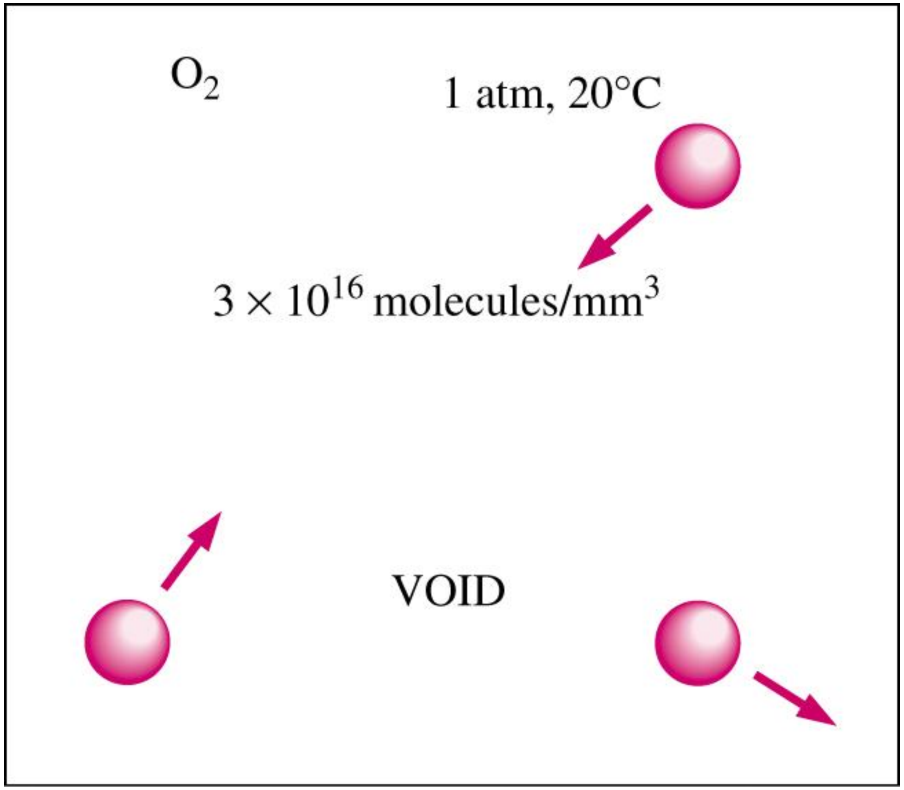
Chapter 2: Properties of Fluids

Introduction

- Any characteristic of a system is called a **property.**
  - Familiar: pressure P, temperature T, volume $\mathcal{V}$, 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 $v = \mathcal{V}/m$ 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.

Mean free path of O_2 at 1 atm and 20°C = 6.3×10^{-8} m $\approx$ 200 x diameter of a molecule

Density and Specific Gravity

- Density is defined as the *mass per unit volume* $\rho = m/\mathcal{V}$. Density has units of kg/m^3
- Specific volume is defined as $v = 1/\rho = \mathcal{V}/m$.
- For a gas, density depends on temperature and pressure (for liquids and solids ρ depends almost only upon T).
- **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., $SG=\rho/\rho_{H_20}$. 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.

