = 9790\ \mathrm{N/m^3}.$

Because the contact angle θ for water against glass is so small, it can be assumed to be 0°; therefore $\cos\theta \approx 1$. Therefore:

1. Force balance: Weight o
surface tension force (up).

$$F_{\sigma,z} - W = 0$$

$$\sigma \pi d \cos\theta - \gamma(\Delta h)(\pi d^2/4) = 0$$

Because the contact angle θ for water against glass is so small, it can be assumed to be 0°; therefore $\cos\theta \approx 1$. Therefore:

$$\sigma \pi d - \gamma(\Delta h)\left(\frac{\pi d^2}{4}\right) = 0$$

$$\Delta h = \frac{4\sigma}{\gamma d} = \frac{4 \times 0.073\ \mathrm{N/m}}{9790\ \mathrm{N/m^3} \times 1.6 \times 10^{-3}\ \mathrm{m}} = \boxed{18.6\ \mathrm{mm}}$$

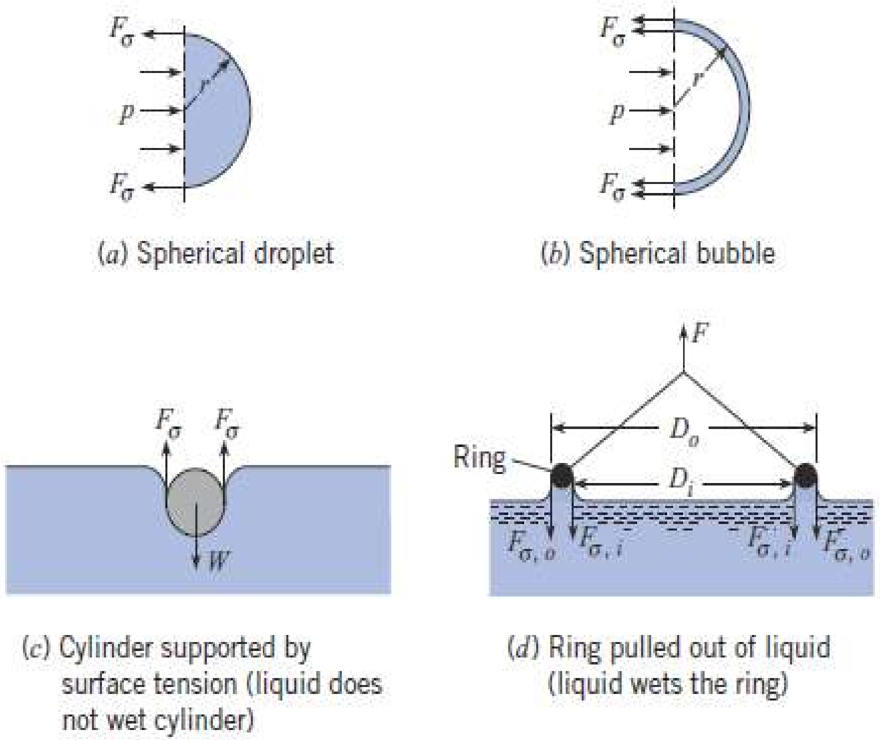
Surface Tension, (continued)

spherical droplet of radius *r*

$F_\sigma = \sigma L = \text{PA}$

$P = \frac{2\sigma}{r}$

- a bubble of radius *r* that has internal and external surfaces and the surface tension force acts on both surfaces, so
- $P = \frac{2\sigma}{r}$
- In a cylinder The maximum weight the surface tension can support is:
- $W = 2F_\sigma = 2\sigma L$
- ring being pulled out of a liquid
- $F_\sigma = F_{\sigma i} + F_{\sigma o} = \pi\sigma(D_i + D_o)$



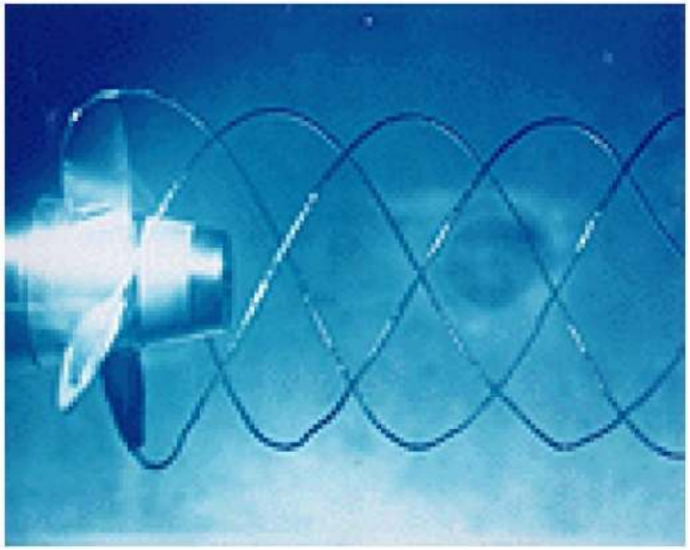
(*a*) Spherical droplet

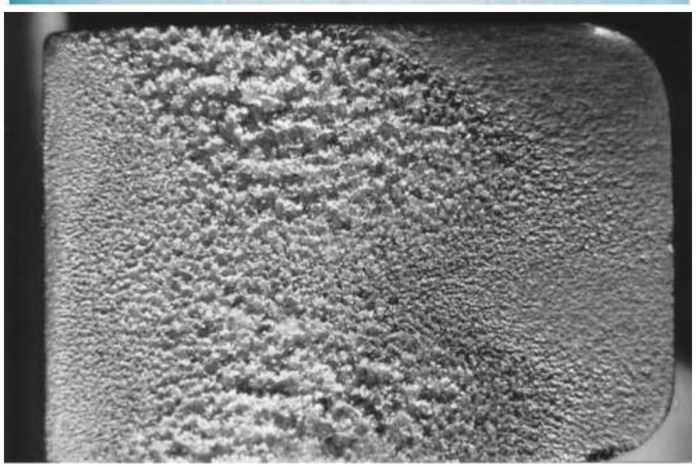
(*b*) Spherical bubble

(*c*) Cylinder supported by surface tension (liquid does not wet cylinder)

(*d*) Ring pulled out of liquid (liquid wets the ring)

Vapor Pressure and Cavitation





- **Vapor Pressure** P_v The pressure at which a liquid will vaporize, or boil, at a given temperature
  If P drops below P_v, liquid is locally vaporized, creating cavities of vapor. (CAVITATION)
- 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.