# Chapter 2
# Fluid Properties

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# Significant learning outcomes

## Conceptual Knowledge

- Define density, specific gravity, viscosity, surface tension, vapor pressure, and bulk modulus of elasticity.
- Describe the differences between absolute viscosity and kinematic viscosity.
- Describe how shear stress, viscosity, and the velocity distribution are related.
- Describe how viscosity, density, and vapor pressure vary with temperature and/or pressure.

## Procedural Knowledge

- Look up fluid property values from figures, tables; know when and how to interpolate.
- Calculate gas density using the ideal gas law.

# 2-1 Properties involving mass and weight

- Mass density ($\rho$)

$$\rho = \lim_{\Delta \forall \to 0} \frac{\Delta m}{\Delta \forall}$$

- Specific Weight ($\gamma$)

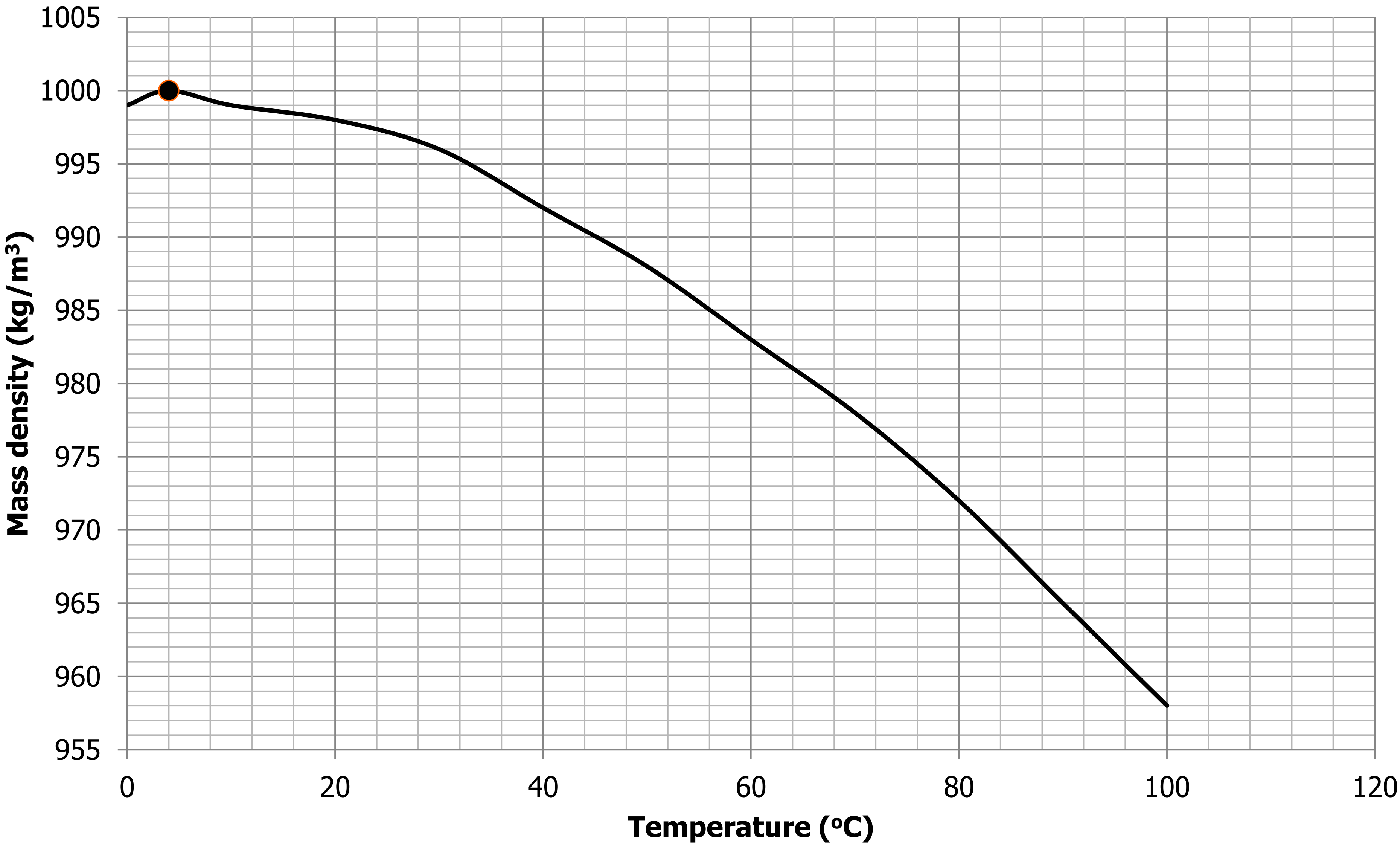
$$\gamma = \rho g$$

- Specific gravity ($S$)

$$S = \frac{\gamma_{fluid}}{\gamma_{water,4^\circ C}} = \frac{\rho_{fluid}}{\rho_{water,4^\circ C}}$$

