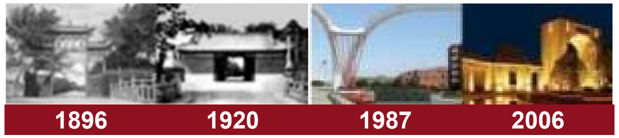


Introduction to Marine Hydrodynamics

(NA235)

Department of Naval Architecture and Ocean Engineering

School of Naval Architecture, Ocean & Civil Engineering

Shanghai Jiao Tong University

First Assignment

- The first assignment can be downloaded from the FTP server:

  Website： ftp://public.sjtu.edu.cn

  Username： dcwan

  Password： 2015mhydro

  Directory： IntroMHydro2015-Assignments

- Six problems
- Submit the assignment on March 12th (in English, written on paper)

Chapter 1

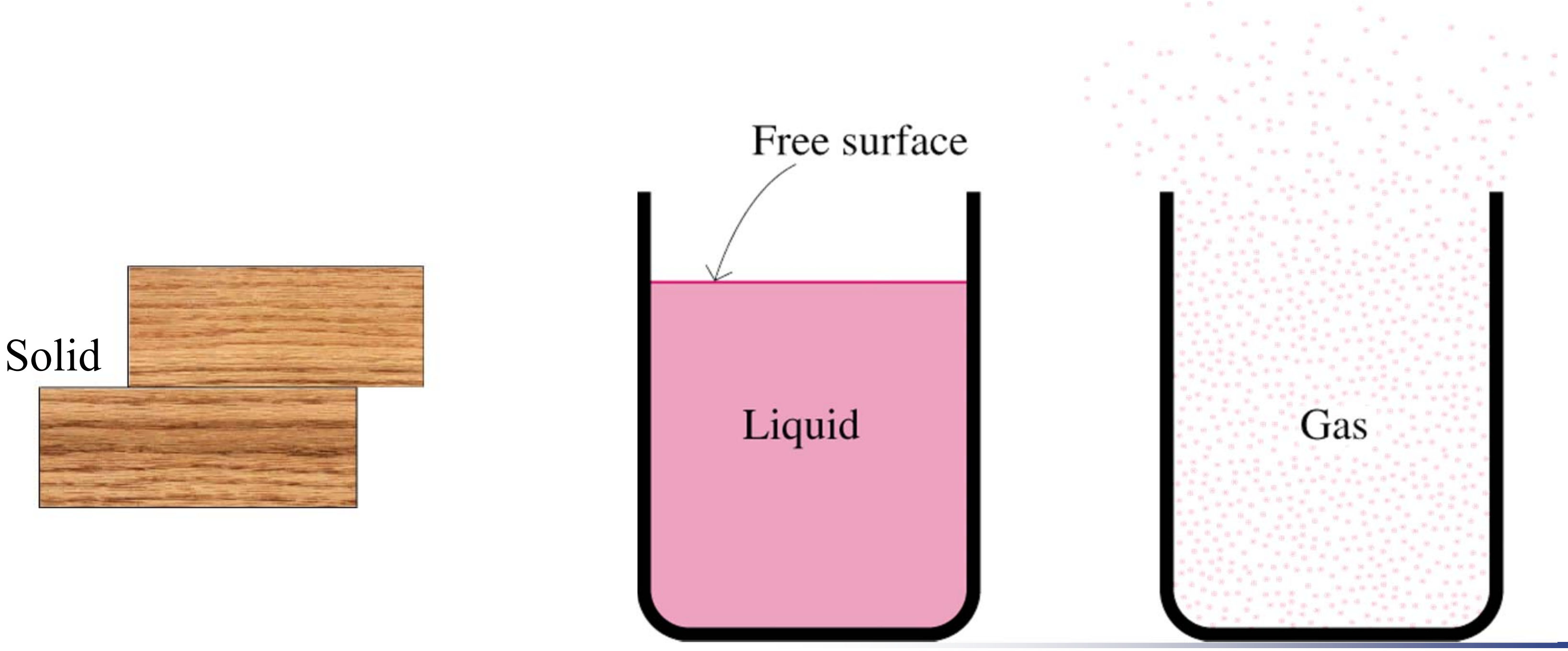
Properties of Fluids

1.1 Definition of Fluids

Fluid mechanics deals with the flow of fluids …

What is a fluid?

Three states of matter: Solid, Liquid, Gas

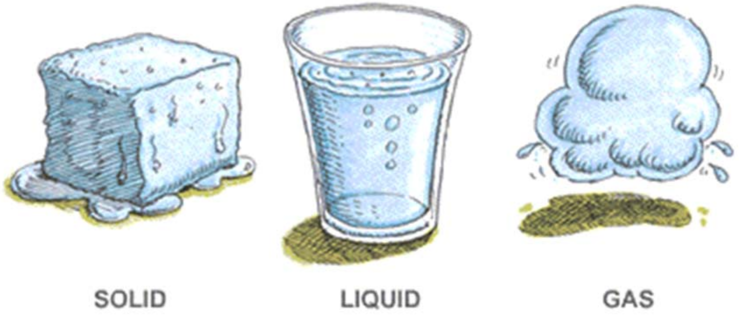


1.1 Definition of Fluids

Solid: **definite** shape and volume, can resist pressure, tension and shear forces

Liquid: **definite** volume, **no** definite shape; cannot be compressed; forms a **free surface** because of gravity

