

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 $e = E/m$.

Introduction

Intensive properties and
Extensive properties

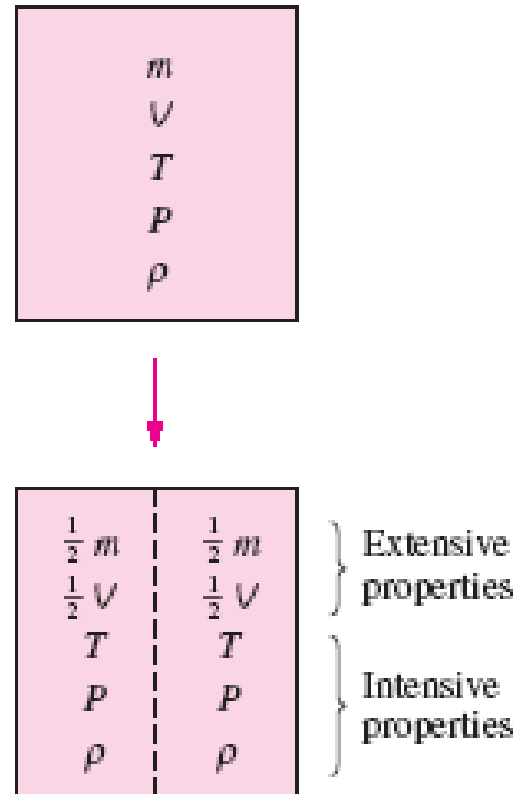
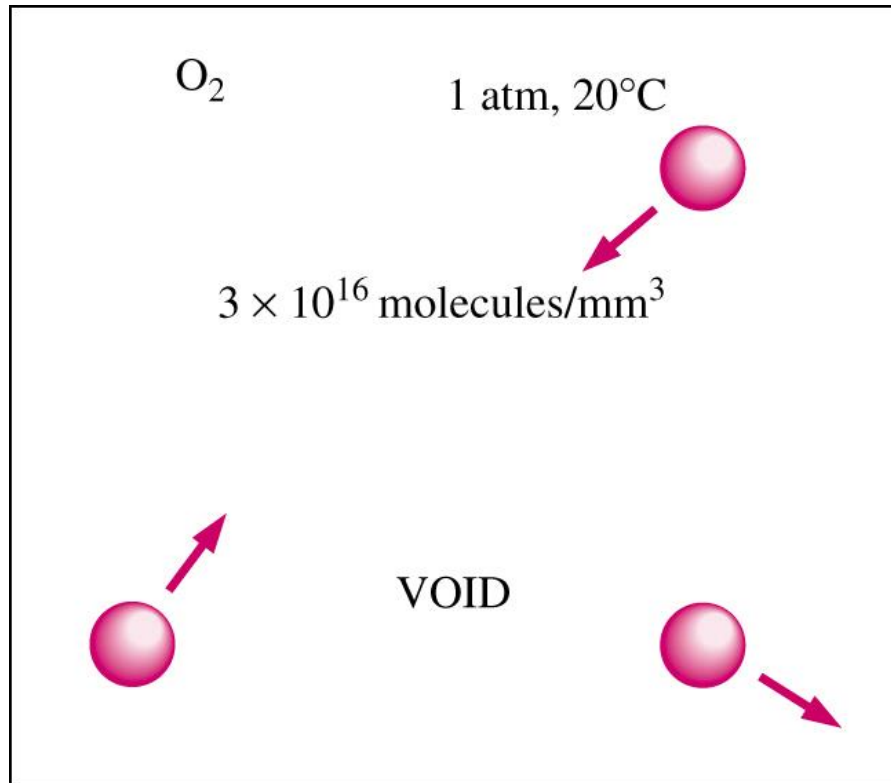


FIGURE 2–1

Criteria to differentiate intensive and extensive properties.

Continuum



$D \text{ of } O_2 \text{ molecule} = 3 \times 10^{-10} \text{ m}$
 $\text{mass of } O_2 = 5.3 \times 10^{-26} \text{ kg}$
 $\text{Mean free path} = 6.3 \times 10^{-8} \text{ m}$
 at 1 atm pressure and 20°C

- 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.
- In this text we limit our consideration to substances that can be modeled as a continuum.

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 and Specific Gravity

TABLE 2–1

Specific gravities of some
substances at 0°C

Substance	SG
Water	1.0
Blood	1.05
Seawater	1.025
Gasoline	0.7
Ethyl alcohol	0.79
Mercury	13.6
Wood	0.3–0.9
Gold	19.2
Bones	1.7–2.0
Ice	0.92
Air (at 1 atm)	0.0013

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.

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

- where P is the absolute pressure, v is the specific volume, T is the thermodynamic (absolute) temperature, ρ is the density, and R is the gas constant.

Density of Ideal Gases

- The gas constant R is different for each gas and is determined from $R = R_u / M$,
- where R_u is the **universal gas constant** whose value is $R_u = 8.314 \text{ kJ/kmol} \cdot \text{K} = 1.986 \text{ Btu/lbmol} \cdot \text{R}$, and M is the molar mass (also called *molecular weight*) of the gas. The values of R and M for several substances are given in Table A–1.

Density of Ideal Gases

- The thermodynamic temperature scale
 - In the SI is the **Kelvin scale**, designated by K.
 - In the English system, it is the **Rankine scale**, and the temperature unit on this scale is the **rankine**, R.
- Various temperature scales are related to each other by

$$T(\text{K}) = T(^{\circ}\text{C}) + 273.15 \quad (2-5)$$

$$T(\text{R}) = T(^{\circ}\text{F}) + 459.67 \quad (2-6)$$

It is common practice to round the constants 273.15 and 459.67 to 273 and 460, respectively.

Density of Ideal Gases

- For an ideal gas of volume V , mass m , and number of moles $N = m/M$, the ideal-gas equation of state can also be written as

$$PV = mRT \text{ or } PV = NR_u T.$$

- For a fixed mass m , writing the ideal-gas relation twice and simplifying, the properties of an ideal gas at two different states are related to each other by

$$P_1 V_1 / T_1 = P_2 V_2 / T_2.$$

Density of Ideal Gases

- An ideal gas is a hypothetical substance that obeys the relation $Pv = RT$.
- 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.

Density of Ideal Gases

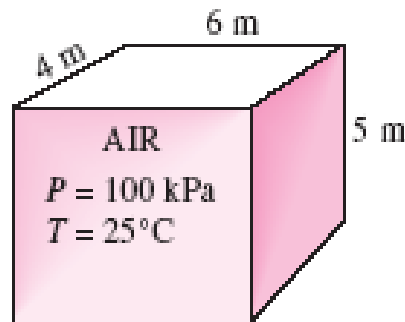


FIGURE 2–4

Schematic for Example 2–1.