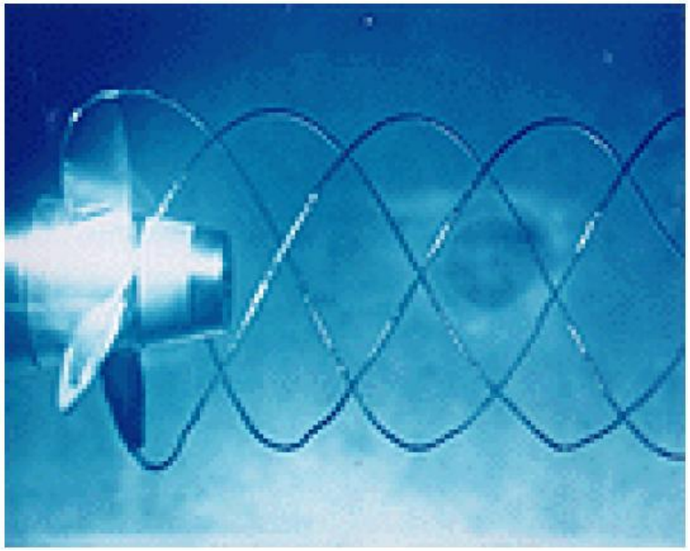
Density of Ideal Gases

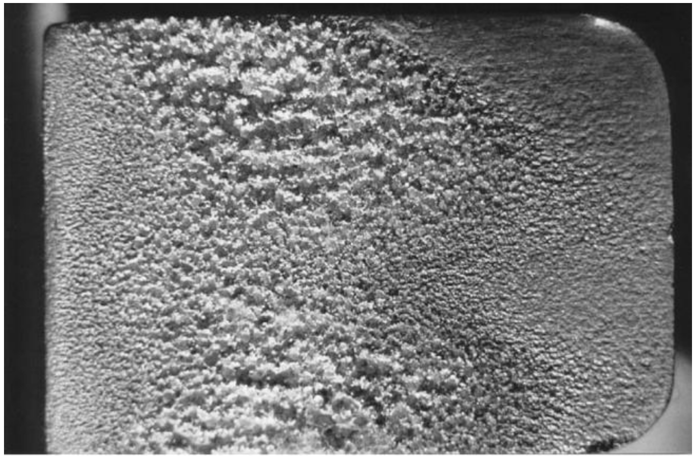
- **Equation of State**: equation for the relationship between pressure, temperature and density.
- The simplest and best-known equation of state is the ideal-gas equation.

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

- 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-1E through A-11E in textbook.

Vapor Pressure and Cavitation





- **Vapor Pressure** P_v of a pure substance is defined as *the pressure exerted by its vapor in phase equilibrium with its liquid at a given temperature*
- 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.

Forms of Energy

- Total energy E 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).
- Microscopic energy
  - Internal energy u is for a non-flowing fluid and is due to molecular activity.
  - Enthalpy $h=u+P\mathcal{v}$ is for a flowing fluid and includes flow energy ($P\mathcal{v}$).
- Macroscopic energy
  - Kinetic energy $ke=V^2/2$
  - Potential energy $pe=gz$
- In the absence of electrical, magnetic, chemical, and nuclear energy, the total energy is $e_{flowing}=h+V^2/2+gz$.

Coefficients of Compressibility and Volume Expansion

- How does fluid volume change with *P* and *T*?
- Fluids expand as *T* ↑ or *P* ↓ ; fluids contract as *T* ↓ or *P* ↑
- Need fluid properties that relate volume changes to changes in *P* and *T*.
  - Coefficient of compressibility or bulk modulus of elasticity

$$\kappa = -v\left(\frac{\partial P}{\partial v}\right)_T = \rho\left(\frac{\partial P}{\partial \rho}\right)_T \qquad \mathcal{K}_{ideal\ gas} = P$$

