Fundamentals of Fluids

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ENGI 2420

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- Introduction
- Classification of Fluid Flows
- System and Control Volume
- Density and Specific Gravity
- Vapor Pressure and Cavitation
- Compressibility and Speed of Sound
- Viscosity
- Surface Tension and Capillary Effect

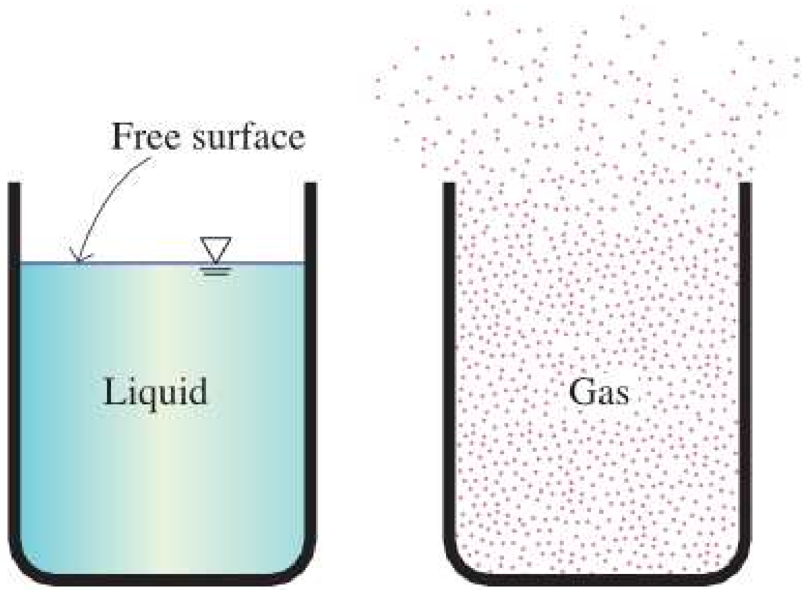
Content

- **Introduction**

Introduction

Fluid Mechanics – the science that deals with the behavior of liquids and gases in motion or at rest.

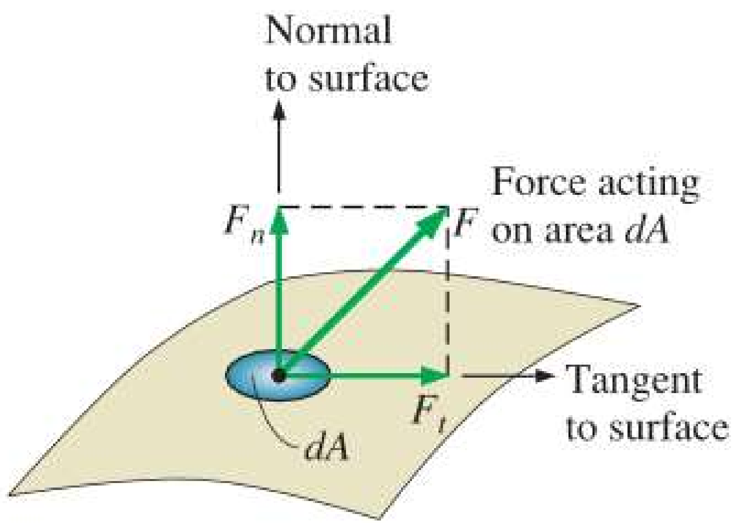
Fluid – is a substance in the liquid or gas phase.



Unlike a liquid, a gas does not form a free surface, and it expands to fill the entire available space

Introduction

Stress – is defined as a force per unit area.



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

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

The normal stress and shear stress at
the surface of a fluid element.

Introduction

Application Areas of Fluid Mechanics

Natural flows and weather
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Power plants
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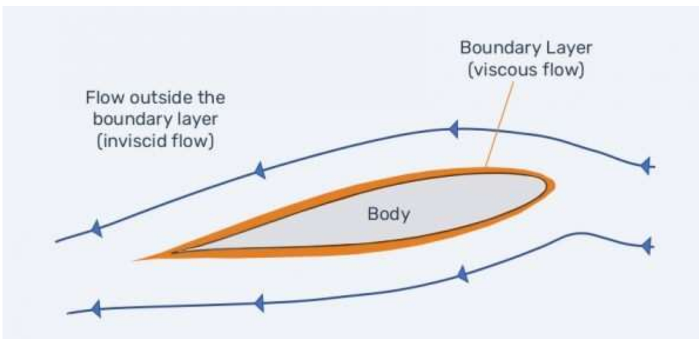
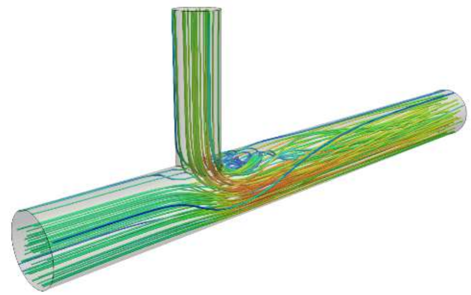
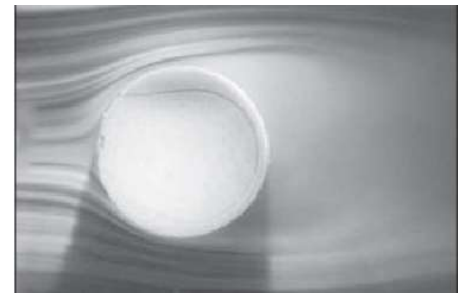
Classification of Fluid Flows