- Variation in density

# Variation in density with temperature



# Specific Gravity of some substances

| Substance | SG |
|---|---|
| Air | 0.0013 |
| Gasoline | 0.7 |
| Ethyl Alcohol | 0.79 |
| Wood | 0.3-0.9 |
| Ice | 0.92 |
| Water | 1.0 |
| Seawater | 1.025 |
| Blood | 1.05 |
| Bones | 1.7-2.0 |
| Mercury | 13.6 |

# 2.2 Ideal gas law

- Equation of state for an Ideal Gas $$p = \rho RT$$

$P$= Absolute pressure
$\rho$= mass density
$R=R_u/M$ (Table A.2)
$R_u$= Universal gas constant = 8.314 kJ/kmol.K
$M$=Molar mass (molecular weight) of the gas
$T$= Temperature on Kelvin scale, $T$(K)=$T$(°C)+273

At low pressure and high temperature most of the gases of practical importance like air, oxygen, nitrogen, hydrogen, helium, argon, neon, krypton and carbon dioxide can be treated as ideal gases.

# 2.3 Properties involving thermal energy

- Specific heat, $c_p$

  Amount of energy to increase the temperature by 1K

- Internal energy, $u$

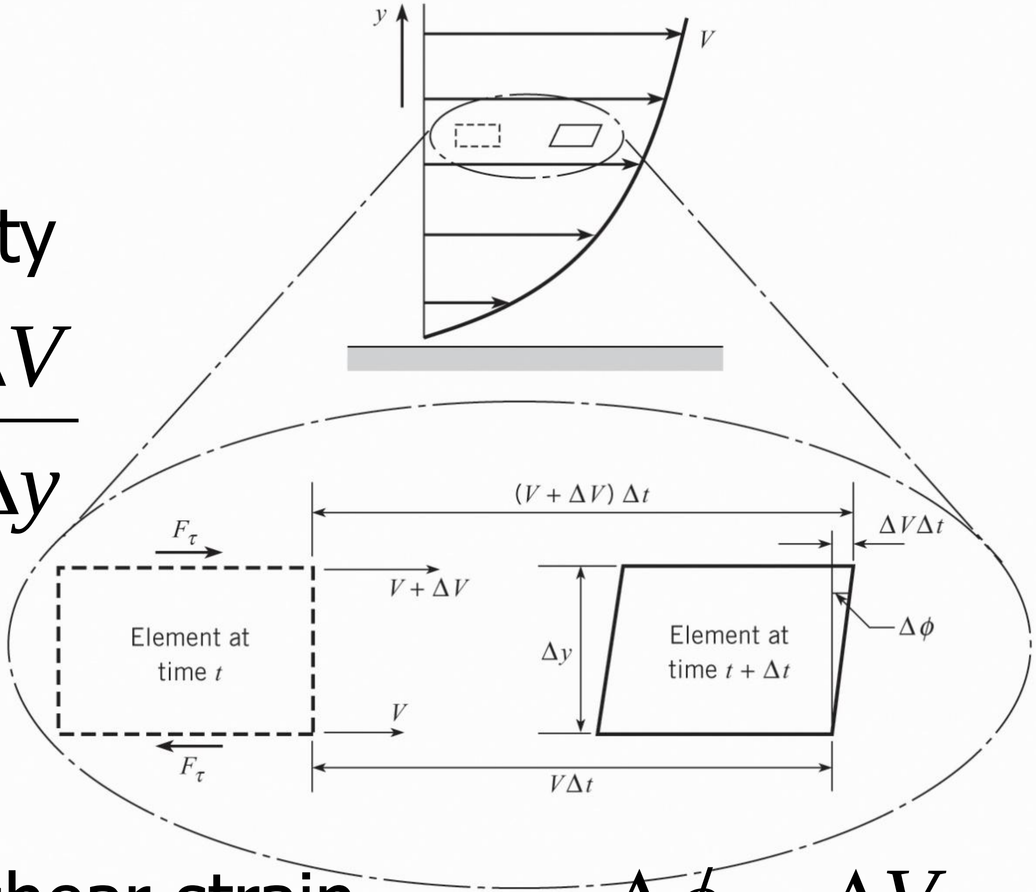
- Enthalpy, $h$

$$h = u + \frac{p}{\rho}$$

# 2.4 Viscosity

- Newton's Law of Vsicosity

$$\Delta\phi \approx \frac{\Delta V \Delta t}{\Delta y} \Rightarrow \frac{\Delta\phi}{\Delta t} \approx \frac{\Delta V}{\Delta y}$$




For a fluid:

Shear stress ∝ Rate of shear strain

$$\tau \propto \frac{\Delta\phi}{\Delta t} \approx \frac{\Delta V}{\Delta y}$$

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

# 2.4 Viscosity (cont'd)

Absolute or dynamic viscosity, $\mu$

$$\mu = \frac{\tau}{dV/dy} = \frac{N/m^2}{(m/s)/m} = N.s/m^2$$

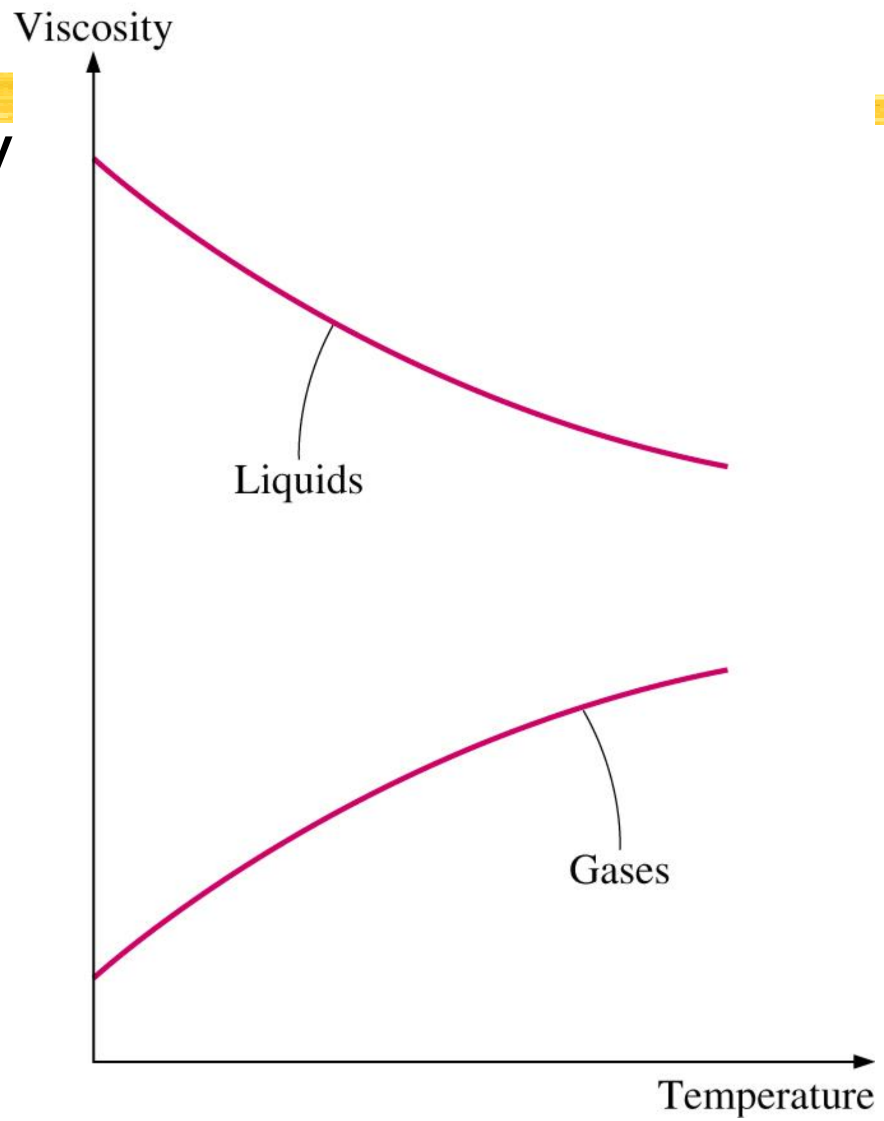
Kinematic viscosity, $\nu$

$$\nu = \frac{\mu}{\rho} = \frac{N.s/m^2}{kg/m^3} = m^2/s$$

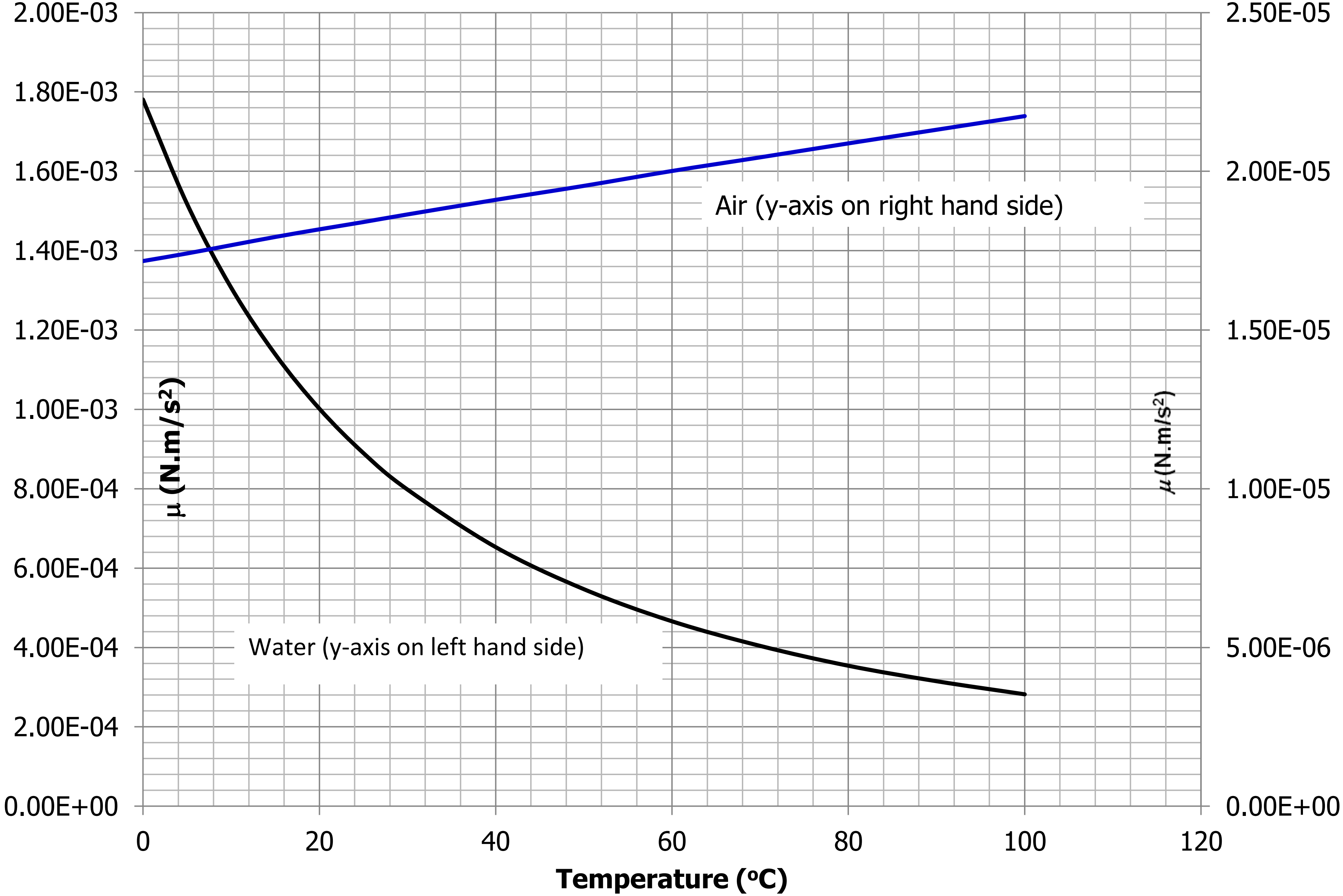
# Temperature dependency

In liquids, viscosity is mainly due to cohesive forces.

In gases, viscosity is mainly due to momentum exchange between molecules.



# Effect of temperature on viscosity of air and water



# Temperature dependency

- Viscosity of liquids

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

*C* and *b* are empirical constants, *T* is absolute temperature

- Sutherland's equation for gases

$$\frac{\mu}{\mu_0} = \left(\frac{T}{T_0}\right)^{3/2} \left(\frac{T_0 + S}{T + S}\right)$$

For air, Sutherland's constant, *S* = 111 K

## EXAMPLE 2.2 CALCULATING VISCOSITY OF LIQUID AS A FUNCTION OF TEMPERATURE

The dynamic viscosity of water at 20°C is $1.00 \times 10^{-3}$ N · s/m², and the viscosity at 40°C is $6.53 \times 10^{-4}$ N · s/m².
Using Eq. (2.9), estimate the viscosity at 30°C.

### *Problem Definition*

**Situation:** Viscosity of water is specified at two temperatures.

**Find:** The viscosity at 30°C by interpolation.

**Properties:**

a) Water at 20°C, $\mu = 1.00 \times 10^{-3}$ N · s/m².

b) Water at 40°C, $\mu = 6.53 \times 10^{-4}$ N · s/m².