$\alpha = 1/\mathcal{K}$ = coefficient of isothermal compressibility

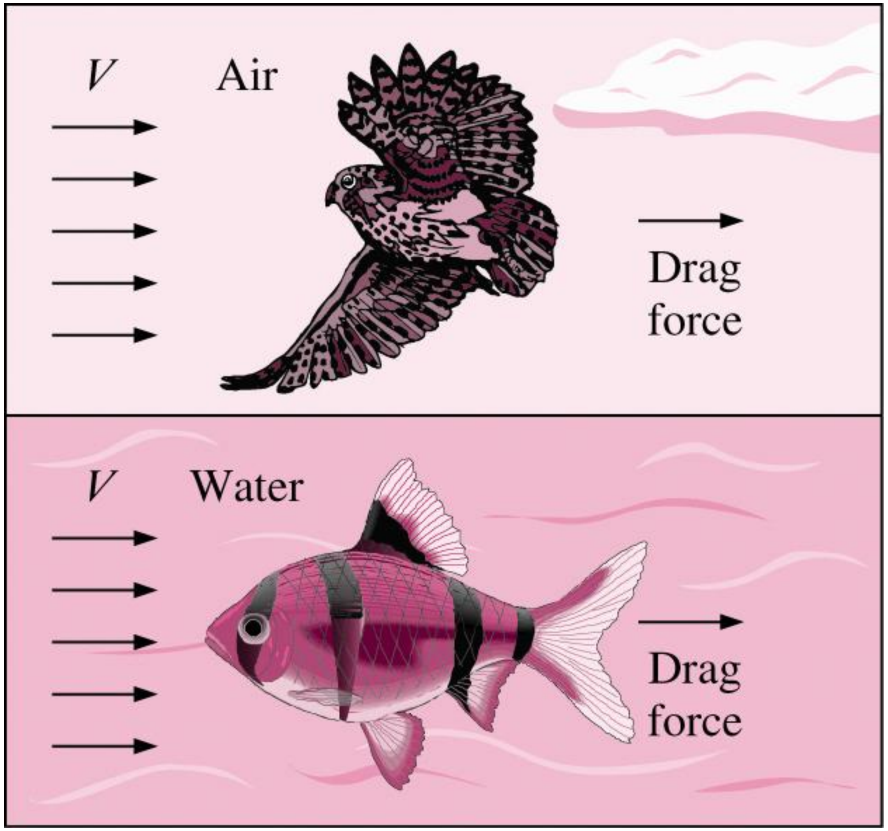
  - Coefficient of volume expansion

$$\beta = \frac{1}{v}\left(\frac{\partial v}{\partial T}\right)_P = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_P \qquad \beta_{ideal\ gas} = 1/T$$

- Combined effects of *P* and *T* can be written as

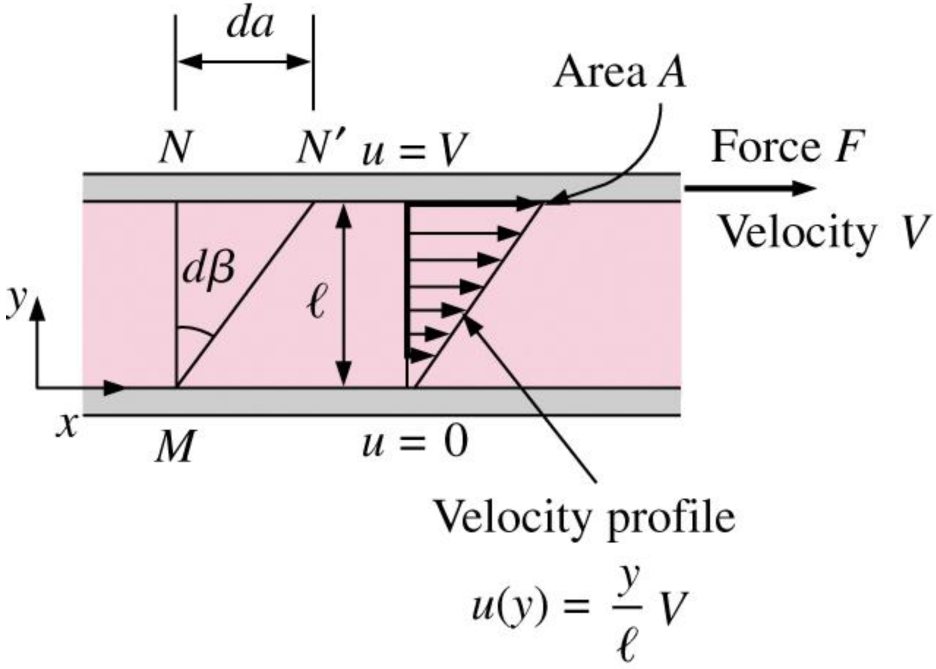
$$dv = \left(\frac{\partial v}{\partial T}\right)_P dT + \left(\frac{\partial v}{\partial P}\right)_T dP$$

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.