Viscous versus Inviscid Regions of Flow

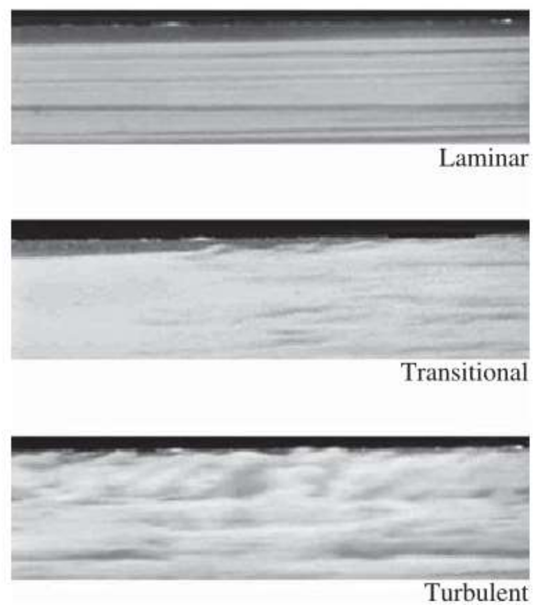


Internal versus External Flow





Laminar versus Turbulent Flow



Compressible versus Incompressible Flow

Compressible Flow : density varies.

Incompressible Flow : density is constant.

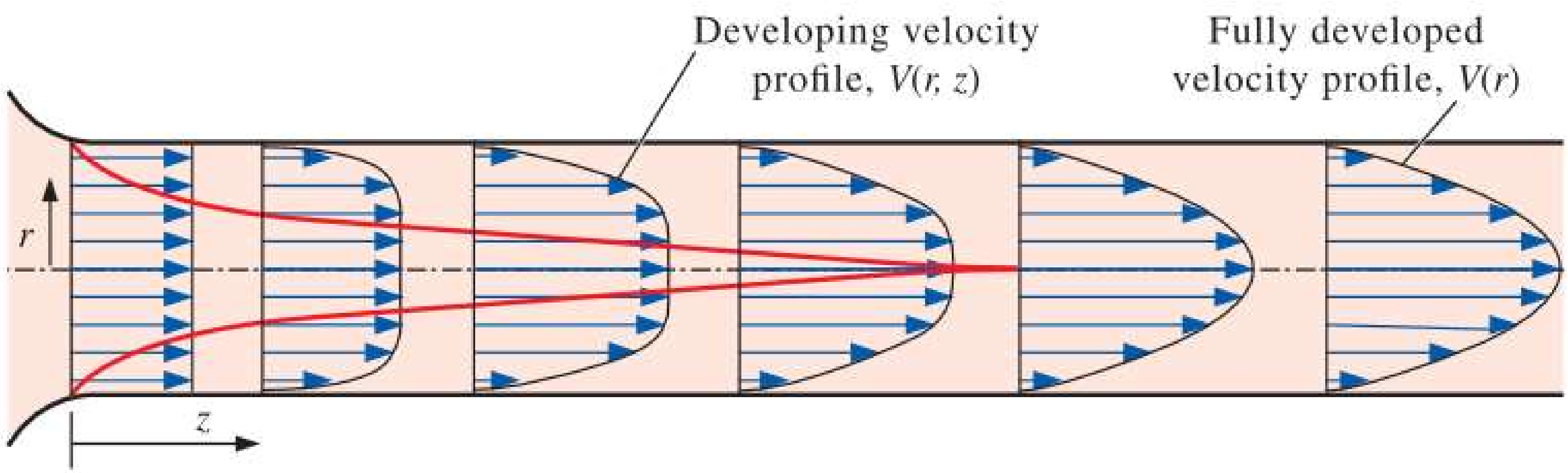
Classification of Fluid Flows

Steady versus Unsteady Flow

Steady : implies NO change of properties, velocity, temperature, etc., at a point with time.

Unsteady : implies change of properties, velocity, temperature, etc., at a point with time.