EXAMPLE 2–1 Density, Specific Gravity, and Mass of Air in a Room

Determine the density, specific gravity, and mass of the air in a room whose dimensions are 4 m \times 5 m \times 6 m at 100 kPa and 25°C (Fig. 2–4).

Solution The density, specific gravity, and mass of the air in a room are to be determined.

Assumptions At specified conditions, air can be treated as an ideal gas.

Properties The gas constant of air is $R = 0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}$.

Analysis The density of air is determined from the ideal-gas relation $P = \rho RT$ to be

$$\rho = \frac{P}{RT} = \frac{100 \text{ kPa}}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(25 + 273) \text{ K}} = \mathbf{1.17 \text{ kg/m}^3}$$

Then the specific gravity of air becomes

$$\text{SG} = \frac{\rho}{\rho_{\text{H}_2\text{O}}} = \frac{1.17 \text{ kg/m}^3}{1000 \text{ kg/m}^3} = \mathbf{0.00117}$$

Finally, the volume and the mass of air in the room are

$$V = (4 \text{ m})(5 \text{ m})(6 \text{ m}) = 120 \text{ m}^3$$

$$m = \rho V = (1.17 \text{ kg/m}^3)(120 \text{ m}^3) = \mathbf{140 \text{ kg}}$$

Vapor Pressure and Cavitation

Pressure – temperature relation at (liquid – solid) phase change

■ At a given pressure, the temperature at which a pure substance changes phase is called the **saturation temperature** T_{sat} .

■ Likewise, at a given temperature, the pressure at which a pure substance changes phase is called the **saturation pressure** P_{sat} .

■ At an absolute pressure of 1 standard atmosphere (1 atm or 101.325 kPa), for example, the saturation temperature of water is 100°C. Conversely, at a temperature of 100°C, the saturation pressure of water is 1 atm.

Vapor Pressure and Cavitation

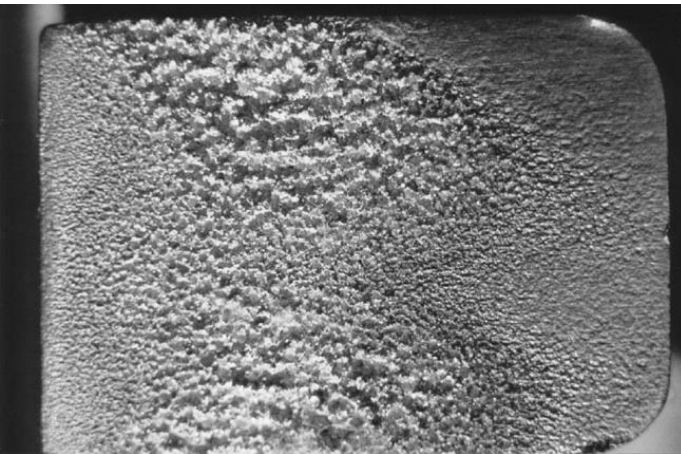
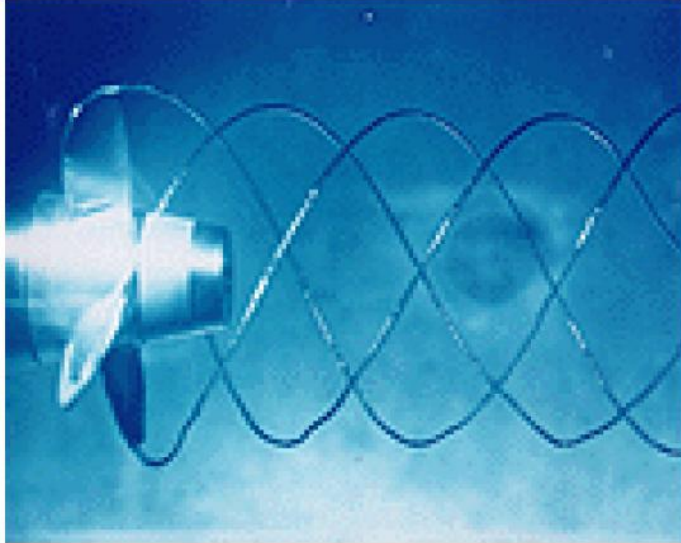
Water boils at 134°C in a pressure cooker operating at 3 atm absolute pressure, but it boils at 93°C in an ordinary pan at a 2000-m elevation, where the atmospheric pressure is 0.8 atm. The saturation (or vapor) pressures are given in Appendices 1 and 2 for various substances.

TABLE 2–2

Saturation (or vapor) pressure of water at various temperatures

Temperature $T, ^{\circ}\text{C}$	Saturation Pressure $P_{\text{sat}}, \text{kPa}$
–10	0.260
–5	0.403
0	0.611
5	0.872
10	1.23
15	1.71
20	2.34
25	3.17
30	4.25
40	7.38
50	12.35
100	101.3 (1 atm)
150	475.8
200	1554
250	3973
300	8581

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*
- **Partial pressure** is defined as *the pressure of a gas or vapor in a mixture with other gases.*
- 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.

Vapor Pressure and Cavitation

EXAMPLE 2-2 Minimum Pressure to Avoid Cavitation

In a water distribution system, the temperature of water is observed to be as high as 30°C. Determine the minimum pressure allowed in the system to avoid cavitation.

SOLUTION The minimum pressure in a water distribution system to avoid cavitation is to be determined.

Properties The vapor pressure of water at 30°C is 4.25 kPa.

Analysis To avoid cavitation, the pressure anywhere in flow should not be allowed to drop below the vapor (or saturation) pressure at the given temperature. That is,

$$P_{\min} = P_{\text{sat}@30^\circ\text{C}} = 4.25 \text{ kPa}$$

Therefore, the pressure should be maintained above 4.25 kPa everywhere in the flow.

Discussion Note that the vapor pressure increases with increasing temperature, and thus the risk of cavitation is greater at higher fluid temperatures.

Energy and Specific Heats

- Total energy E (or e on a unit mass basis) 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).

Energy and Specific Heats

Microscopic energy

- Internal energy U (or u on a unit mass basis) 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).
where Pv is the *flow energy*, also called the *flow work*, which is the energy per unit mass needed to move the fluid and maintain flow.
- Note that enthalpy is a quantity per unit mass, and thus it is a *specific* property.