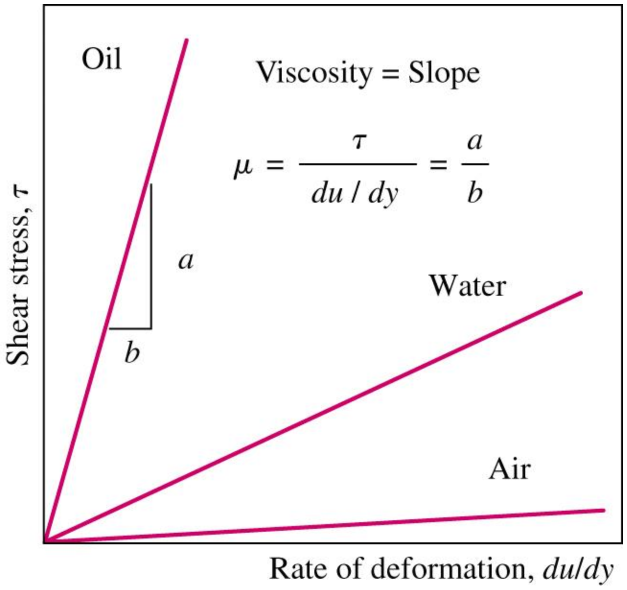
Viscosity

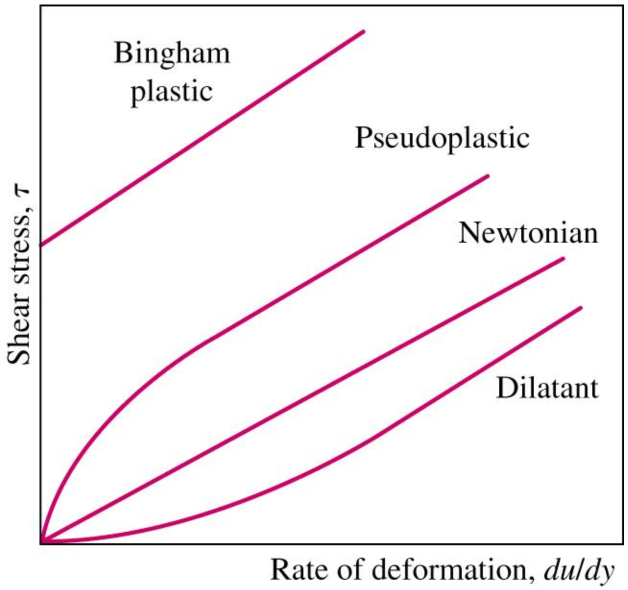


$$u(y) = \frac{y}{\ell} V$$

- To obtain a relation for viscosity, consider a fluid layer between two very large parallel plates separated by a distance ℓ. *F* is the force applied on the upper plate
- 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: $\tau \propto d\beta/dt = du/dy$ (deformation rate)
- μ is the constant of proportionality: **dynamic viscosity**. Units of *kg/m·s*, *Pa·s*, or ***poise*** = 0.1 *Pa·s*.
- The viscosity of water at 20°C is 1 *centipoise*

Viscosity





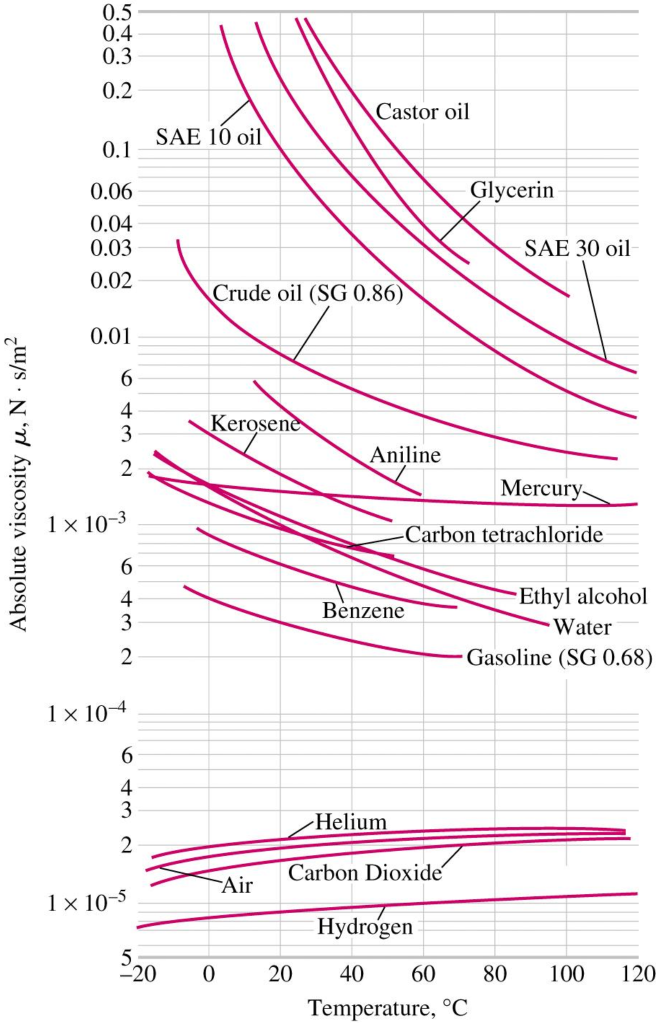
Kinematic viscosity: $\nu = \mu/\rho$, units are m^2/s and *stoke* (= 1 cm^2/s).
The kinematic viscosity of water at 20°C is 1 *centistokes*.