One-, Two-, and Three- Dimensional Flows



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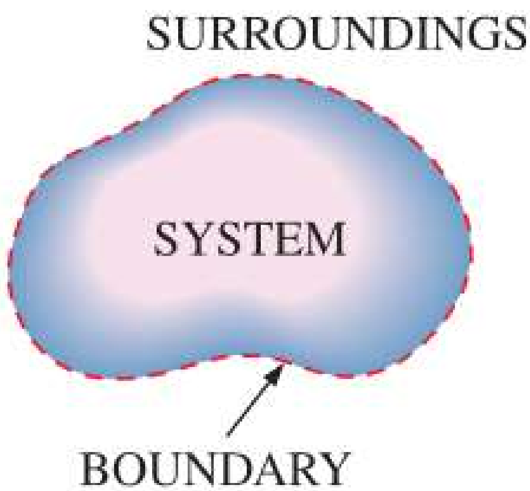
System and Control Volume

System – is defined as a quantity of matter or a region in space chosen for study.

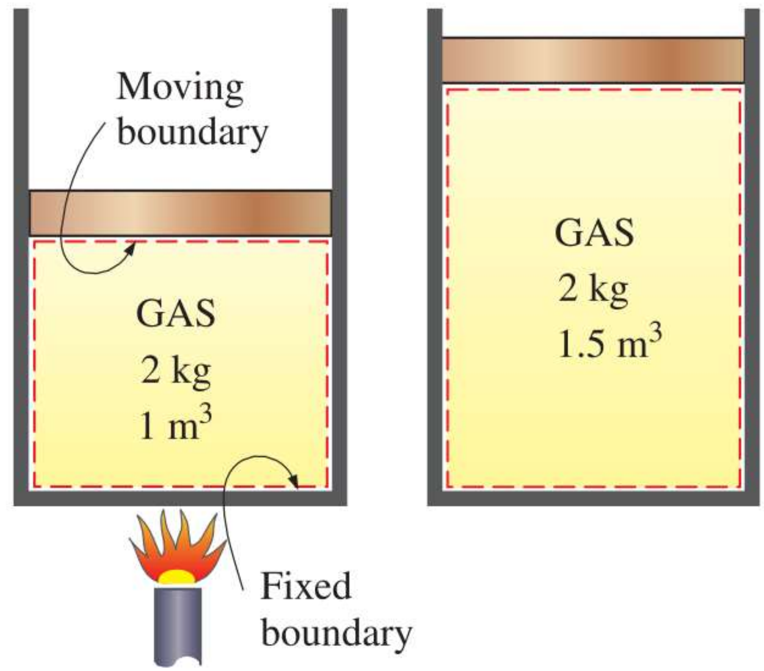


Types

– Closed system

– Open system (or Control Volume)

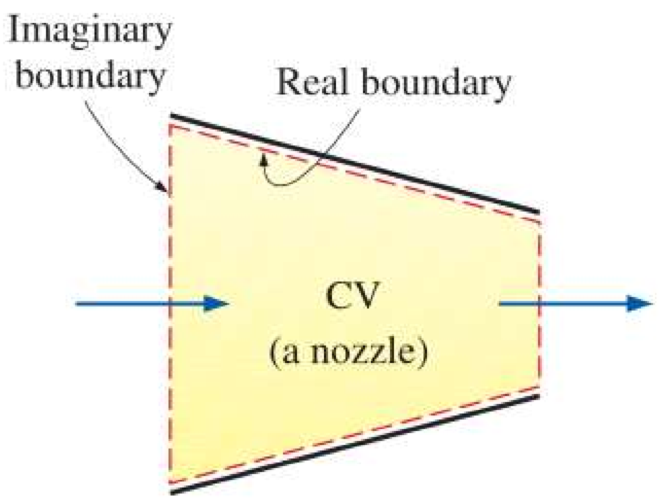
Closed system – consist of a fixed amount of mass, and no mass can cross its boundary.



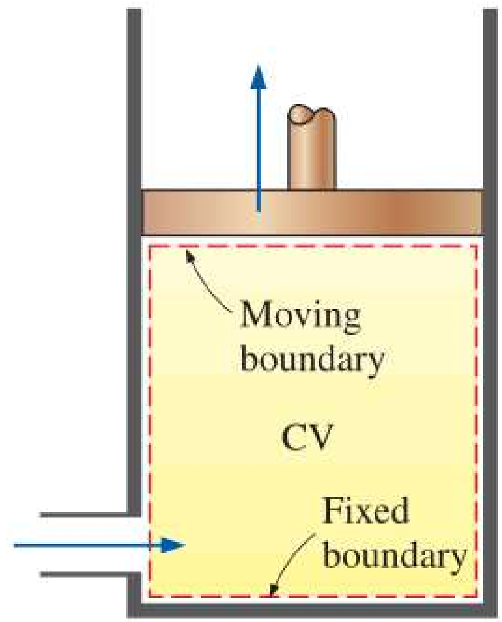
A closed system with a moving boundary.

System and Control Volume

Open System (or Control Volume) – is a selected region in space where mass can cross its boundary.