Gas: **no definite** shape and volume; may be compressed



Fluids include both liquid and gas

1.1 Definition of Fluids

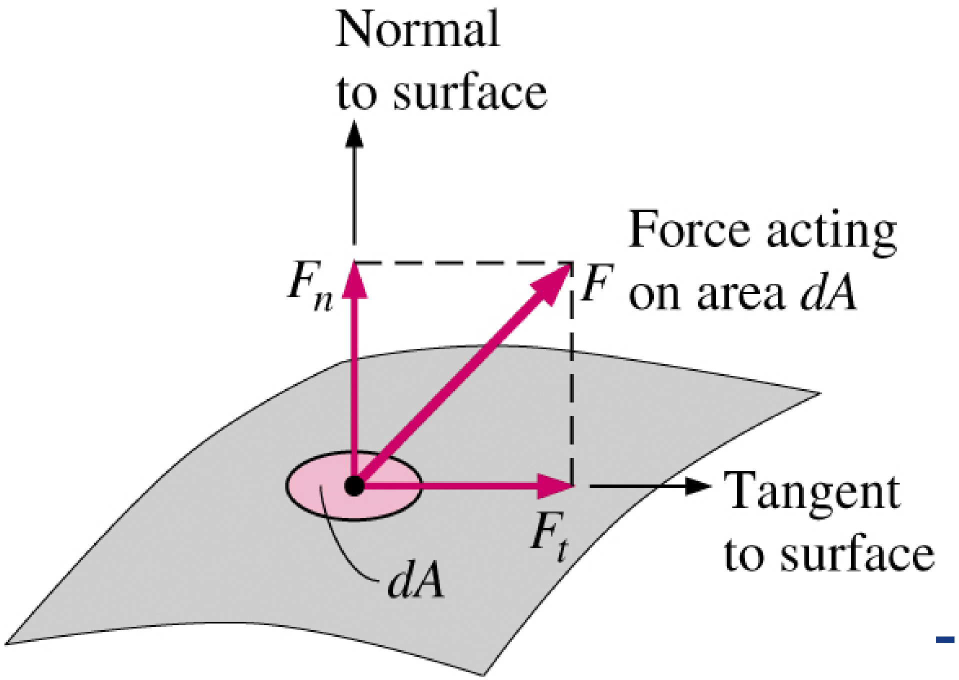
Features of a fluid: unable to resist tensile normal stress and shear stress.

A fluid deforms continuously under the application of a ***shearing stress****, no matter how small the shear stress maybe.*

$$\text{Normal stress} = \frac{F_n}{dA}$$

$$\text{Shear stress} = \frac{F_t}{dA}$$

(tangential stress)



1.1 Definition of Fluids

Definition:

A *fluid* is a substance which *deforms* continuously under the application of a *shear stress*.

In short, a substance that can flow is called fluid.

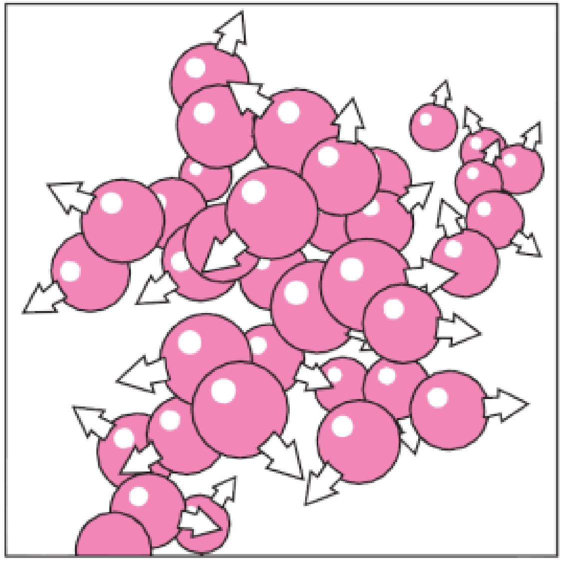
Examples: water, air, steam, gasoline, alcohol, lubricant, blood, sand in water, plasma under high temperature conditions, etc.

1.2 Properties of Fluids

- Fluidity
- Deformability
- Viscosity
- Compressibility

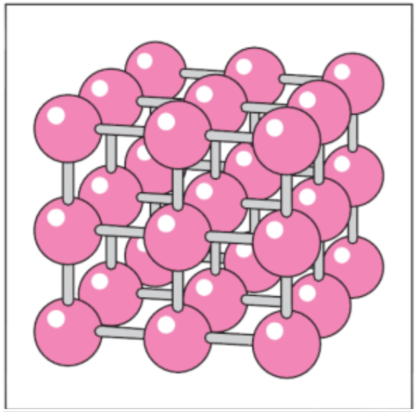
1.2.1 Fluidity

Fluidity: intermolecular forces of a fluid are **small**, so it is difficult to maintain a fixed shape like a solid. As long as an external force exists or the energy is imbalance, the fluid will flow.