Air at 20°C and 1 atm:
$\mu = 1.83 \times 10^{-5}$ kg/m · s
$\nu = 1.52 \times 10^{-5}$ m^2/s

Air at 20°C and 4 atm:
$\mu = 1.83 \times 10^{-5}$ kg/m · s
$\nu = 0.380 \times 10^{-5}$ m^2/s

dynamic viscosity varies little with P

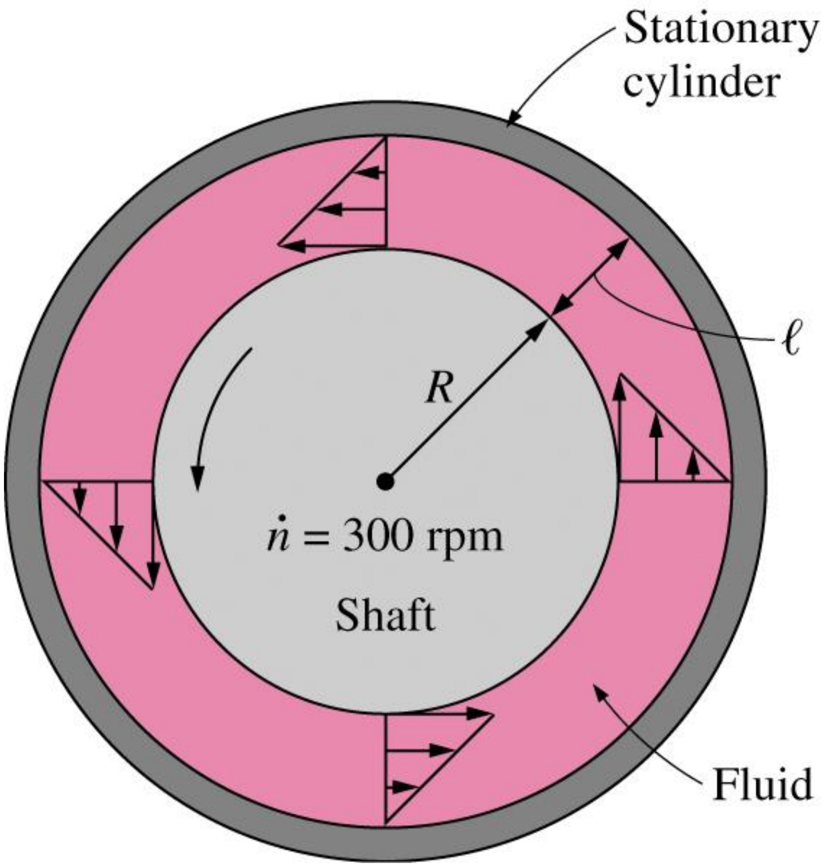
Viscosity



The viscosity of liquids decreases and the viscosity of gases increases with temperature.

