Fluid Mechanics

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Properties of Fluids

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 $e=E/m$.

Continuum

O₂   1 atm, 20°C

3×10^{16} molecules/mm³

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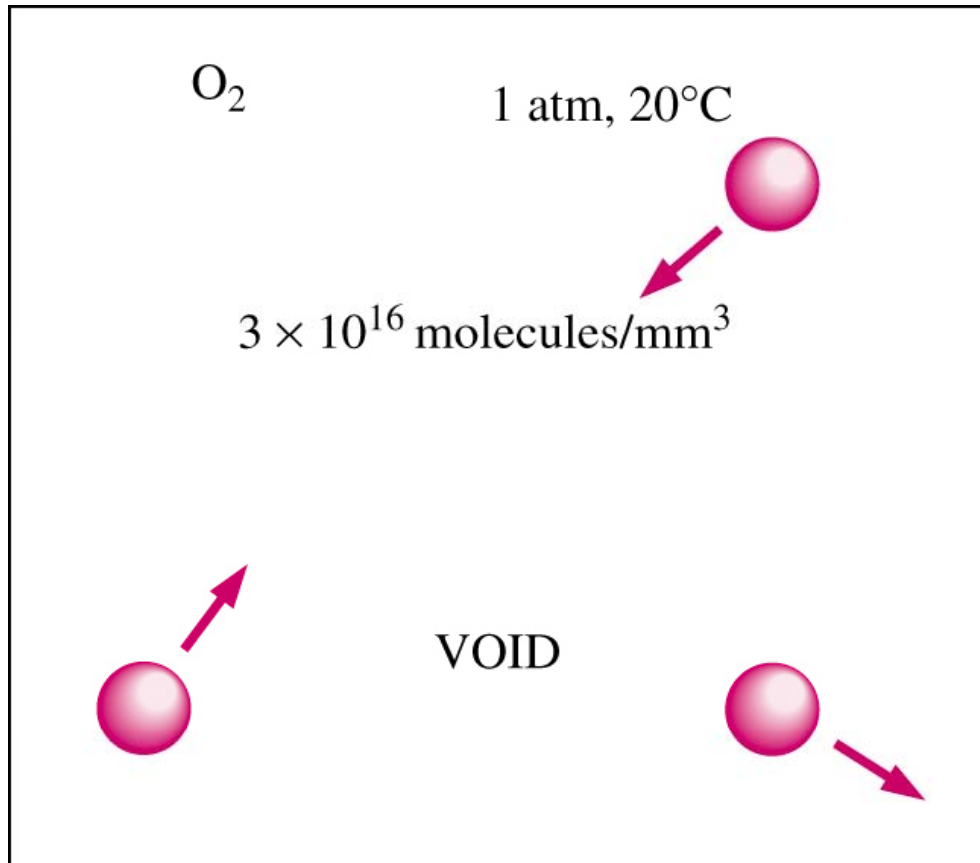
D of O_2 molecule = 3×10^{-10} m
mass of O_2 = 5.3×10^{-26} kg
Mean free path = 6.3×10^{-8} m
     at 1 atm pressure and 20°C

- 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.

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

- 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 $R_u = 8.314$ kJ/kmol · K = 1.986 Btu/lbmol · 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

$$T(K) = T(°C) + 273.15 \qquad \textbf{(2–5)}$$

$$T(R) = T(°F) + 459.67 \qquad \textbf{(2–6)}$$

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

$$PV = mRT \text{ or } PV = NR_uT.$$

- 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

$$P_1V_1/T_1 = P_2V_2/T_2.$$

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.
(Refer. Cengel & Cimbala)