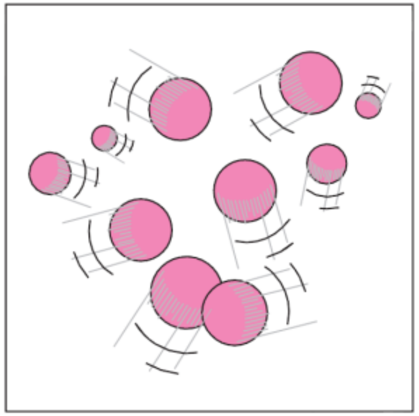


1.2.1 Fluidity

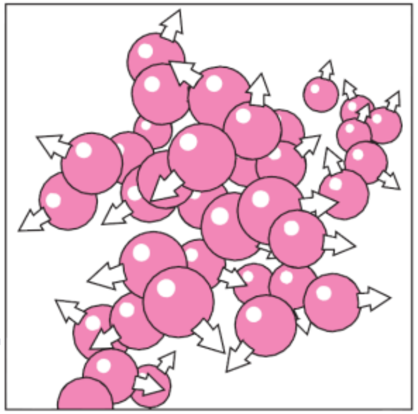
Solid: **large** intermolecular cohesive forces and hence molecules are **not free** to move; **definite** shape; able to **resist** normal stress and shear stress



Gas: **great** freedom of motion with **negligible** intermolecular cohesive forces, **no definite** shape and volume: **cannot** resist tensile normal stress and shear stress



Liquid: intermolecular cohesive forces are smaller than for solids but larger than for gas; **fixed** volume, **no definite** shape; **cannot** resist tensile normal stress and shear stress



1.2.2 Deformability

Deformability: a solid can resist a shear stress by a finite deformation which does not change with time; while any shear stress applied to a fluid, no matter how **small**, will result in motion of that fluid.

1.2.2 Deformability

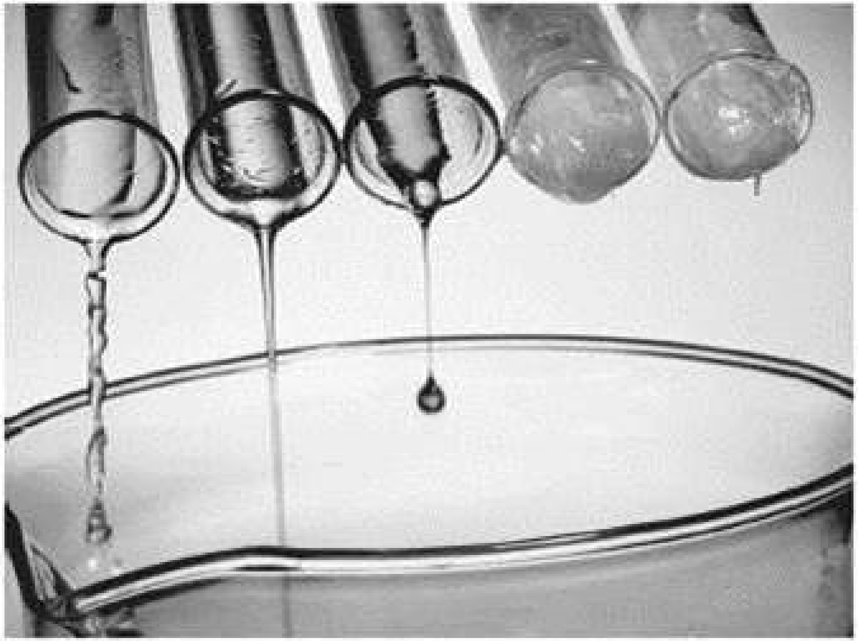
- A solid deforms by a shear stress and **returns** to its original state once the shear stress is removed, but a fluid **cannot return** to the original state after the deformation.

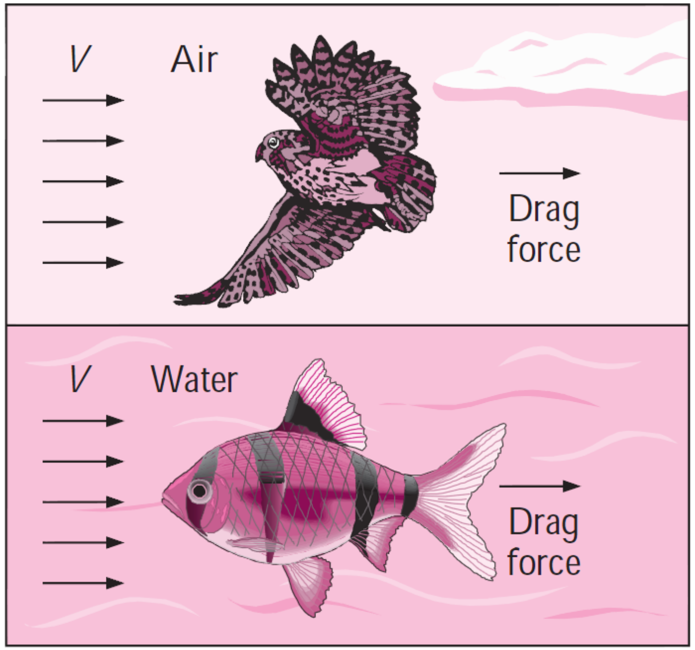
- Within the elastic limit of a **solid**, the deformation of the solid is proportional to the applied force, according to **Hooke's law**. The shear stress imposed on a solid is determined by the strain produced. However, the shear stress in a **fluid** is independent of the strain, it is determined by its velocity gradient, following **Newton's Law of Viscosity**.

1.2.3 Viscosity

Definition: a quantitative measure of the internal resistance (fluid friction) of a fluid to motion.