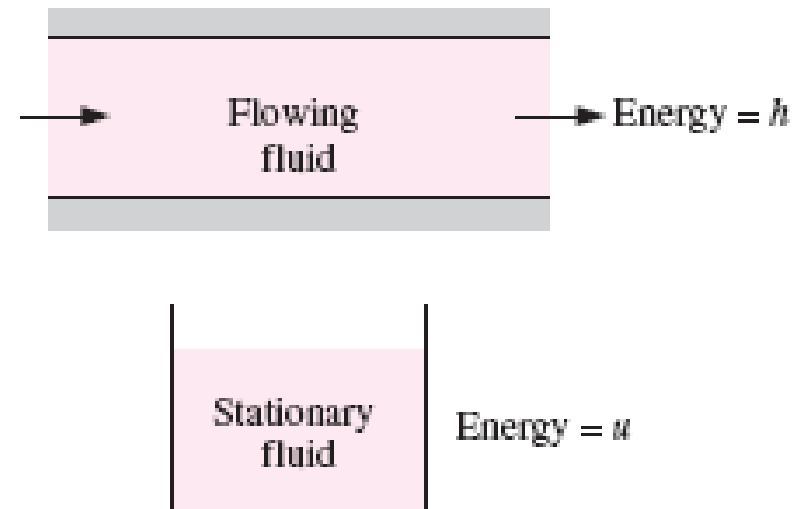


FIGURE 2-6

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 fluid per unit mass.

Energy and Specific Heats

- Macroscopic energy
 - Kinetic energy $ke = V^2/2$
 - Potential energy $pe = gz$
- In the absence of magnetic, electric, and surface tension, a system is called a simple compressible system. The total energy of a simple compressible system consists of internal, kinetic, and potential energies.
- On a unit-mass basis, it is expressed as $e = u + ke + pe$. The fluid entering or leaving a control volume possesses an additional form of energy—the *flow energy* P/ρ . Then the total energy of a **flowing fluid** on a unit-mass basis becomes

$$e_{\text{flowing}} = P/\rho + e = h + ke + pe = h + V^2/2 + gz.$$

Energy and Specific Heats

- By using the enthalpy instead of the internal energy to represent the energy of a flowing fluid, one does not need to be concerned about the flow work. The energy associated with pushing the fluid is automatically taken care of by enthalpy. In fact, this is the main reason for defining the property enthalpy.
- *The changes of internal energy and enthalpy of an ideal gas are expressed as*

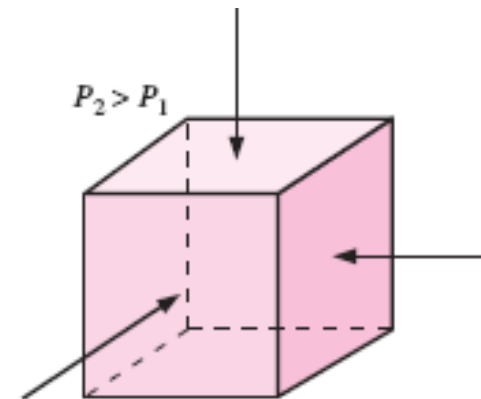
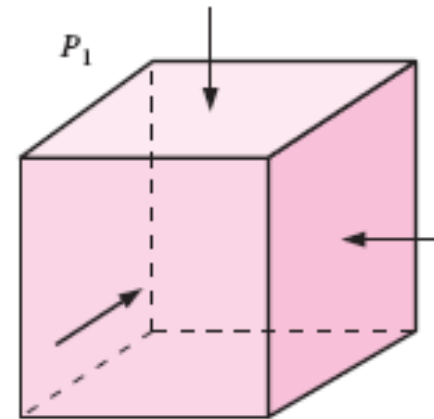
$$du=c_vdT \quad \text{and} \quad dh=c_pdT$$

where c_v and c_p are the constant-volume and constant-pressure specific heats of the ideal gas.

- For *incompressible substances*, c_v and c_p are identical.

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 $P \uparrow$



Coefficient of Compressibility

- Need fluid properties that relate volume changes to changes in P and T .

- Coefficient of compressibility

$$\kappa = -v \left(\frac{\partial P}{\partial v} \right)_T = \rho \left(\frac{\partial P}{\partial \rho} \right)_T \quad \text{(or **bulk modulus of compressibility** or **bulk modulus of elasticity**)}$$

- κ must have the dimension of pressure (Pa or psi).
- What is the coefficient of compressibility of a truly incompressible substance ? ($v=\text{constant}$). is infinity

Coefficient of Compressibility

- A large κ implies incompressible.
- This is typical for liquids considered to be *incompressible*.
- For example, the pressure of water at normal atmospheric conditions must be raised to **210 atm** to compress it **1 percent**, corresponding to a coefficient of compressibility value of $\kappa = 21,000 \text{ atm}$.

Coefficient of Compressibility

- Small density changes in liquids can still cause interesting phenomena in piping systems such as the ***water hammer***—characterized by a sound that resembles the sound produced when a pipe is “hammered.” This occurs when a liquid in a piping network encounters an abrupt flow restriction (such as a closing valve) and is locally compressed. The acoustic waves produced strike the pipe surfaces, bends, and valves as they propagate and reflect along the pipe, causing the pipe to vibrate and produce the familiar sound.

Coefficient of Compressibility

- Differentiating $\rho = 1/v$ gives $d\rho = -dv/v^2$; therefore, $d\rho/\rho = -dv/v$
- For an ideal gas, $P = \rho RT$ and $(\partial P/\partial \rho)_T = RT = P/\rho$, and thus

$$\kappa_{\text{ideal gas}} = P \quad (\text{Pa})$$

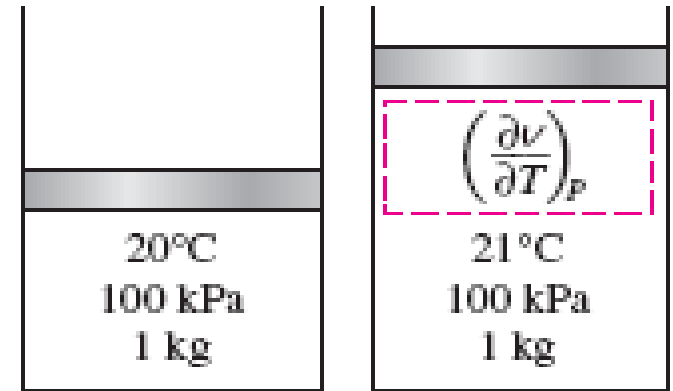
- The inverse of the coefficient of compressibility is called the **isothermal compressibility** α and is expressed as

$$\alpha = \frac{1}{\kappa} = -\frac{1}{v} \left(\frac{\partial v}{\partial P} \right)_T = \frac{1}{\rho} \left(\frac{\partial \rho}{\partial P} \right)_T \quad (1/\text{Pa})$$