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, °C	Saturation Pressure P_{sat}, 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
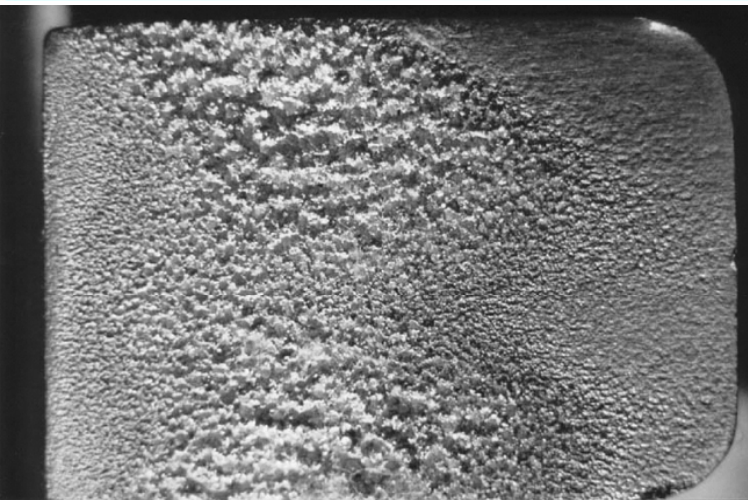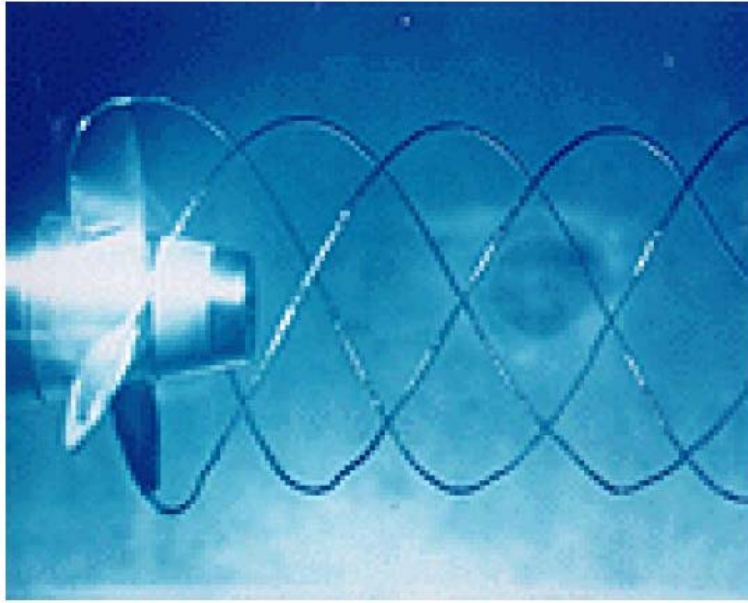
- **Vapor Pressure** P_v is defined as *the pressure exerted by its vapor in phase equilibrium with its liquid at a given temperature*
- **Partial pressure** is defined as *the pressure of a gas or vapor in a mixture with other gases*.
- If P drops below P_v, liquid is locally vaporized, creating cavities 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.

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.

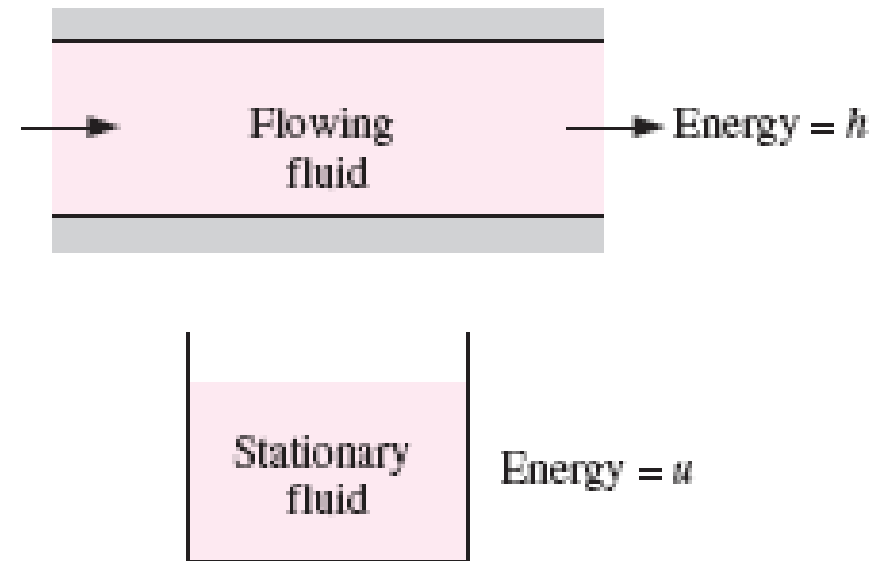- Note that enthalpy is a quantity per unit mass, and thus it is a *specific* property.

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

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

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.