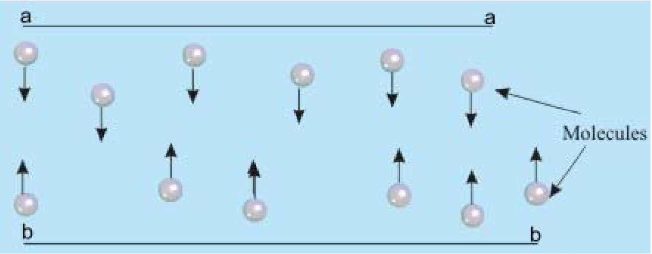
We can easily move through air, which has very low viscosity. Movement is more difficult in water, which has 50 times higher.



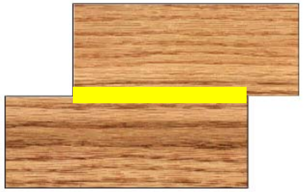


1.2.3 Viscosity

Relative movement takes place between two adjacent layers of fluid, viscosity arises from the shear stress between the layers that ultimately opposes any applied force. Unlike a solid, the shear stress depends on the rate, not the size, of the deformation.



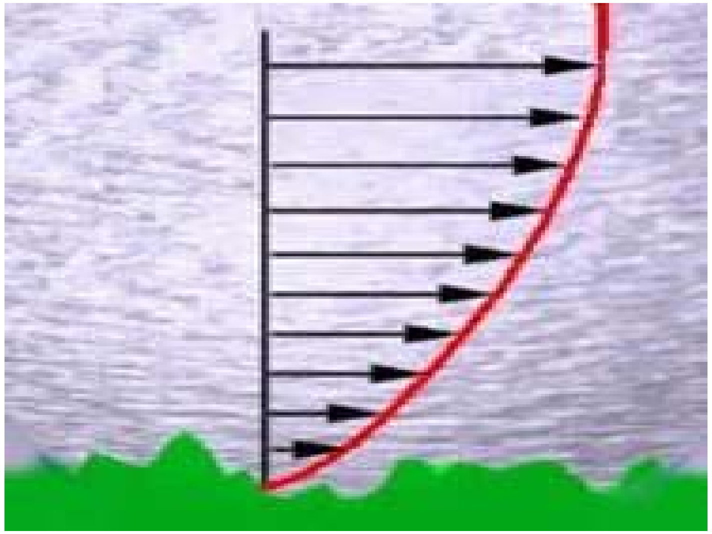
* **Solid**: when two solid bodies in contact move relative to each other, a friction force (sliding friction) develops at the contact surface in the direction opposite to motion, it is affected by surface roughness.

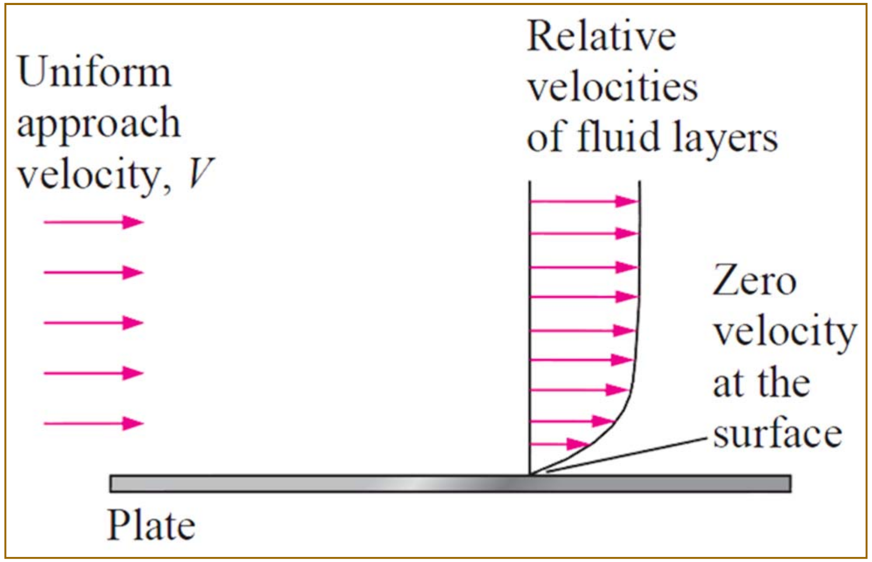


1.2.3 Viscosity

The no-slip condition

No-slip assumption: a fluid flowing over a solid surface comes to a complete **stop** at the surface and assumes a **zero velocity** relative to the surface.

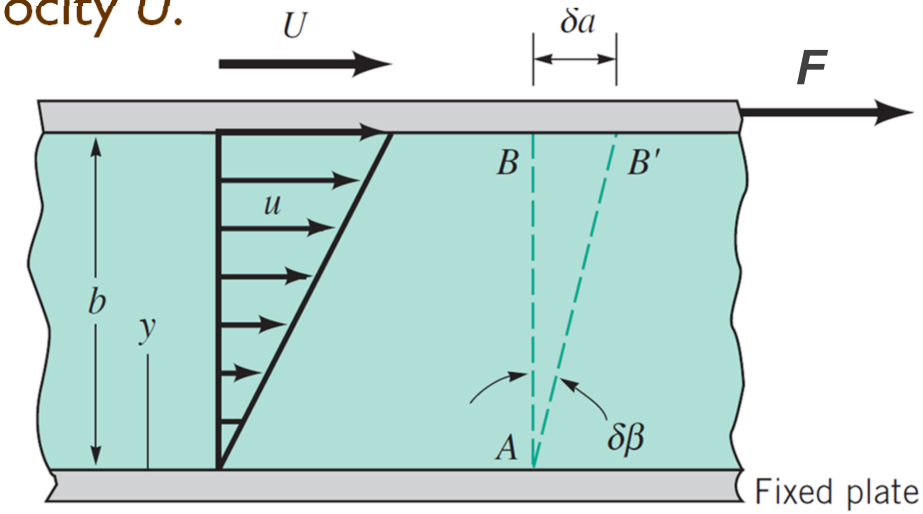




- No slip assumption has been verified in a large number of experiments, and is named **no-slip condition**.