(*a*) A control volume (CV) with real and imaginary boundaries



(*b*) A control volume (CV) with fixed and moving boundaries as well as real and imaginary boundaries

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Density and Specific Gravity

Density, ρ, is defined as mass per unit volume.

$$\rho = \frac{m}{\mathcal{V}} \qquad \rho = \frac{1}{v}$$

***m* :** Mass.

$\mathcal{V}$: Volume.

Specific volume, *v*, is defined as volume per unit mass.

$$v = \frac{\mathcal{V}}{m}$$

Specific weight, γ, is defined as its weight per unit volume.

$$\gamma = \rho g \quad \text{or} \quad \gamma = \frac{W}{\mathcal{V}}$$

Specific gravity (or relative density) is defined as the ratio of the density of a substance ρ to the density of some standard substance at a specified temperature (usually water at 4°C, for which $\rho_{H_2O} = 1000\ kg/m^3$).

$$SG = \frac{\rho}{\rho_{H_2O}}$$

Perfect gas equation

$$\rho = \frac{P}{RT}$$

ρ : Absolute pressure.
P : Absolute pressure.
T : Absolute temperature.
R : Gas Constant.

The specific gravity of some substances at 20°C and 1 atm unless stated otherwise

Substance	SG
Water	1.0
Blood (at 37°C)	1.06
Seawater	1.025
Gasoline	0.68
Ethyl alcohol	0.790
Mercury	13.6
Balsa wood	0.17
Dense oak wood	0.93
Gold	19.3
Bones	1.7–2.0
Ice (at 0°C)	0.916
Air	0.001204

Density and Specific Gravity

Example 1.1

A reservoir of glycerin has a mass of 1200 kg and a volume of 0.952 m^3. Find the glycerin's a) weight; b) mass density; c) specific weight; and d) specific gravity.

Density and Specific Gravity

Example 1.2

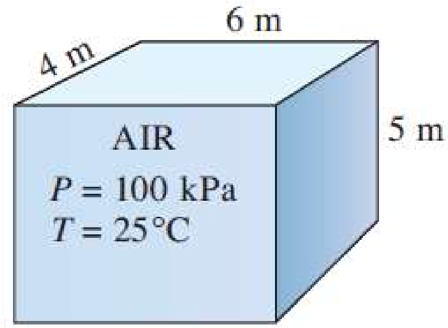
If 200 ft^3 of oil weights 10,520 lbf, calculate a) specific weight; b) density; and c) specific gravity.

Hint $$1\,lbf = 32.17\frac{lbm \cdot ft}{s^2}$$

Density and Specific Gravity

Example 1.3

Determine the density, specific gravity, and mass of the air in a room whose dimensions are 4 m × 5 × 6 m at 100 kPa and 25°C.



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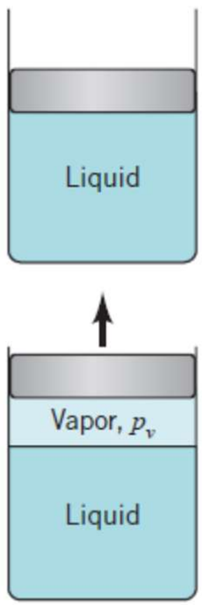
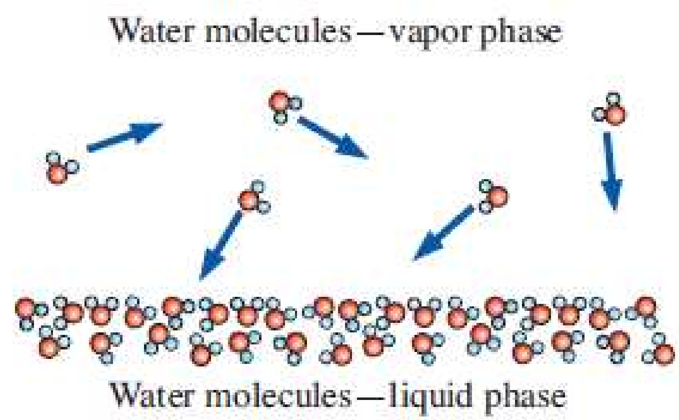
Vapor Pressure and Cavitation

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.