*Solution*

1. Logarithm of Eq. (2.9)

$$\ln \mu = \ln C + b/T$$

2. Interpolation

$$-6.908 = \ln C + 0.00341\,b$$

$$-7.334 = \ln C + 0.00319\,b$$

3. Solution for $\ln C$ and $b$

$$\ln C = -13.51 \qquad b = 1936\ (\mathrm{K})$$

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

4. Substitution back in exponential equation

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

At 30°C

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

## EXAMPLE 2.3 MODELING A BOARD SLIDING ON A LIQUID LAYER

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

### *Problem Definition*

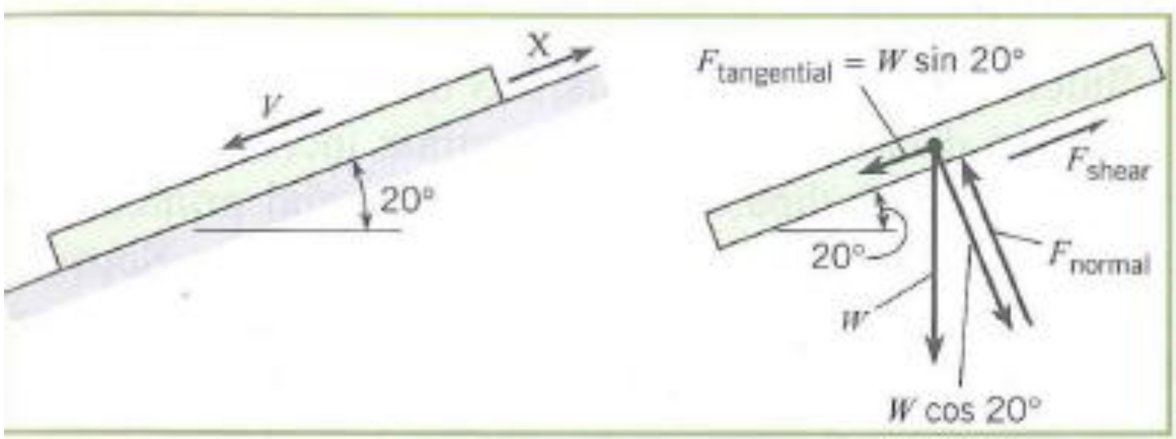
**Situation:** A board is sliding down a ramp, on a thin film of oil.

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

**Assumptions:** A linear velocity distribution in the oil.

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

**Sketch:**



### Solution

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 $\Delta y$

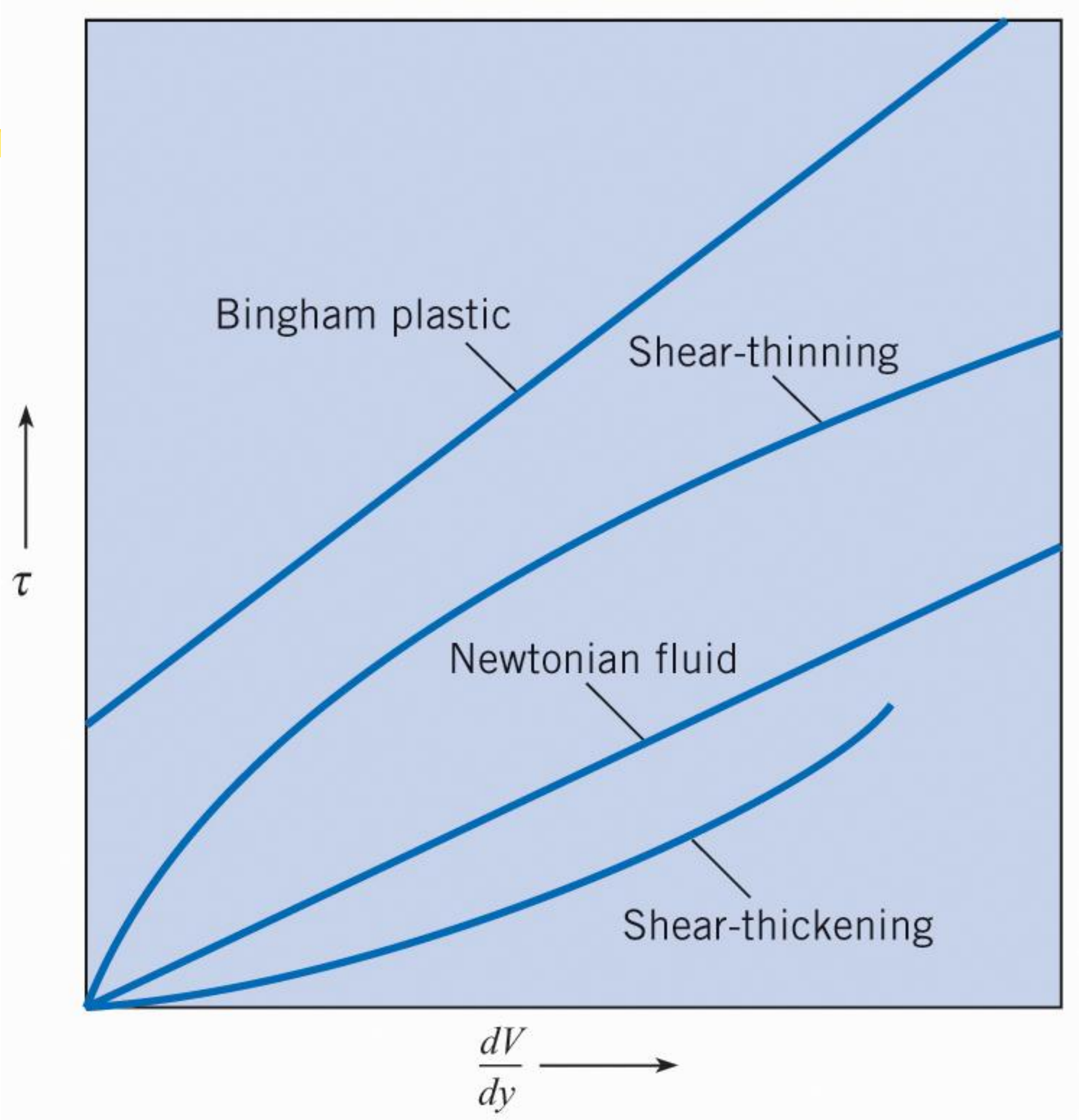
$$\Delta y = \frac{\mu \Delta V A}{W \sin 20°}$$