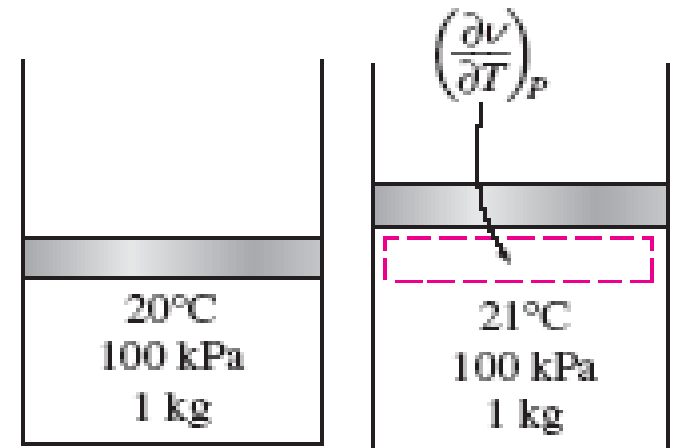
Coefficient of Volume Expansion

- The density of a fluid depends more strongly on temperature than it does on pressure.
- To represent the *variation of the density of a fluid with temperature at constant pressure*. The Coefficient of volume expansion (or volume expansivity) is defined as

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



(a) A substance with a large β



(b) A substance with a small β

Coefficient of Volume Expansion

- For an ideal gas, $\beta_{\text{ideal gas}} = 1/T$ (1/K)
- In the study of natural convection currents, the condition of the main fluid body that surrounds the finite hot or cold regions is indicated by the subscript “infinity” to serve as a reminder that this is the value at a distance where the presence of the hot or cold region is not felt. In such cases, the volume expansion coefficient can be expressed approximately as

$$\beta \approx -\frac{(\rho_{\infty} - \rho)/\rho}{T_{\infty} - T} \quad \text{or} \quad \rho_{\infty} - \rho = \rho\beta(T - T_{\infty})$$

- where ρ_{∞} is the density and T_{∞} is the temperature of the quiescent fluid away from the confined hot or cold fluid pocket.

Coefficient of Compressibility

- The combined effects of pressure and temperature changes on the volume change of a fluid can be determined by taking the specific volume to be a function of T and P . Differentiating $v = v(T, P)$ and using the definitions of the compression and expansion coefficients α and β give

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

Coefficient of Compressibility

EXAMPLE 2-3 Variation of Density with Temperature and Pressure

Consider water initially at 20°C and 1 atm. Determine the final density of water (a) if it is heated to 50°C at a constant pressure of 1 atm, and (b) if it is compressed to 100-atm pressure at a constant temperature of 20°C. Take the isothermal compressibility of water to be $\alpha = 4.80 \times 10^{-5} \text{ atm}^{-1}$.

SOLUTION Water at a given temperature and pressure is considered. The densities of water after it is heated and after it is compressed are to be determined.

Assumptions 1 The coefficient of volume expansion and the isothermal compressibility of water are constant in the given temperature range. 2 An approximate analysis is performed by replacing differential changes in quantities by finite changes.

Properties The density of water at 20°C and 1 atm pressure is $\rho_1 = 998.0 \text{ kg/m}^3$. The coefficient of volume expansion at the average temperature of $(20 + 50)/2 = 35^\circ\text{C}$ is $\beta = 0.337 \times 10^{-3} \text{ K}^{-1}$. The isothermal compressibility of water is given to be $\alpha = 4.80 \times 10^{-5} \text{ atm}^{-1}$.

Coefficient of Compressibility

Analysis When differential quantities are replaced by differences and the properties α and β are assumed to be constant, the change in density in terms of the changes in pressure and temperature is expressed approximately as (Eq. 2-23)

$$\Delta\rho = \alpha\rho \Delta P - \beta\rho \Delta T$$

(a) The change in density due to the change of temperature from 20°C to 50°C at constant pressure is

$$\begin{aligned}\Delta\rho &= -\beta\rho \Delta T = -(0.337 \times 10^{-3} \text{ K}^{-1})(998 \text{ kg/m}^3)(50 - 20) \text{ K} \\ &= -10.0 \text{ kg/m}^3\end{aligned}$$

Noting that $\Delta\rho = \rho_2 - \rho_1$, the density of water at 50°C and 1 atm is

$$\rho_2 = \rho_1 + \Delta\rho = 998.0 + (-10.0) = \mathbf{988.0 \text{ kg/m}^3}$$

Coefficient of Compressibility

which is almost identical to the listed value of 988.1 kg/m^3 at 50°C in Table A-3. This is mostly due to β varying with temperature almost linearly, as shown in Fig. 2-10.

(b) The change in density due to a change of pressure from 1 atm to 100 atm at constant temperature is

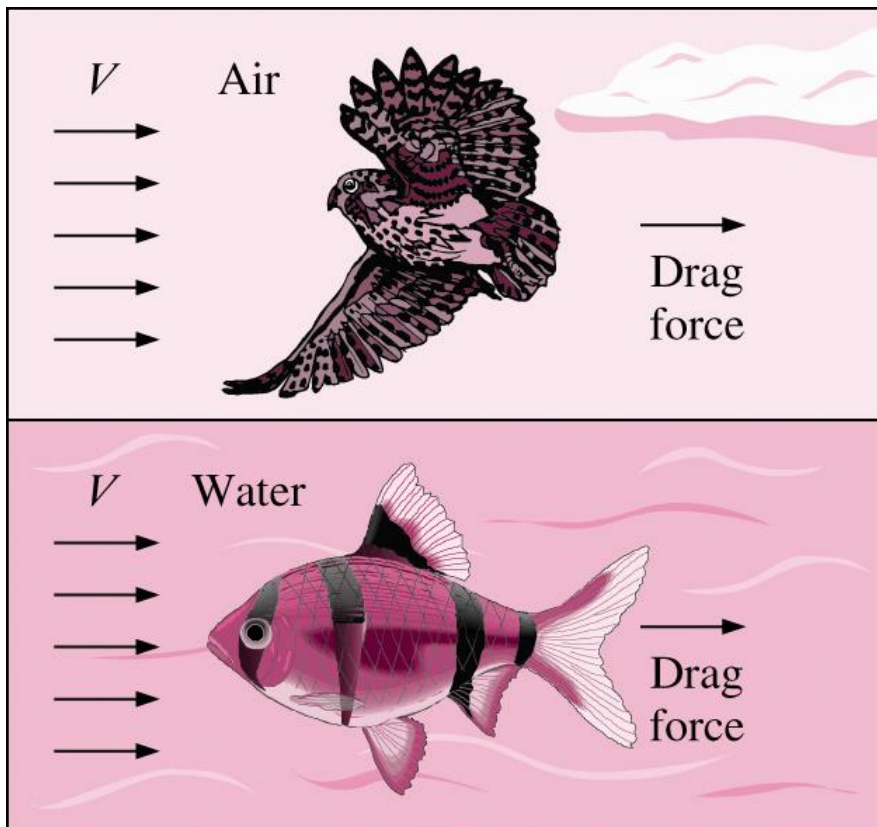
$$\Delta\rho = \alpha\rho \Delta P = (4.80 \times 10^{-5} \text{ atm}^{-1})(998 \text{ kg/m}^3)(100 - 1) \text{ atm} = 4.7 \text{ kg/m}^3$$