1.2.3 Viscosity

Consider a fluid layer between two very large parallel plates separated by a distance. A constant parallel force *F* is applied to the upper plate while the lower plate is fixed. The upper plate moves continuously under the influence of this force at a constant velocity *U*.



In steady laminar flow, the fluid velocity between the plates varies linearly between 0 and *U*, the velocity profile is written as:

$$\boxed{u(y)=Uy/b}$$

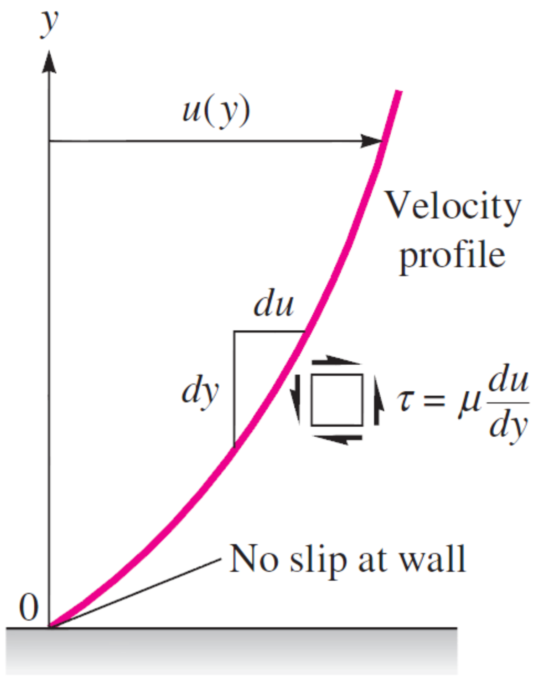
The shear stress *τ* acting on this fluid layer is proportional to the velocity gradient (rate of deformation):

$$\boxed{\frac{F}{A}=\tau\propto U/b}$$

1.2.3 Viscosity

Newton's law of viscosity: the shear stress is proportional to the velocity gradient, the constant of proportionality μ is called the coefficient of viscosity, or the dynamic viscosity of the fluid, kg/m · s

$$\boxed{\tau = \mu \frac{du}{dy}}$$



#Compared with the Hooke's law

for solid materials: $f = kx$

1.2.3 Viscosity

μ is dynamic viscosity, from Newton's law of viscosity:

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

Unit: $kg/(s \cdot m),\ N \cdot s/m^2$ or $Pa \cdot s$

Quite often the term 'kinematic viscosity' appears in fluid flow problems, expressed as the ratio of dynamic viscosity to density:

$$\nu = \frac{\mu}{\rho}$$

Unit: m^2/s

$\boldsymbol{\rho}$ is the density of fluid, unit: kg/m^3

1.2.3 Viscosity

- In the normal atmospheric temperature and pressure, dynamic viscosity of water is 55.4 times of air's

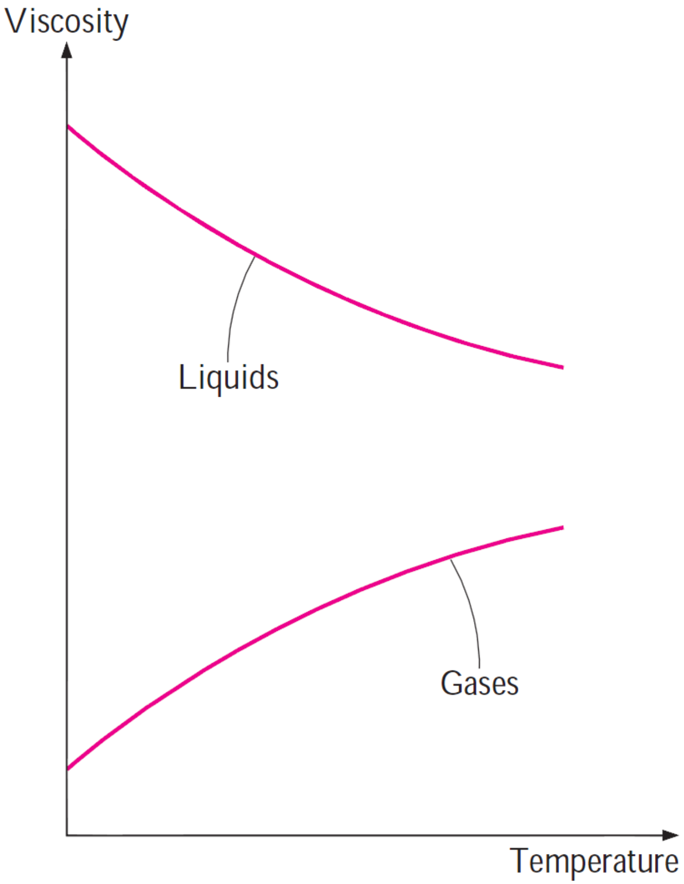
Water	$\mu = 1\times10^{-3}\,\mathrm{Pa}\cdot\mathrm{s} = 0.01\mathrm{P}$
Air	$\mu = 1.8\times10^{-5}\,\mathrm{Pa}\cdot\mathrm{s} = 0.00018\mathrm{P}$