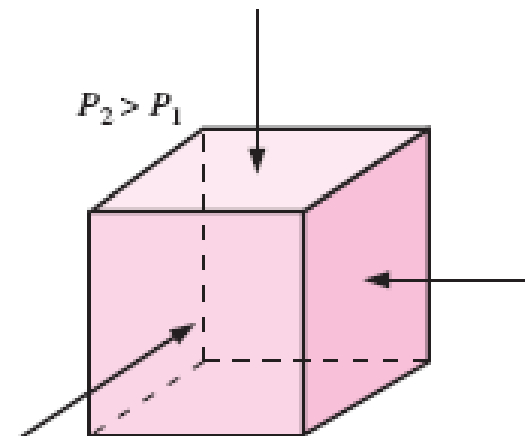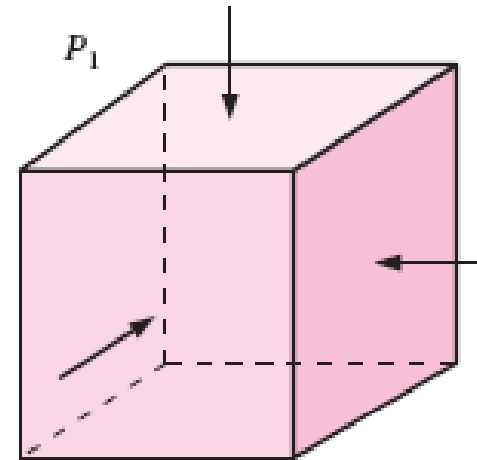■ *The changes of internal energy and enthalpy of an ideal gas are expressed as*

$$du = c_v dT \quad and \quad dh = c_p dT$$

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

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

    (or **bulk modulus of compressibility** or **bulk modulus of elasticity**)

  - k must have the dimension of pressure (Pa or psi).

  - What is the coefficient of compressibility of a truly incompressible substance ?(*v*=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 κ = 21,000 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.