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

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

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

# Newtonian versus non-Newtonian fluids



# 2.5 Bulk modulus of elasticity

$$E_v = -\frac{dp}{d\forall / \forall} = \frac{\text{Change in pressure}}{\text{Volumetric strain}}$$

$$E_v = \frac{dp}{d\rho / \rho}$$

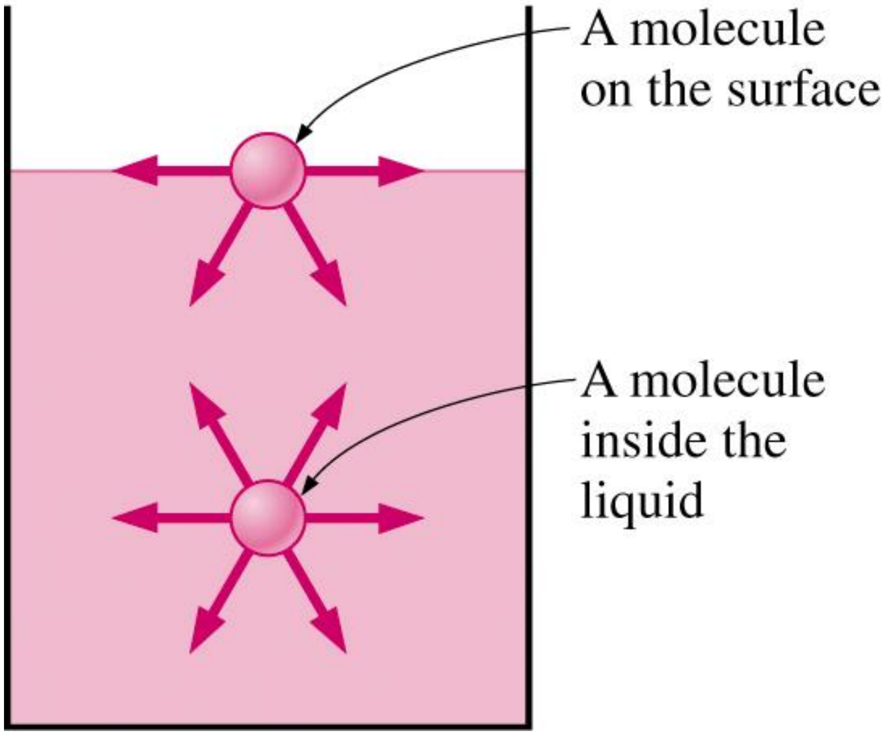
- For an ideal gas under constant temperature

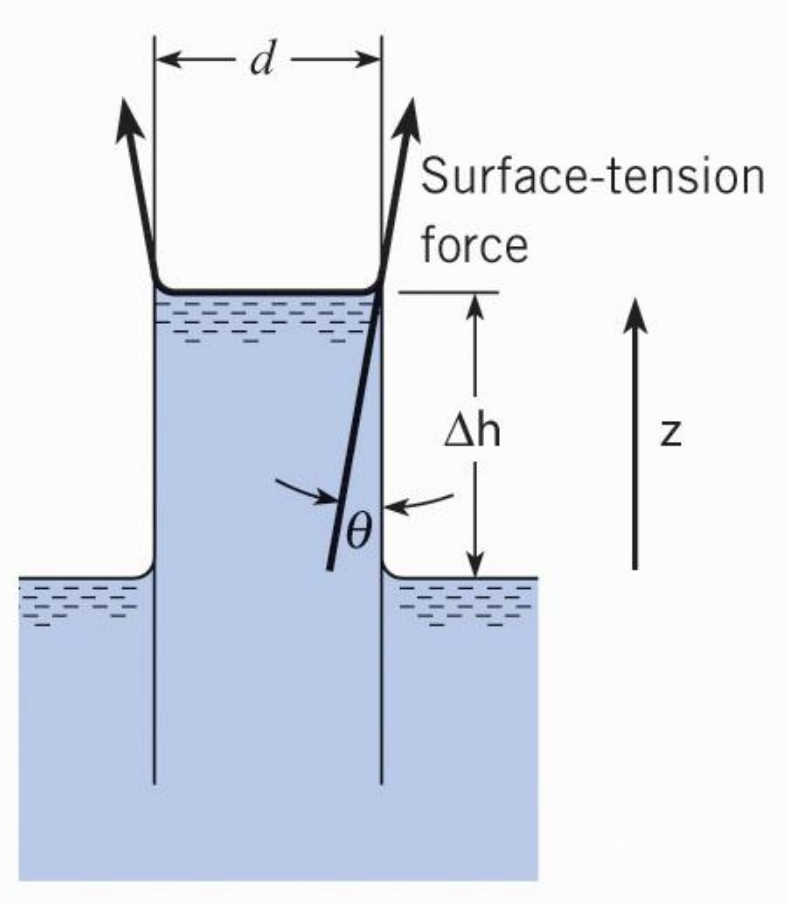
$$E_v = \rho \frac{dp}{d\rho} = \rho RT = p$$