Then the density of water at 100 atm and 20°C becomes

$$\rho_2 = \rho_1 + \Delta\rho = 998.0 + 4.7 = \mathbf{1002.7 \text{ kg/m}^3}$$

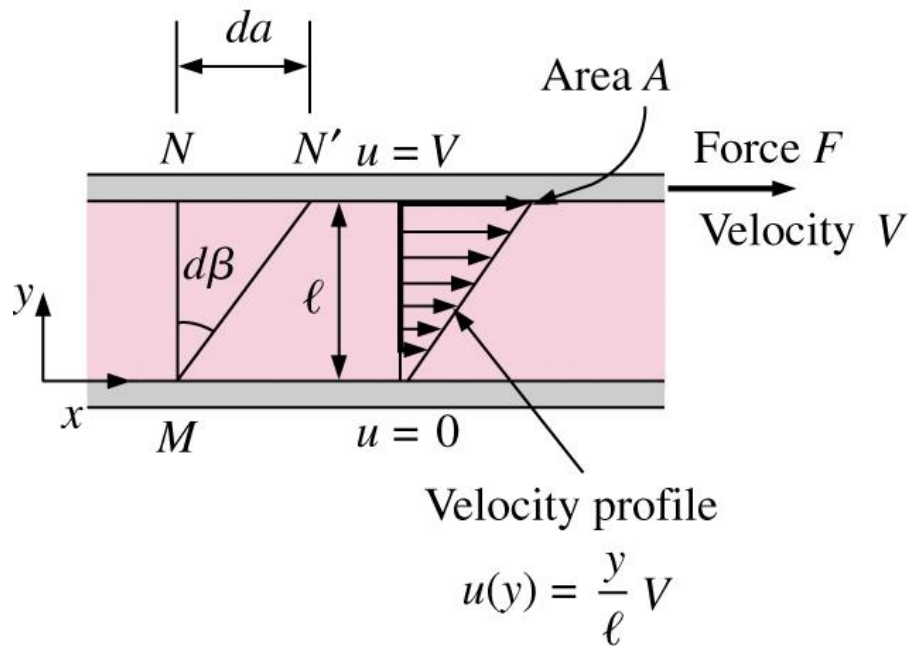
Discussion Note that the density of water decreases while being heated and increases while being compressed, as expected. This problem can be solved more accurately using differential analysis when functional forms of properties are available.

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 $du/dy = V/\ell$

Viscosity

$$d\beta \cong \tan d\beta = da/\ell = Vdt/\ell = (du/dy)dt$$

Rearranging

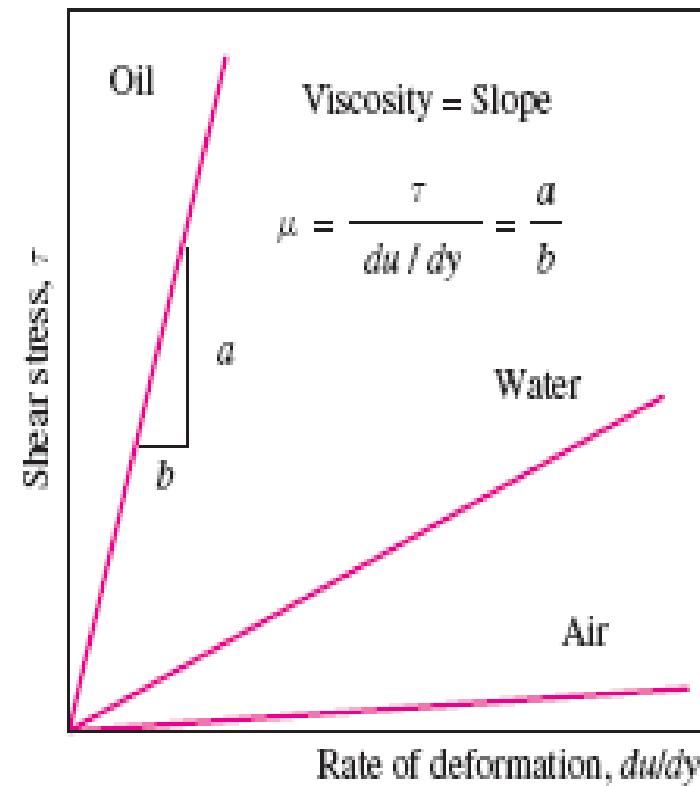
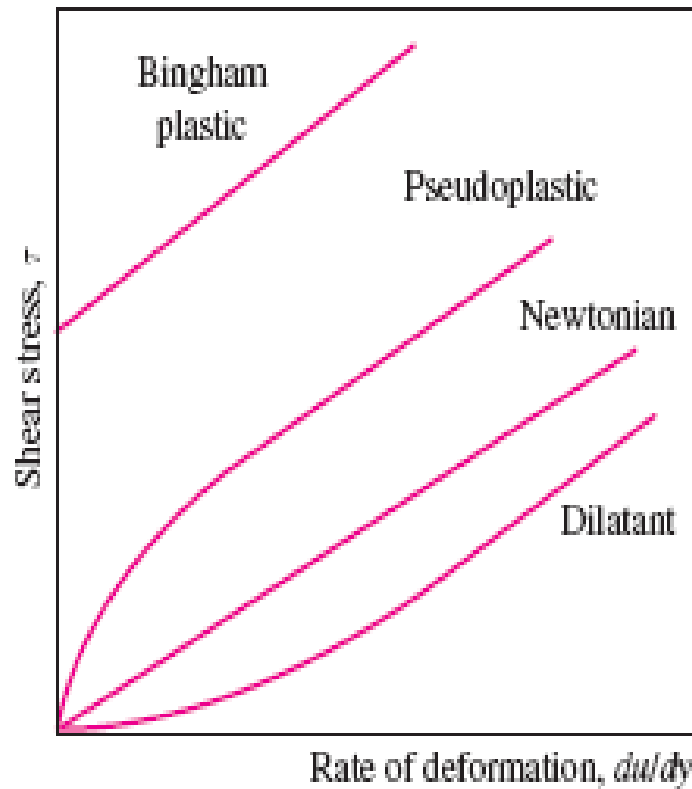
$$du/dy = d\beta/dt \Rightarrow \tau \propto d\beta/dt \quad \text{or} \quad \tau \propto du/dy$$