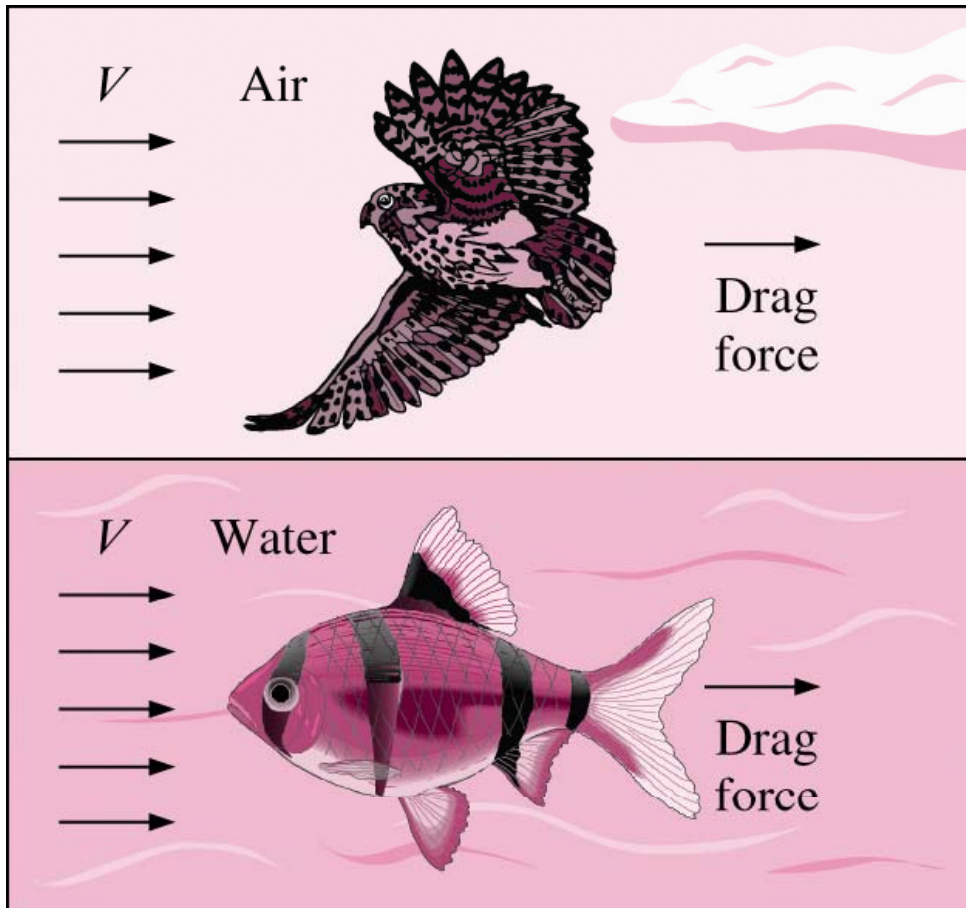# Coefficient of Compressibility

- 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

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

- The inverse of the coefficient of compressibility is called the **isothermal compressibility** α and is expressed as
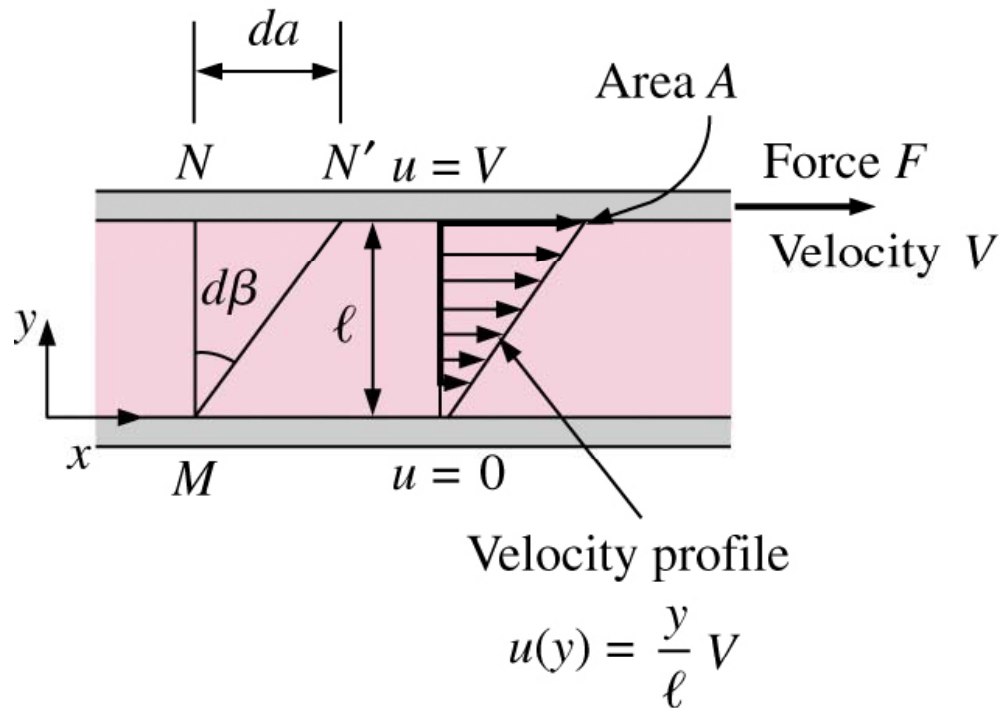
$$\alpha = \frac{1}{\kappa} = -\frac{1}{v}\left(\frac{\partial v}{\partial P}\right)_T = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial P}\right)_T \quad (1/Pa)$$

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

$$u(y) = \frac{y}{\ell} V$$

- 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

$$du/dy = d\beta/dt \;\Rightarrow\; \tau \propto d\beta/dt \quad or \quad \tau \propto du/dy$$

- 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·s*, *Pa·s*, or **poise**.