- In the normal atmospheric temperature and pressure, kinematic viscosity of air is 15 times of water's

Water	$\nu = 1\times10^{-6}\,\mathrm{m}^2/\mathrm{s} = 0.01\mathrm{cm}^2/\mathrm{s}$
Air	$\nu = 15\times10^{-5}\,\mathrm{m}^2/\mathrm{s} = 0.15\mathrm{cm}^2/\mathrm{s}$

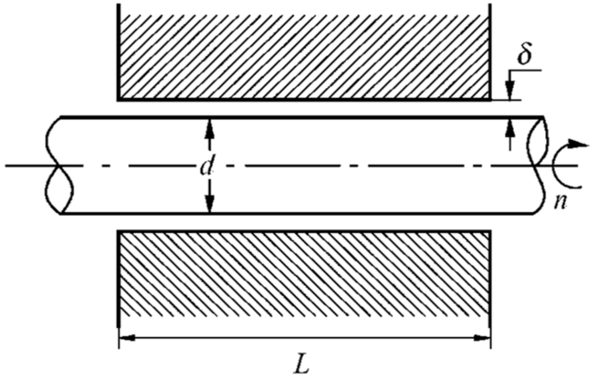
1.2.3 Viscosity

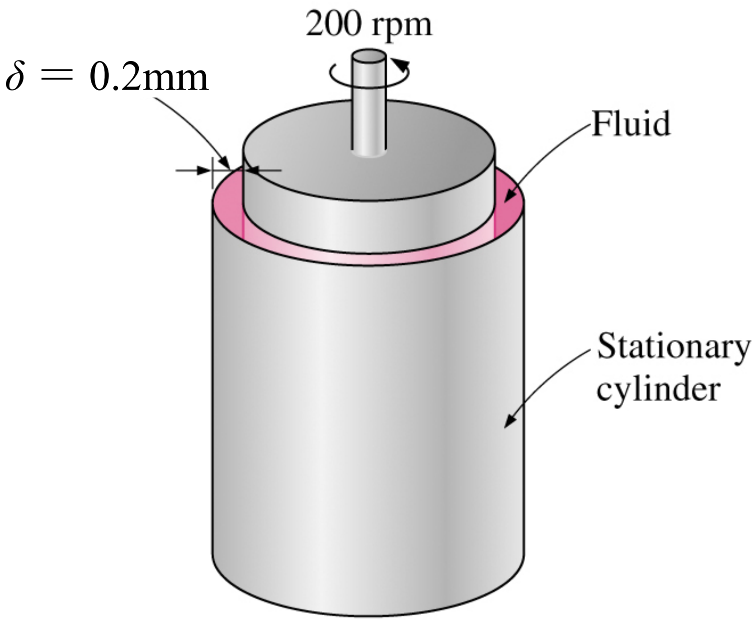
In general, the viscosity of a fluid depends on both **temperature** and **pressure**, but the dependence on pressure is rather weak. The viscosity of liquids decreases with temperature, whereas the viscosity of gases increases with temperature.

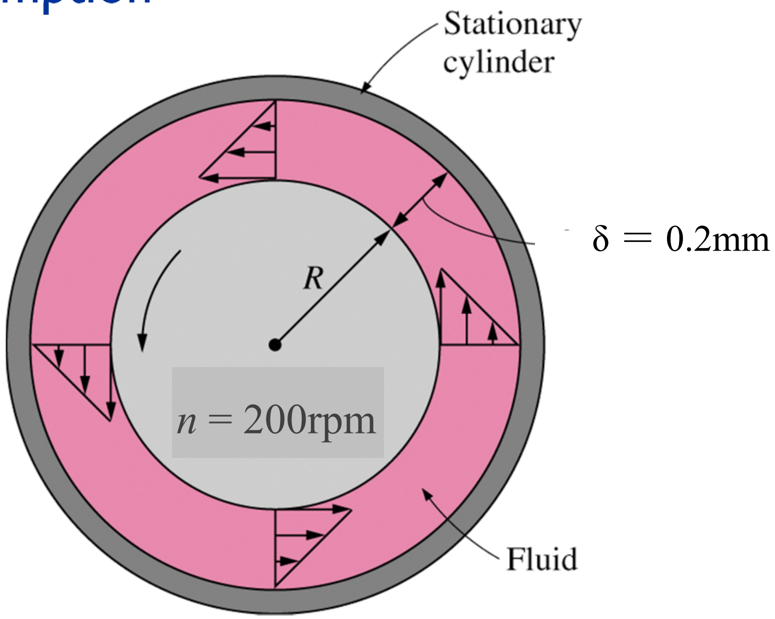


Newton's Law of Viscosity

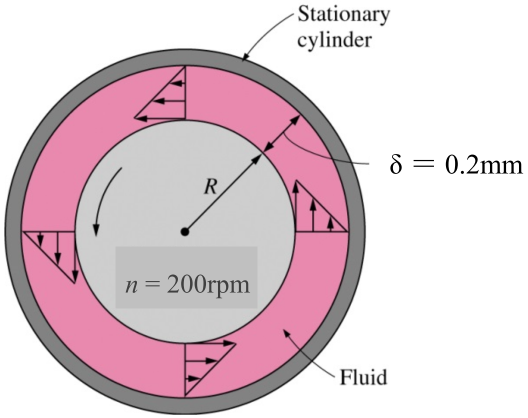
Example 1: The viscosity of a fluid is to be measured by a viscometer constructed of two 1-m-long concentric cylinders. The outer diameter of the inner cylinder is 0.36m, the gap between the two cylinders δ is 0.2mm. The inner cylinder is completely submerged in oil with a dynamic viscosity $\mu = 0.72$ Pa.s. The inner cylinder is rotated at 200 rpm. Determine the power consumption to overcome the resistance of the oil.