- Fluids for which the rate of deformation is proportional to the shear stress are called **Newtonian fluids**, such as water, air, gasoline, and oils. Blood and liquid plastics are examples of non-Newtonian fluids.
- In one-dimensional flow, shear stress for Newtonian fluid:

$$\tau = \mu du/dy$$
- μ is the **dynamic viscosity** and has units of $kg/m \cdot s$, $Pa \cdot s$, or **poise**.
- **kinematic viscosity** $\nu = \mu/\rho$. Two units of kinematic viscosity are m^2/s and **stoke**.
- $1 \text{ stoke} = 1 \text{ cm}^2/s = 0.0001 \text{ m}^2/s$

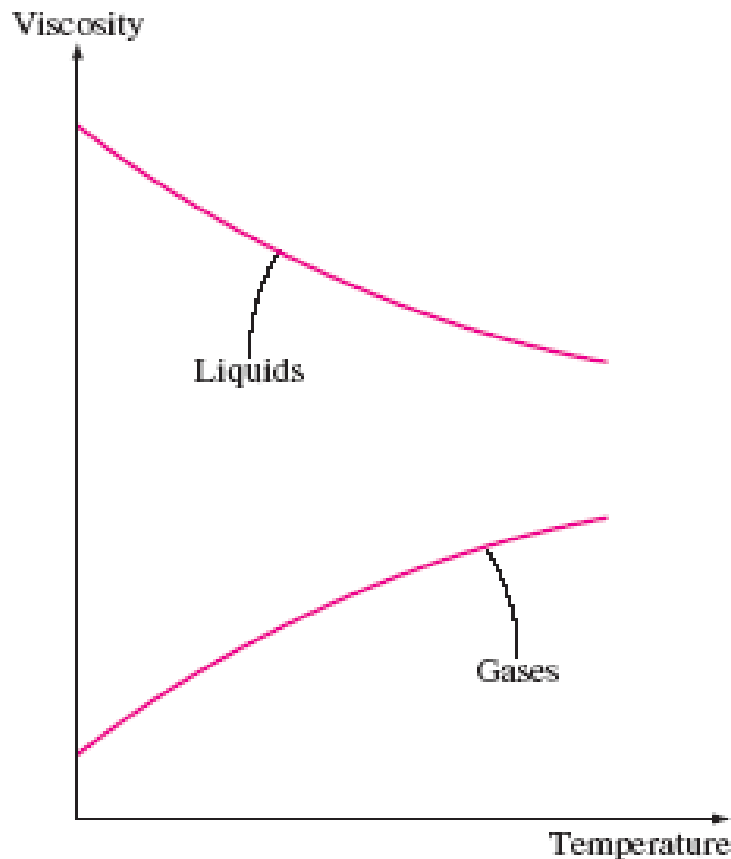
Viscosity

Non-Newtonian vs. Newtonian Fluid



Viscosity

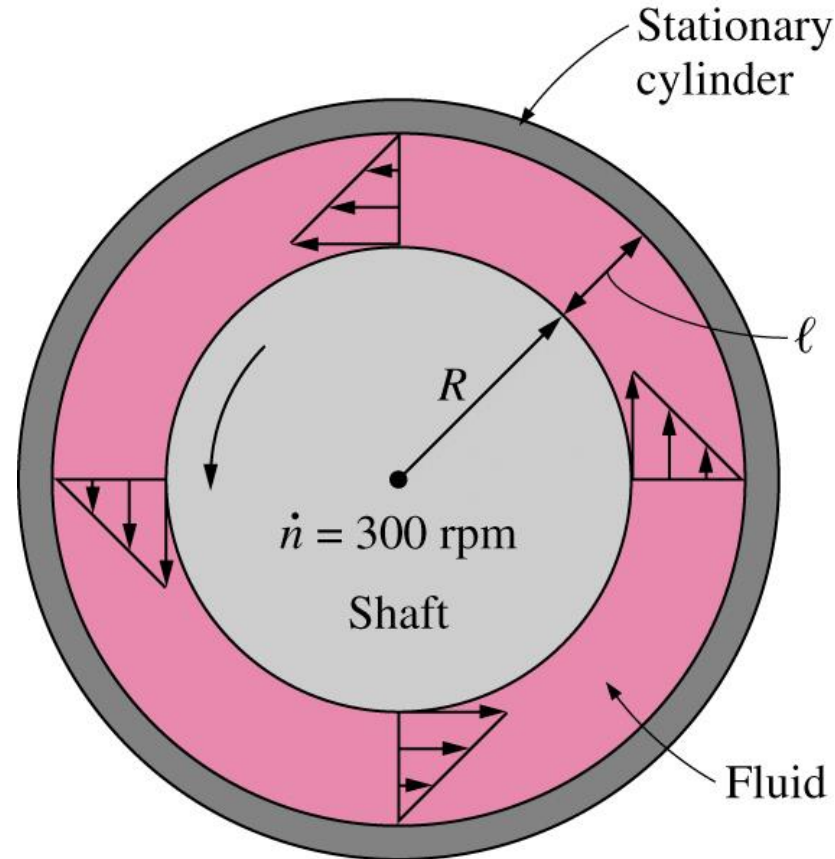
Gas vs. Liquid



Dynamic viscosities of some fluids
at 1 atm and 20°C (unless
otherwise stated)

Fluid	Dynamic Viscosity μ , kg/m · s
Ethyl alcohol	0.0012
Water:	
0°C	0.0018
20°C	0.0010
100°C (liquid)	0.00028
100°C (vapor)	0.000012
Blood, 37°C	0.00040
Gasoline	0.00029
Ammonia	0.00015
Air	0.000018

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.