Variation of μ with *T* at 1 *atm* for different fluids

Viscometry

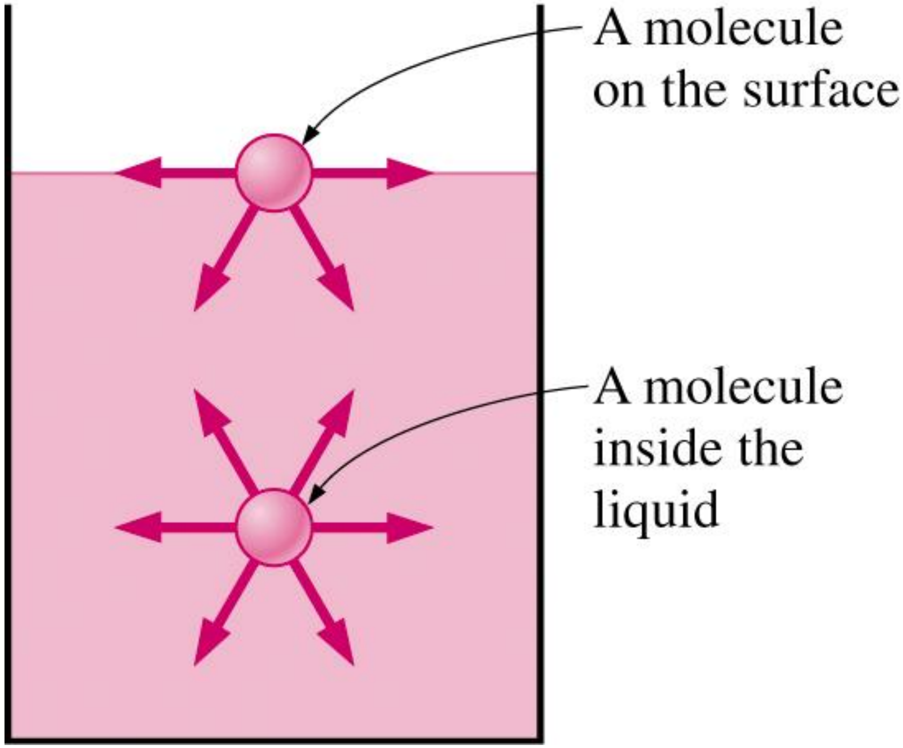


- How is viscosity measured? A rotating viscometer.
  - Two concentric cylinders with a fluid in the small gap ℓ.
  - Inner cylinder is rotating, outer one is fixed.
- Use definition of shear force:

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

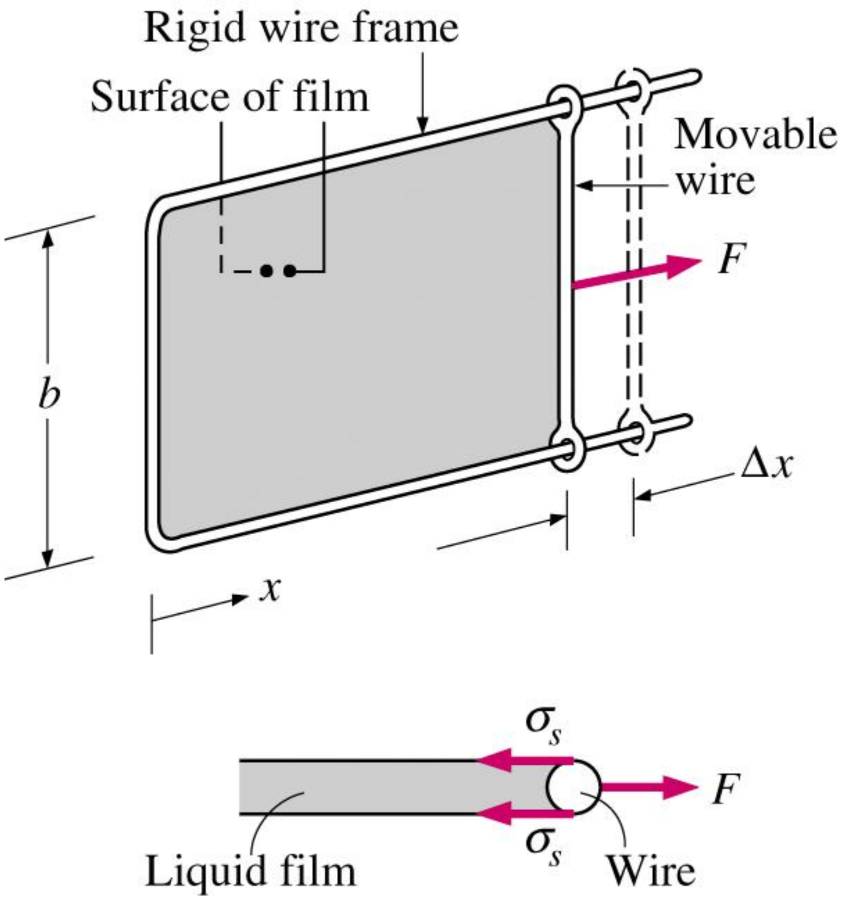
- If $\ell/R \ll 1$, then cylinders can be modeled as flat plates.
- Torque $T = FR$, and tangential velocity $V=\omega R$
- Wetted surface area $A=2\pi RL$.
- Measure T and ω to compute μ