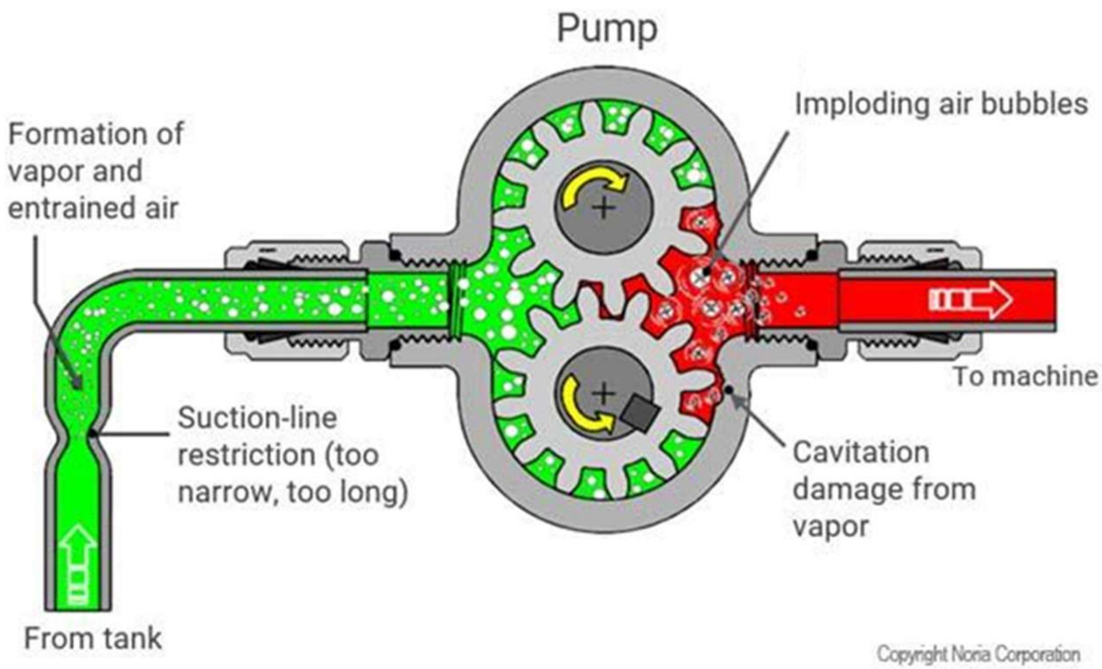
$$P_v = P_{sat}$$



A liquid boils when the pressure is reduced to the vapor pressure.

Cavitation is the formation and subsequent collapse of vapor bubbles in a flowing fluid.

Vapor Pressure and Cavitation



Formation of vapor pockets in pump

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

Example 1.4

In a water distribution system, the water temperature is as high as 52°C. Determine the minimum pressure allowed in the system to avoid cavitation.

Hint: See Table A-3 (Cengel & Cimbala, 2014)

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Compressibility and Speed of Sound

Coefficient of Compressibility κ

Represents the change in pressure corresponding to a fractional change in volume or density of the fluid while the temperature remains constant.

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

v : Volume

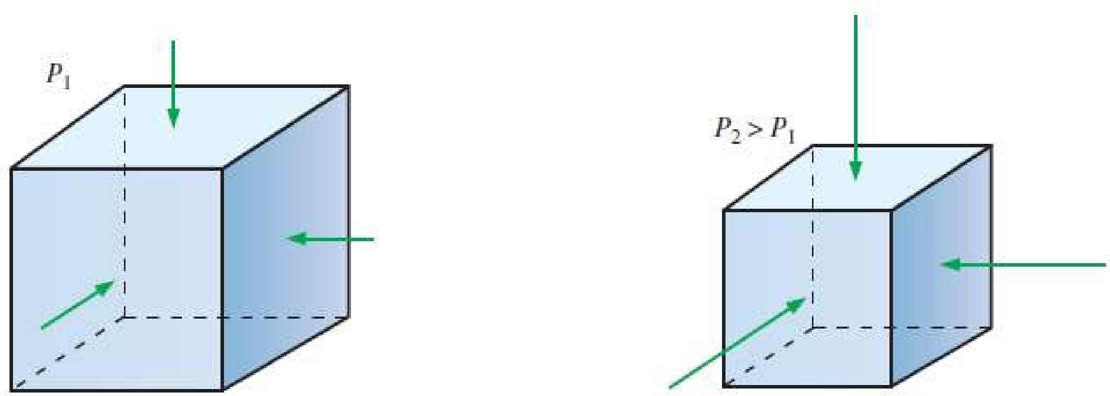
P : Pressure

ρ : Density

T : Temperature

In terms of finite changes

$$\kappa \approx -\frac{\Delta P}{\Delta v / v} \cong \frac{\Delta P}{\Delta \rho / \rho} \qquad (T = \text{constant})$$



Fluids, like solids, compress when the applied pressure is increased from P_1 to P_2.