- **kinematic viscosity** $\nu = \mu/\rho$. Two units of kinematic viscosity are m^2/s and **stoke.**
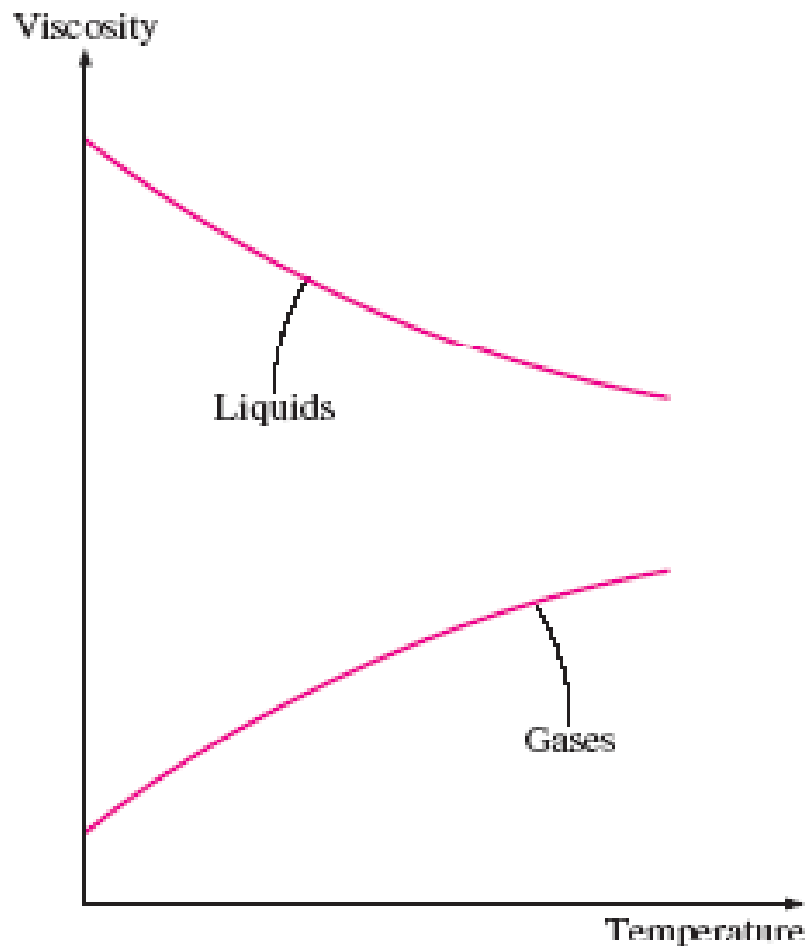
- 1 stoke = 1 cm^2/s = 0.0001 m^2/s

Viscosity

Non-Newtonian vs. Newtonian Fluid
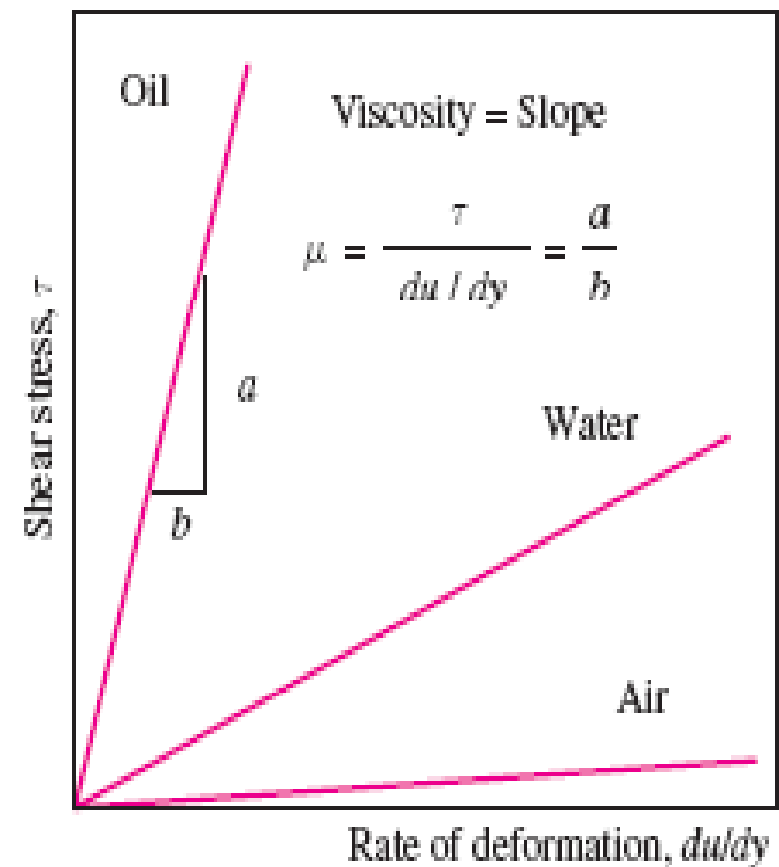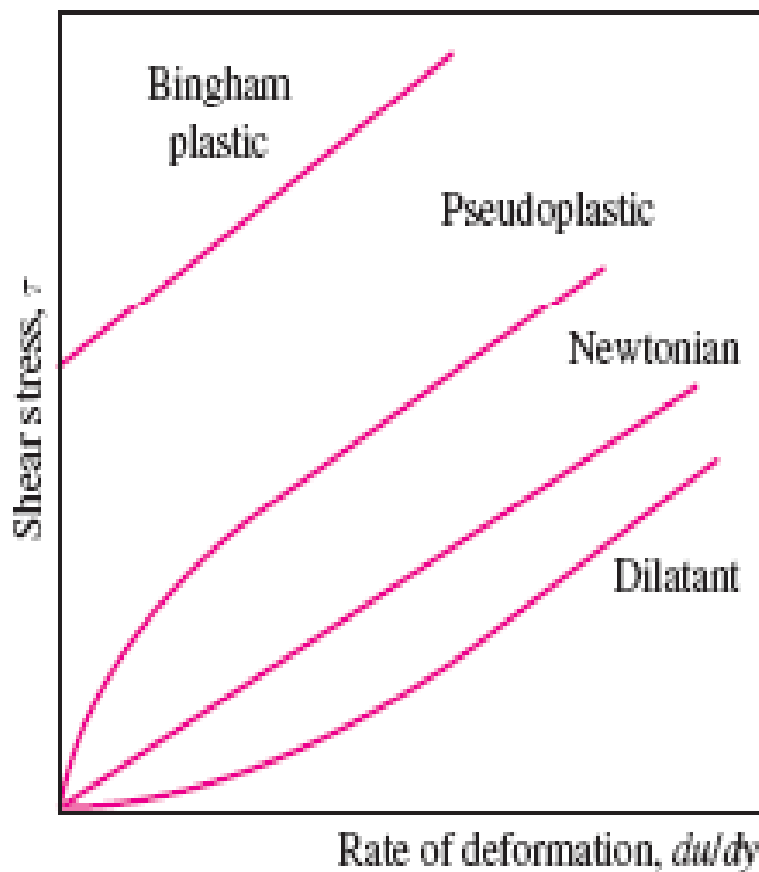
Viscosity