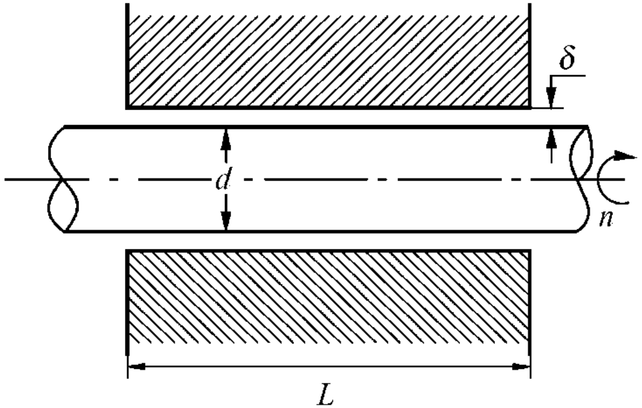






Newton's Law of Viscosity





Solution: the velocity profile is linear only when the curvature effects are negligible, and the profile can be approximated as being linear in this case:

$$U=\omega r=2\pi\frac{n}{60}\frac{d}{2}=\frac{n\pi d}{60}=\frac{\pi\times200\times0.36}{60}=3.77m/s$$

The total tangential force on the cylinder surface is:

$$T=\tau A=\mu\frac{U}{\delta}(\pi d L)=\frac{0.72\times3.77\times\pi\times0.36\times1}{2\times10^{-4}}=1.535\times10^{4}(N)$$

The power consumption to overcome the resistance of the oil is determined to be:

$$N=TU=1.535\times10^{4}\times3.77=5.79\times10^{4}(Nm/s)=57.9\ (kW)$$

1.2.3 Viscosity

Real fluids and Ideal fluids

- **Real fluids (viscous fluids):** have viscosity; when they are in motion, two contacting layers of the fluids experience tangential as well as normal stresses. Internal friction plays an important role in viscous fluids during the motion of the fluid.

- **Ideal fluids (inviscid fluids)**: fluids with no viscosity, no internal resistance; two contacting layers experience no tangential force (shearing stress) but act on each other with normal force (pressure) when the fluids are in motion.

Practical significance of ideal fluids:

Ideal fluids are also known as friction less fluids. However, no such fluid exists in nature. The concept of ideal fluids facilitates simplification of the mathematical analysis. Fluids with low viscosities such as water and air can be treated as ideal fluids under certain conditions.

1.2.3 Viscosity

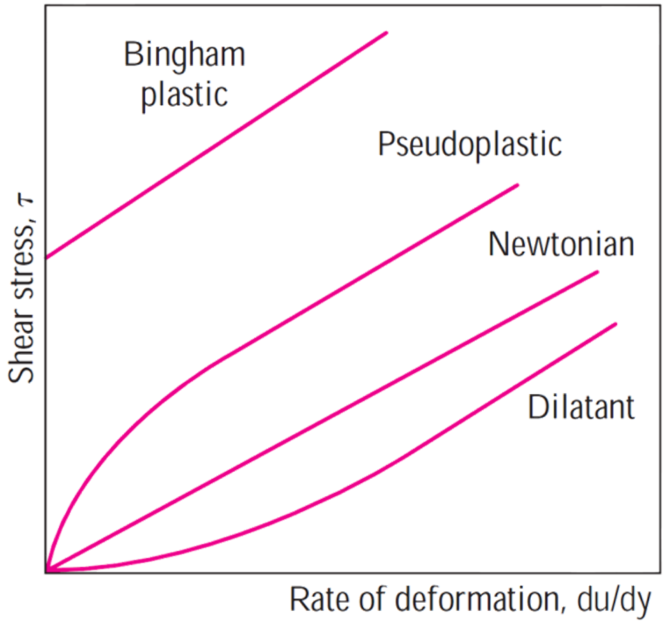
Newtonian fluids and Non-Newtonian fluids

Newtonian fluids: fluids obeying the Newton’s law of viscosity (the shear stress is proportional to the rate of deformation)

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

Non-Newtonian fluids: Fluids for which the shearing stress is **not** linearly related to the rate of shearing strain

$$\tau = \mu(T,\ p)\left(\frac{du}{dy}\right)^2$$



Examples: Soap solutions, gums, blood, butter, cheese, soup, yogurt, etc.

1.2.4 Compressibility

Compressibility is a measure of the relative volume change of a fluid, as a response to a pressure. The decrease in volume per unit volume of a fluid (resulting from a unit increase in pressure) is defined as a **coefficient of compressibility**.

$$k = -\frac{dV/V}{dp} = -\frac{dV}{Vdp}$$

Unit : m^2/N

V is volume of unit mass, p is pressure. A large value of coefficient of compressibility indicates that a large change in pressure, and the fluid can easily be compressed.

Bulk modulus: $K = \frac{1}{k} = -\frac{Vdp}{dV}$

Large values for the bulk modulus indicate that the fluid is relatively incompressible

1.2.4 Compressibility

Density of a fluid is defined as its mass per unit volume, it is typically used to characterize the mass of a fluid system.