Compressibility and Speed of Sound

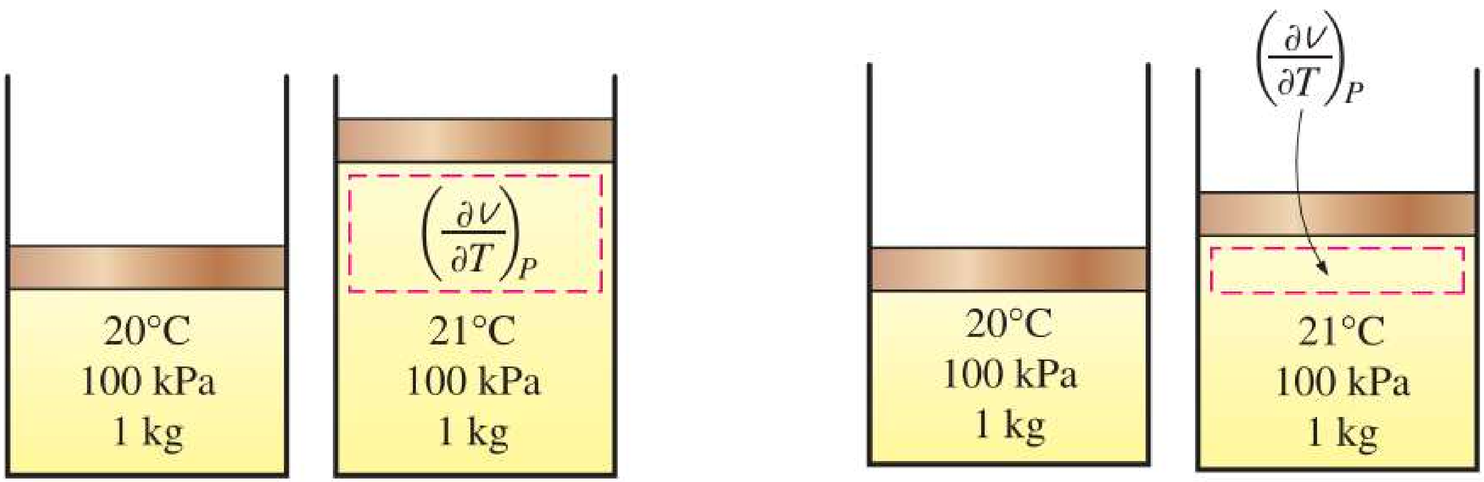
Coefficient of Volume Expansion β

Represents the variation of the density of a fluid with temperature at constant pressure.

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

In terms of finite changes

$$\beta \approx \frac{\Delta v / v}{\Delta T} = -\frac{\Delta \rho / \rho}{\Delta T} \qquad (P = \text{constant})$$



(*a*) A substance with a large β

(*b*) A substance with a small β

The coefficient of volume expansion is a measure of the change in volume of a substance with temperature at constant pressure.

Compressibility and Speed of Sound

Speed of Sound *c* – is defined as the speed at which an infinitesimally small pressure wave travels through a medium.

$$c^2 = k\left(\frac{\partial P}{\partial \rho}\right)_T$$

k ; Specific heat ratio of the fluid.

$$k = \frac{c_p}{c_v}$$

For an ideal gas

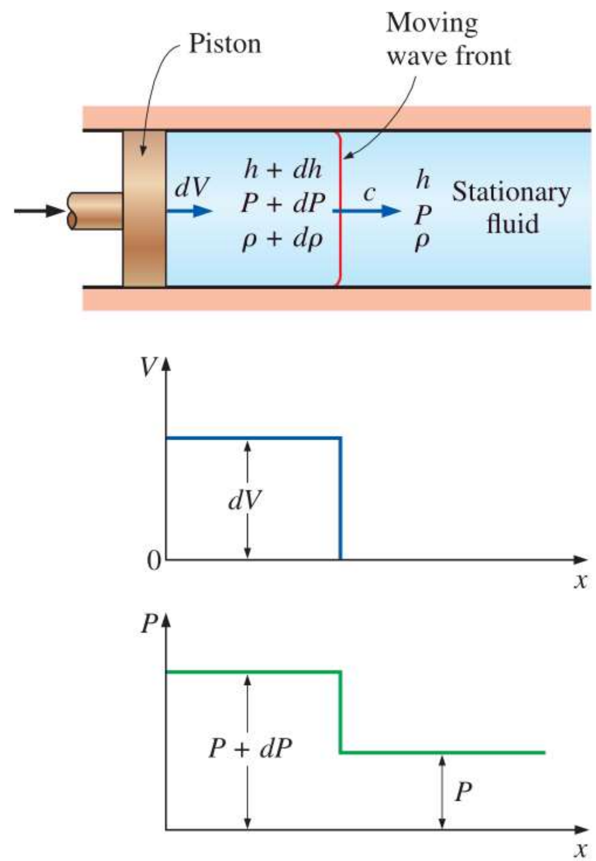
$$c = \sqrt{kRT}$$

c_p ; Specific heat at constant pressure.

c_v ; Specific heat at constant volume.

R ; Gas constant.

h ; Enthalpy.



Propagation of a small pressure wave along a duct.

Mach number *Ma* – is the ratio of the actual speed of the fluid, V, to the speed of sound, c, in the same fluid at the same state.

$$Ma = \frac{V}{c}$$

V : Local fluid velocity.