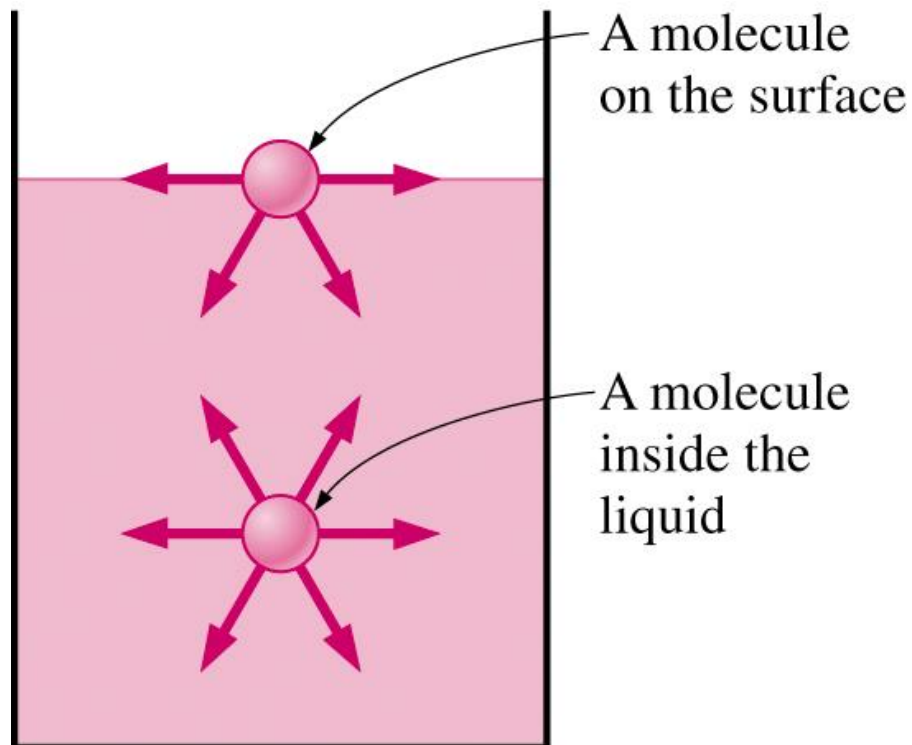
- Use definition of shear force:

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

- If $\ell/R \ll 1$, 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

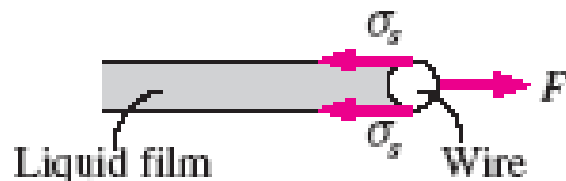
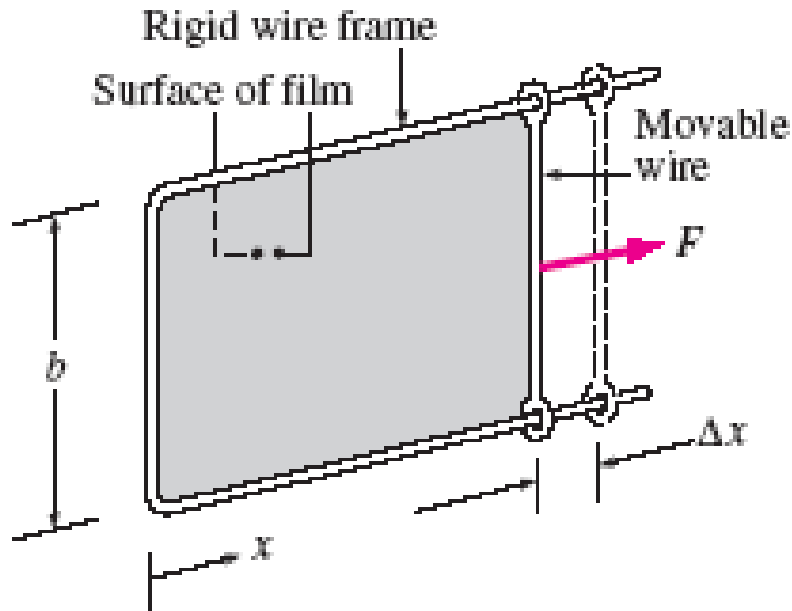
$$T = FR = \mu \frac{2\pi R^3 \omega L}{\ell} = \mu \frac{4\pi^2 R^3 \dot{n} L}{\ell}$$

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



$$\sigma_s = F/2b$$

The change of surface energy =
 $W = \text{Force} \times \text{Distance}$
 $= F \Delta x = 2b \sigma_s \Delta x$
 $= \sigma_s \Delta A$

Surface Tension

■ The surface tension of a substance can be changed considerably by *impurities*, called ***surfactants***. For example, soaps and detergents lower the surface tension of water and enable it to penetrate through the small openings between fibers for more effective washing.

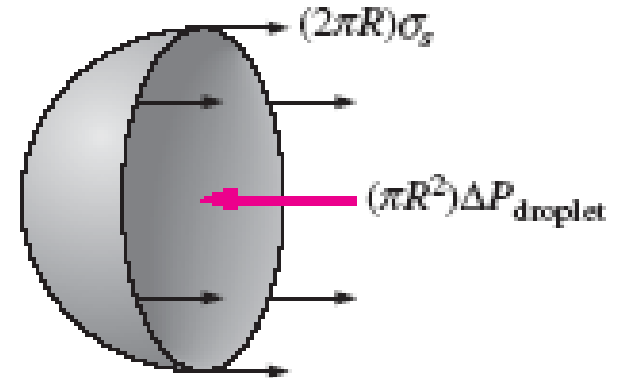
Surface Tension

Droplet: $(2\pi R)\sigma_s = (\pi R^2)\Delta P_{\text{droplet}}$
 $\rightarrow \Delta P_{\text{droplet}} = P_i - P_o = 2\sigma_s/R$

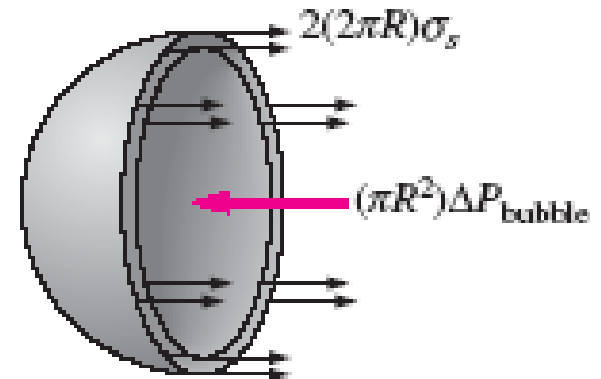
Bubble: $2(2\pi R)\sigma_s = (\pi R^2)\Delta P_{\text{droplet}}$
 $\rightarrow \Delta P_{\text{droplet}} = P_i - P_o = 4\sigma_s/R$

where P_i and P_o are the pressures inside and outside the droplet or bubble, respectively.

When the droplet or bubble is in the atmosphere, P_o is simply atmospheric pressure. The factor 2 in the force balance for the bubble is due to the bubble consisting of a film with *two* surfaces (inner and outer surfaces) and thus two circumferences in the cross section.