- For an adiabatic process: $E_v = kp \quad (k = c_p / c_v)$

# 2.6 Surface Tension

- Surface Tension




$$F_\sigma = \sigma L$$

# Surface Tension in different cases

(*a*) Spherical droplet (*b*) Spherical bubble

$$F_\sigma = \sigma L = pA$$

$$2\pi r\sigma = p\pi r^2$$

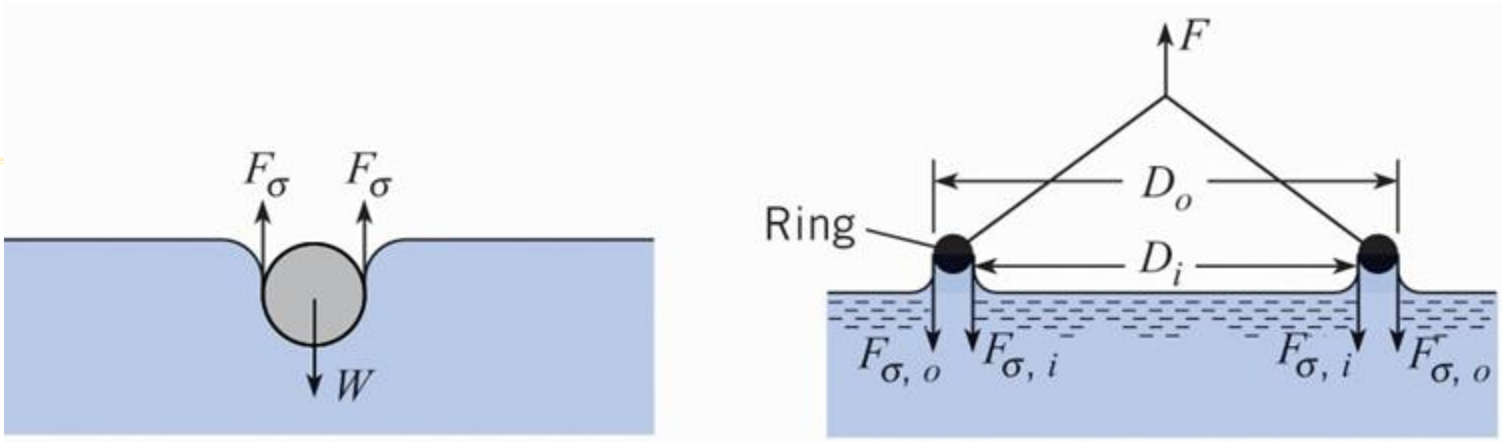
$$p = \frac{2\sigma}{r}$$

$$F_\sigma = \sigma L = pA$$

$$4\pi r\sigma = p\pi r^2$$

$$p = \frac{4\sigma}{r}$$

# Surface Tension in different cases




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

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

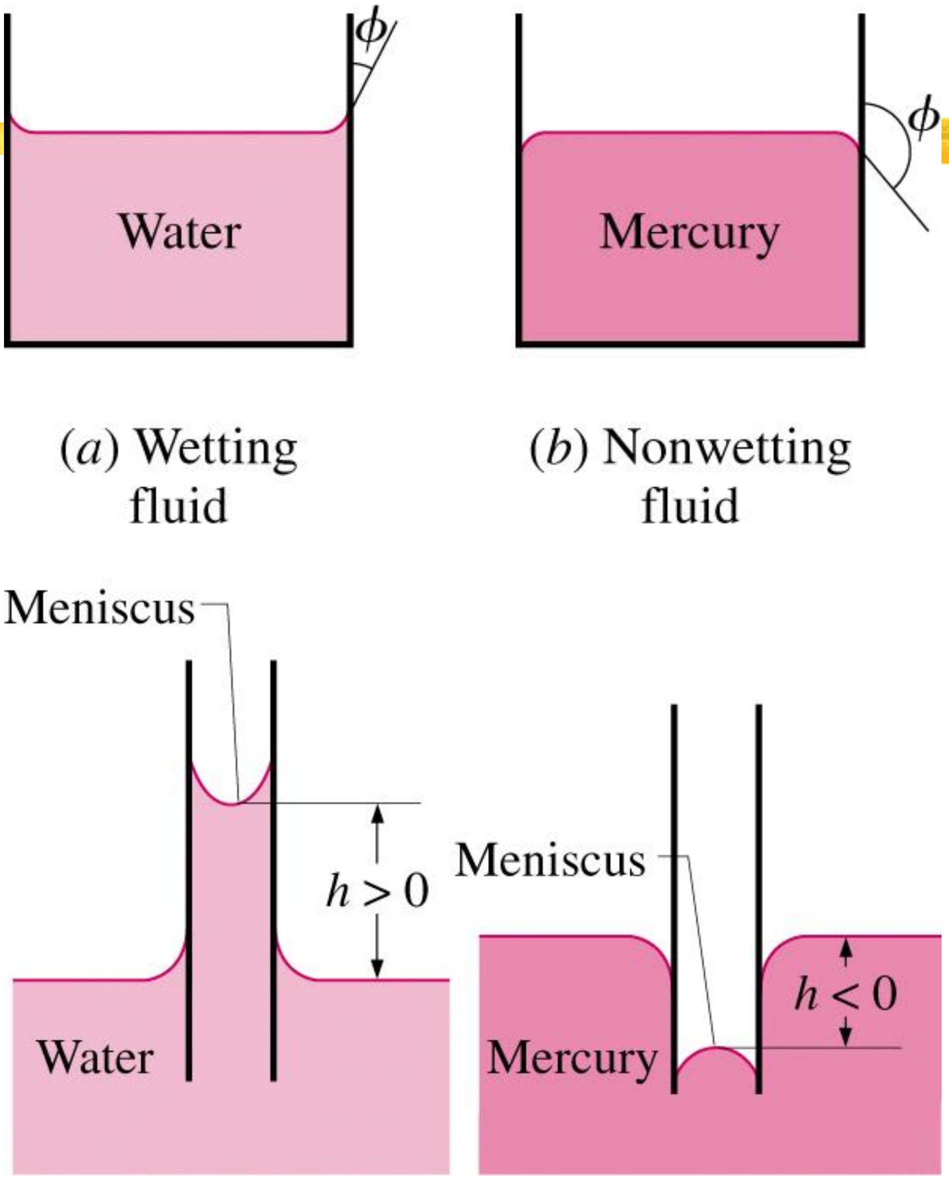
$$W = 2F_\sigma = 2\sigma L$$

$$F = ??$$

Surface Tension of some fluids in air at 1atm and 20°C

| Fluid | $\sigma$ (N/m) |
|---|---|
| Mercury | 0.440 |
| Water | 0.073 |
| Glycerin | 0.063 |
| SAE 30 oil | 0.035 |
| Kerosene | 0.028 |
| Soap solution | 0.025 |
| Ethyl Alcohol | 0.023 |
| Gasoline | 0.022 |
| Ammonia | 0.021 |

# Capillary Effect



## EXAMPLE 2.4 CAPILLARY RISE IN A TUBE

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?