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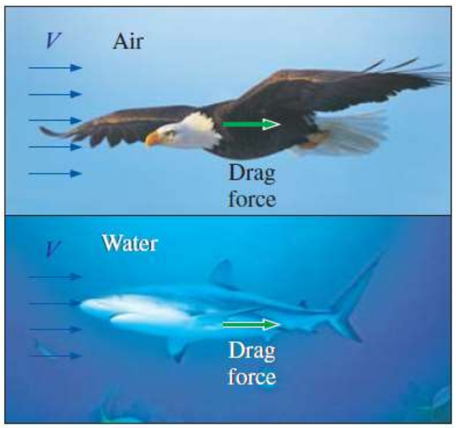
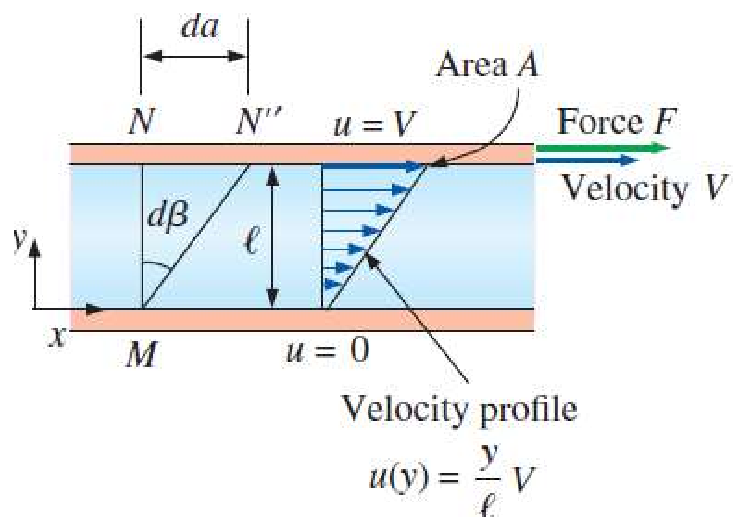
Viscosity

Viscosity – is the property that represents the internal resistance of a fluid to motion or the "fluidity".

Drag force – is the force a flowing fluid exerts on a body in the flow direction.



A fluid moving relative to a body exerts a drag force on the body.



The behavior of a fluid in laminar flow between two parallel plates.

Shear Stress τ

$$\tau = \frac{F}{A}$$

Rate of deformation *dβ/dt*

$$\frac{d\beta}{dt} = \frac{du}{dy}$$

Viscosity

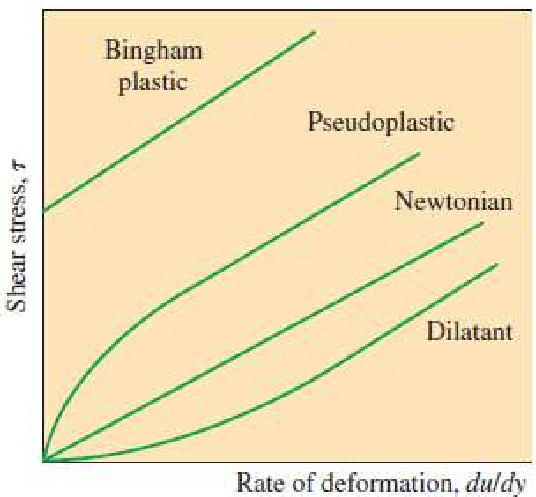
Shear Stress

$$\tau \propto \frac{d\beta}{dt} \qquad \Rightarrow \qquad \boxed{\tau = \mu \frac{du}{dy}}$$

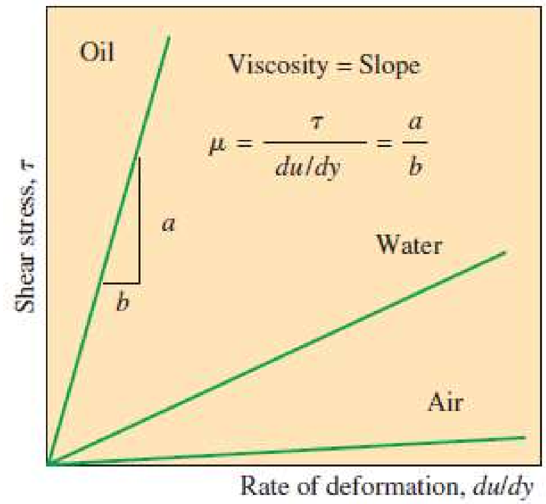
μ : Dynamic Viscosity [kg/m·s].