(a) Half a droplet



(b) Half a bubble

Surface Tension

The pressure difference of a droplet due to surface tension

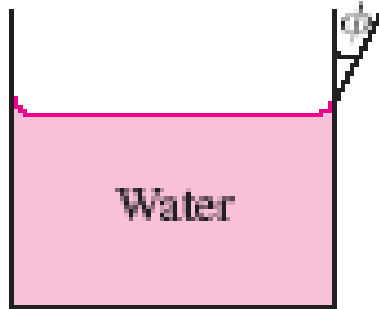
$$dW_{\text{surface}} = \sigma_s dA = \sigma_s d(4\pi R^2) = 8\pi R \sigma_s dR$$

$$\begin{aligned} dW_{\text{expansion}} &= \text{Force} \times \text{Distance} = F dR \\ &= (\Delta P A) dR = 4\pi R^2 \Delta P dR \end{aligned}$$

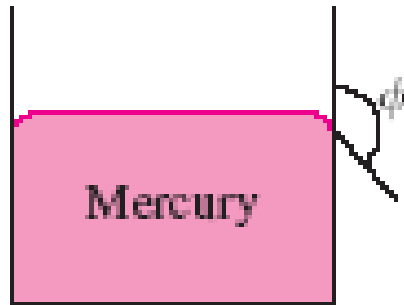
$$dW_{\text{surface}} = dW_{\text{expansion}}$$

$$\text{Therefore, } \Delta P_{\text{droplet}} = 2\sigma_s / R,$$

Capillary Effect



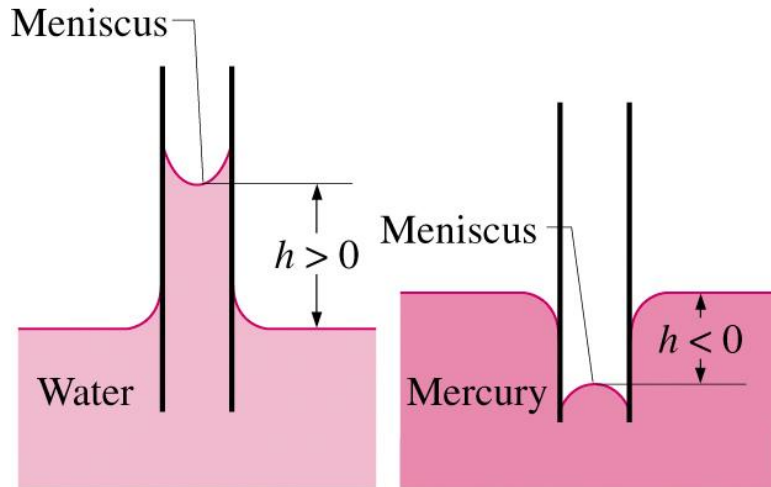
(a) Wetting fluid



(b) Nonwetting fluid

- **Capillary effect** is the rise or fall of a liquid in a small-diameter tube.
- The curved free surface in the tube is called the **meniscus**.
- **Contact** (or *wetting*) **angle** ϕ , defined as *the angle that the tangent to the liquid surface makes with the solid surface at the point of contact*.
- Water meniscus curves up because water is a *wetting* ($\phi < 90^\circ$) fluid (*hydrophilic*).
- Mercury meniscus curves down because mercury is a *nonwetting* ($\phi > 90^\circ$) fluid (*hydrophobic*).

Capillary Effect



- Force balance can describe magnitude of capillary rise.

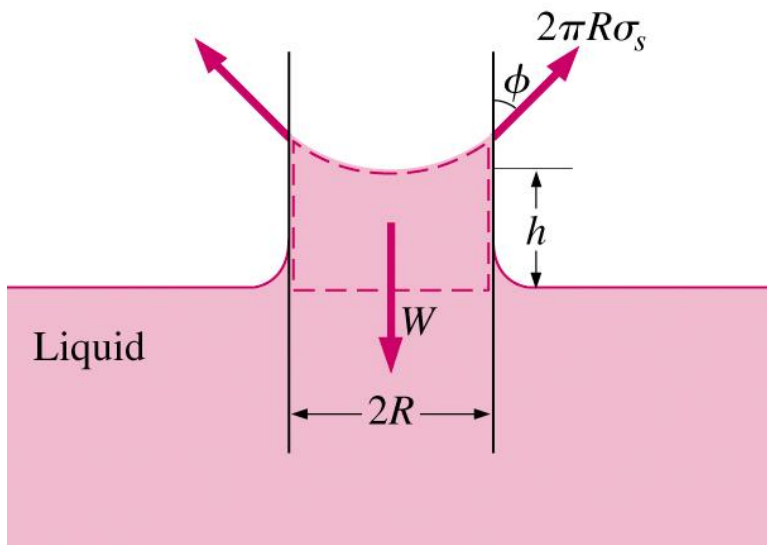
$$W = mg = \rho Vg = \rho g(\pi R^2 h)$$

$$W = F_{\text{surface}} \rightarrow \rho g(\pi R^2 h) = 2\pi R \sigma_s \cos \phi$$

Capillary rise:

$$\rightarrow h = 2\sigma_s \cos \phi / \rho g R$$

(R = constant)



Capillary Effect

EXAMPLE 2–5 The Capillary Rise of Water in a Tube

A 0.6-mm-diameter glass tube is inserted into water at 20°C in a cup. Determine the capillary rise of water in the tube (Fig. 2–27).

Properties The surface tension of water at 20°C is 0.073 N/m (Table 2–3). The contact angle of water with glass is 0° (from preceding text). We take the density of liquid water to be 1000 kg/m³.

Capillary rise:

$$\rightarrow h = 2\sigma_s \cos \phi / \rho g R = 0.050 \text{ m} = \mathbf{5.0 \text{ cm}}$$

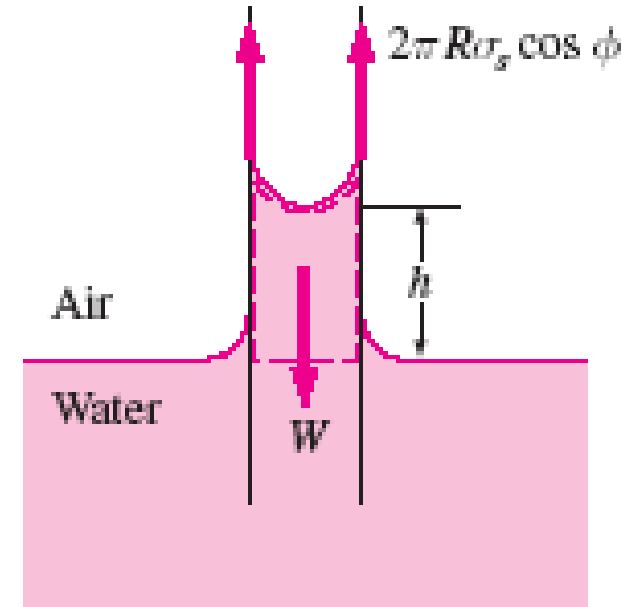


FIGURE 2–27

Note that if the tube diameter were 1 cm, the capillary rise would be 3 mm. Actually, the capillary rise in a large-diameter tube occurs only at the rim. Therefore, the capillary effect can be ignored for large-diameter tubes.