Surface Tension



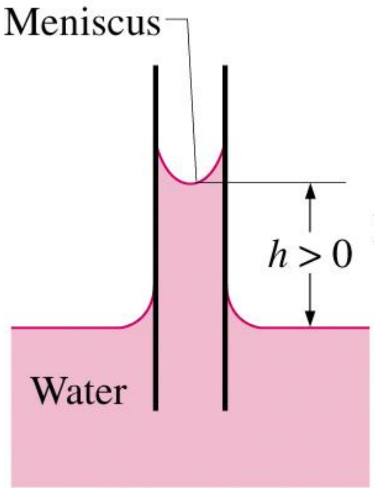
- Liquid droplets behave like small spherical balloons filled with liquid, and the surface of the liquid acts like a stretched elastic membrane under tension.
- The pulling force that causes this is
  - due to the attractive forces between molecules
  - called **surface tension** σ_s *(N/m).*
- Attractive force on surface molecule is not symmetric → the interface is not necessarily flat.
- σ_s is also measured in *J/m²*. It can be interpreted as the stretching work needed to be done to increase the surface area of a liquid by a unit amount.

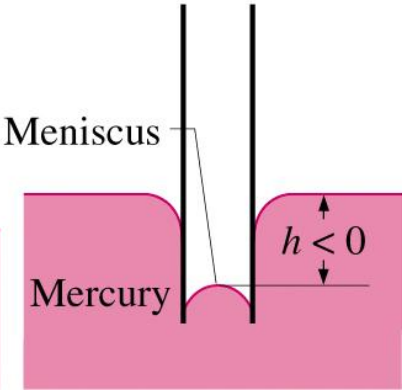
Surface Tension

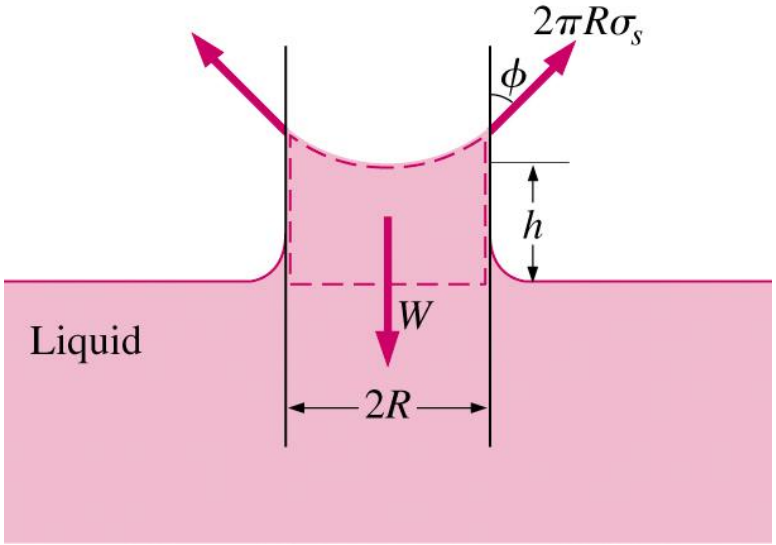


- Film of soapy water suspended on a U-shaped wire frame with a movable side
- The liquid film tends to pull the wire inwards to minimize surface area (σ_s)
- F can be applied to balance the pulling effect; equilibrium requires that $F = 2b\ \sigma_s$
- To stretch the film and increase surface area by $\Delta A = 2b\ \Delta x$ the work done is $W = F\ \Delta x = \sigma_s\ \Delta A$
- During the stretching process the surface energy of the film is increased by $\sigma_s\ \Delta A$
- σ_s varies greatly from substance to substance and is function of the two fluids in contact

Capillary Effect







- **Capillary effect** is the rise or fall of a liquid in a small-diameter tube. The curved free surface of the liquid in the tube is called the **meniscus**.
- Water meniscus curves up because water is a *wetting fluid (*ϕ = contact angle*).*
- Mercury meniscus curves down because mercury is a *nonwetting fluid*.
- Force balance (*cohesive vs adhesive* forces) can describe magnitude of capillary rise/fall.