Definition: $\rho = \lim\limits_{\Delta V \to 0} \dfrac{\Delta m}{\Delta V}$ $(\ kg/m^3\ )$

For homogeneous fluids: $\rho = \dfrac{m}{V}$

Specific volume: the reciprocal of the density $V = \dfrac{1}{\rho}$

Relative density (specific gravity):

$$d = \rho_f / \rho_w$$

ρ_f is the density of fluid

ρ_w is the density of water at 4℃

1.2.4 Compressibility

From the definition of specific volume: $V = \dfrac{1}{\rho}$

$$V\rho = 1\,,\ \text{after differentiation}: \quad \rho\, dV + V\, d\rho = 0$$

Thus, the coefficient of compressibility can be written as:

$$k = -\frac{dV/V}{dp} = -\frac{dV}{Vdp} = \frac{1}{\rho}\frac{d\rho}{dp}$$

The bulk modulus is written as:

$$K = \frac{1}{k} = -\frac{Vdp}{dV} = \rho\frac{dp}{d\rho}$$

1.2.4 Compressibility

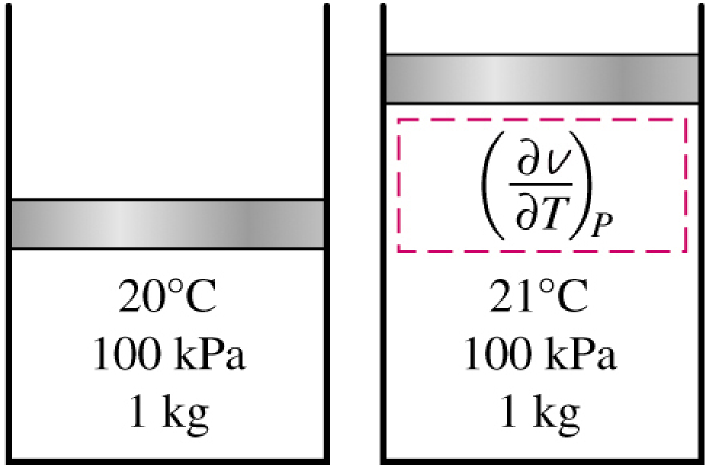
Dilatability (expansion)

The tendency of a fluid to change in volume in response to a change in temperature is termed as dilatability. The degree of dilatability (expansion) is expressed by coefficient of thermal expansion and generally varies with temperature:

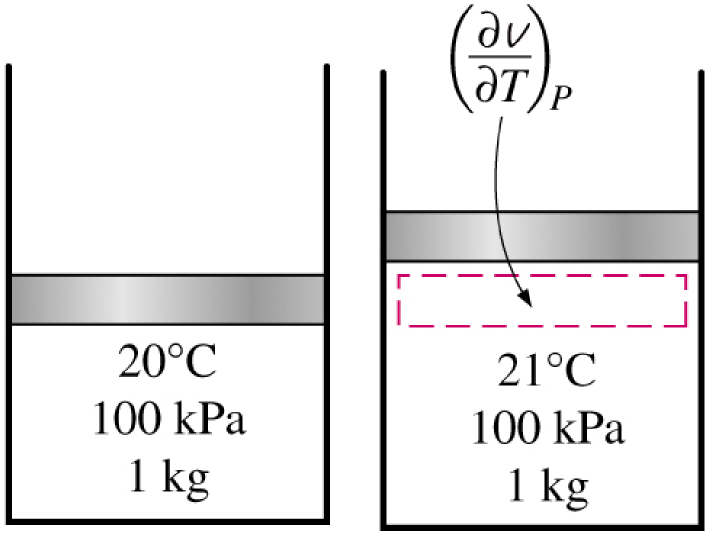
$$\beta = \frac{dV/V}{dT} = \frac{1}{V}\frac{dV}{dT} = -\frac{1}{\rho}\frac{d\rho}{dT}$$

dT is the change in temperature, dV/V is the rate of change of volume. The unit of β is 1/K or 1/℃.

1.2.4 Compressibility



(*a*) A substance with a large β



(*b*) A substance with a small β

1.2.4 Compressibility

Compressible versus Incompressible Fluids

A flow is said to be **incompressible** if the density remains nearly constant throughout. Therefore, the volume of every portion of fluid remains unchanged over the course of its motion. The fluid density varies significantly in response to a change in pressure, when the fluid is **compressible**.

All fluids are compressible to some extent, but liquids are usually referred to be incompressible, while gases are compressible.

1.3 Continuum Hypothesis

A fluid is composed of a large number of molecules in constant motion and undergoing collisions with each other. When the molecular density of the fluid and the size of the region of interest are large enough, such average properties are sufficient for the explanation of macroscopic phenomena and the discrete molecular structure of matter may be ignored and replaced with a continuous distribution, which is called a **continuum**. This is the "**continuum hypothesis**" proposed by Euler in 1755.

In a continuum, fluid properties like temperature, density, or velocity are defined at every point in space, and these properties are known to be appropriate averages of molecular characteristics in a small region surrounding the point of interest.

1.3 Continuum Hypothesis

A **fluid particle** is a small deforming volume carried by the flow that:

1) always contains the same fluid molecules;

2) from microscopic aspect: is large enough compared to the mean free path so that its properties are well defined when it is at equilibrium;

3) from macroscopic aspect: it is small enough compared to the typical length scales of the specific flow under consideration, so that it can be treated as a point.

1.4 Forces on Fluids

- Body force
- Surface force
- Surface tension