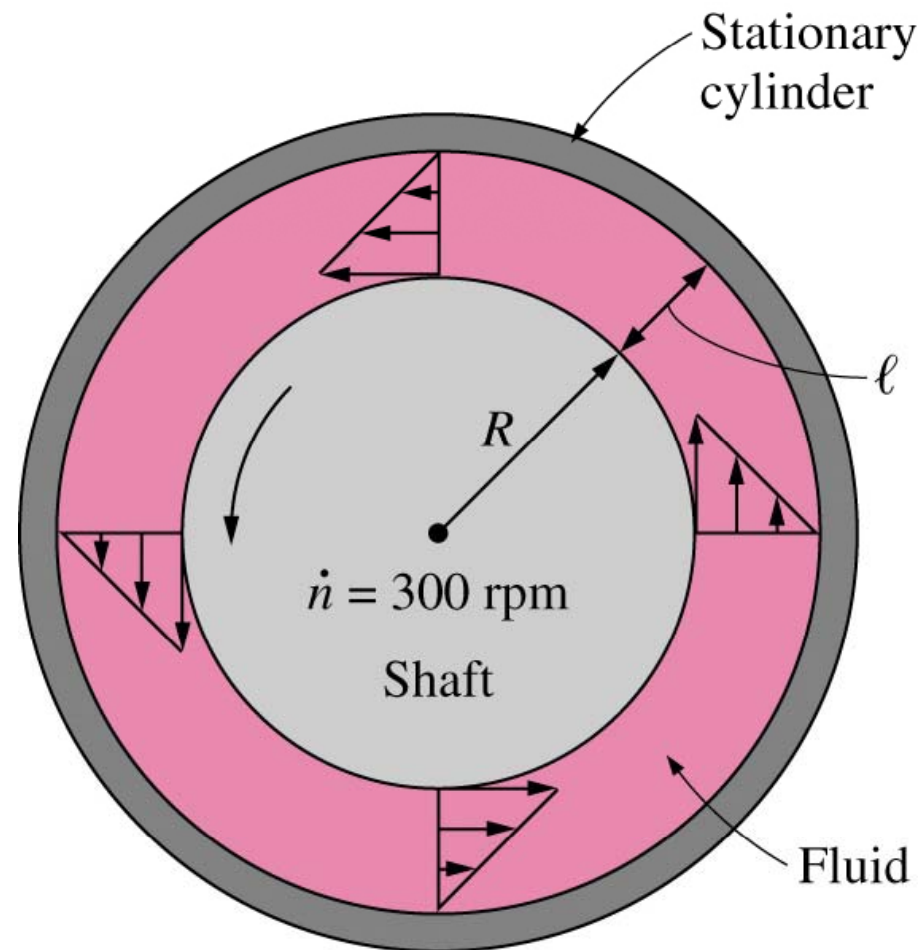## Gas vs. Liquid

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

- 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 ℓ/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