### *Problem Definition*

**Situation:** A glass tube of small diameter placed in an open reservoir of water induces capillary rise.

**Find:** The height the water will rise above the reservoir level.

**Sketch:** See Figure 2.7.

**Properties:** Water (20 °C), Table A.5, $\sigma = 0.073\ N/m$; $\gamma = 9790\ N/m^3$.

## Solution

1. Force balance: Weight of water (down) is balanced by surface tension force (up).

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

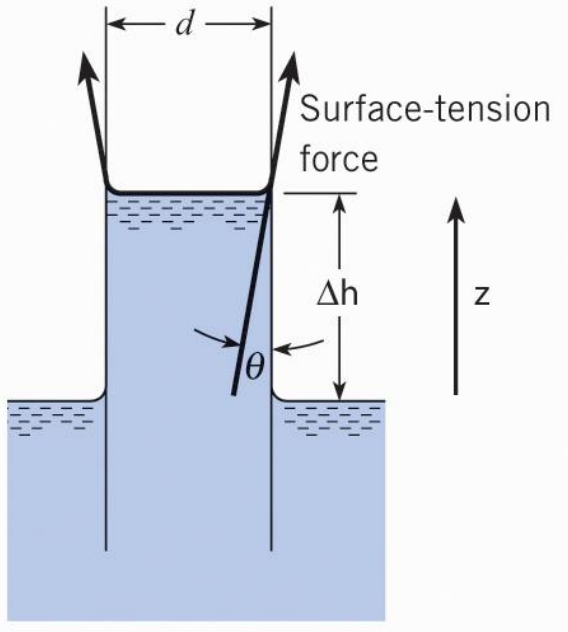
$$\sigma \pi d \cos\theta - \gamma(\Delta h)(\pi d^2/4) = 0$$

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:

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

2. Solve for $\Delta h$:

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



# 2.7 Vapor Pressure

Vapor pressure of a liquid is defined as the pressure, at a given temperature, it will boil.

Vapor pressure increases with temperature.

Vapor pressure of water is shown in the table.

| Temperature, ºC | $p_v$ , kPa |
|---|---|
| -10 | 0.26 |
| -5 | 0.403 |
| 0 | 0.611 |
| 5 | 0.872 |
| 10 | 1.23 |
| 20 | 2.34 |
| 30 | 4.25 |
| 40 | 7.38 |
| 50 | 12.35 |
| **100** | **101.3** |
| 200 | 1554 |
| 300 | 8581 |