Shear Force

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



Variation of shear stress with the rate of deformation for Newtonian and non-Newtonian fluids



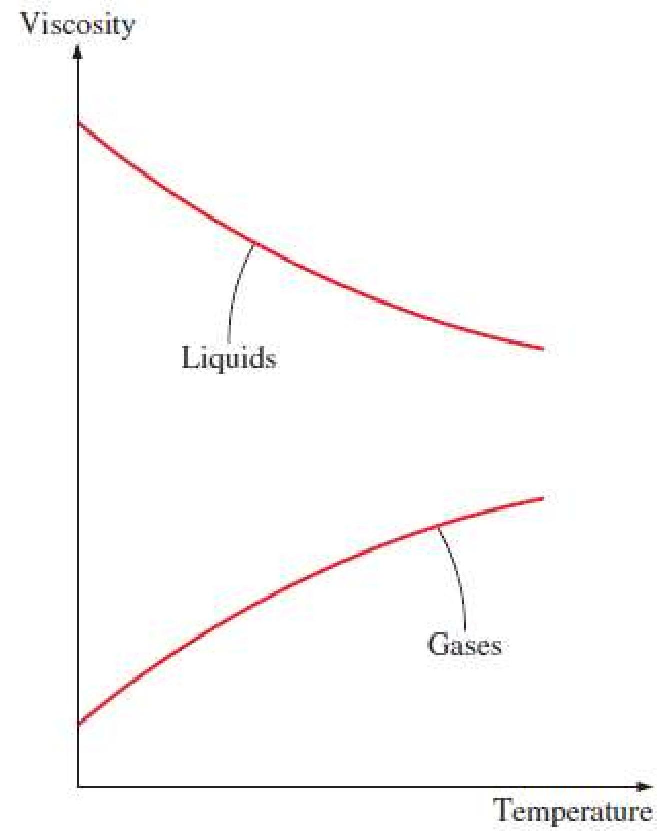
The rate of deformation (velocity gradient) of a Newtonian fluid is proportional to shear stress.

Kinematic Viscosity

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

Viscosity

Viscosity is caused by the cohesive forces between the molecules in liquids and by the molecular collisions in gases, and it varies greatly with temperature.



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

Viscosity of gases (Sutherland correlation)

$$\mu = \frac{aT^{1/2}}{1 + b/T}$$

For air at atmospheric conditions

$$a = 1.458 \times 10^{-6}\ kg/m \cdot s \cdot K^{1/2}$$

$$b = 110.4K$$

Viscosity of liquids

$$\mu = a10^{b/(T-c)}$$

$$a = 2.414 \times 10^{-5}\ N \cdot s/m^2$$

$$b = 247.8K$$

$$c = 140K$$

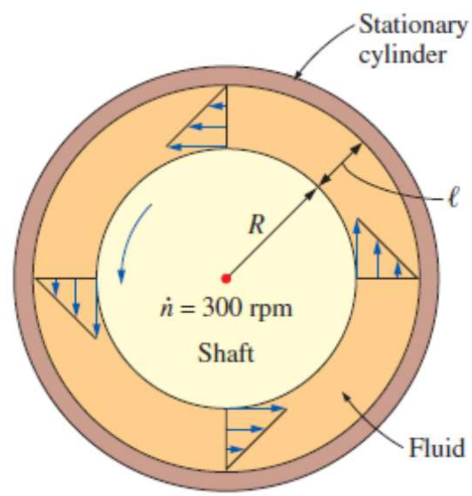
Temperature range: 0°C to 370 °C

Viscosity

Example 1.5

The viscosity of a fluid is to be measured by a viscometer constructed of two 40-cm-long concentric cylinders (Fig. below). The outer diameter of the inner cylinder is 12 cm, and the gap between the two cylinders is 0.15 cm. The inner cylinder is rotated at 300 rpm, and the torque is measured to be 1.8 N·m. Determine the viscosity of the fluid.

Hint: $T = FR = \mu \dfrac{4\pi^2 R^3 \dot{n} L}{l}$



Data:

$L = 40 \text{ cm} = 0.4 \text{ m}$

$D = 12 \text{ cm} = 0.12 \text{ m}$

$\dot{n} = 300 \text{ rpm}$

$T = 1.8 \text{ N·m}$

$l = 0.15 \text{ cm} = 0.0015 \text{ m}$

Solution:

$$\mu = \frac{Tl}{4\pi^2 R^3 \dot{n} L} = \frac{(1.8\,Nm)(0.0015\,m)}{4\pi^2 (0.06\,m)^3 \left(300 \dfrac{rev}{\min} \dfrac{1\min}{60\,s}\right)(0.4\,m)} = 0.158\,Pa \cdot s$$

$$= 0.158 \frac{kg}{m \cdot s}$$

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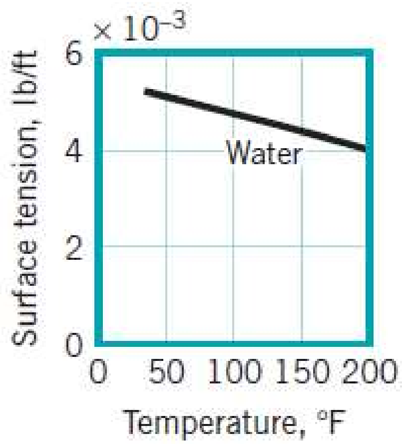
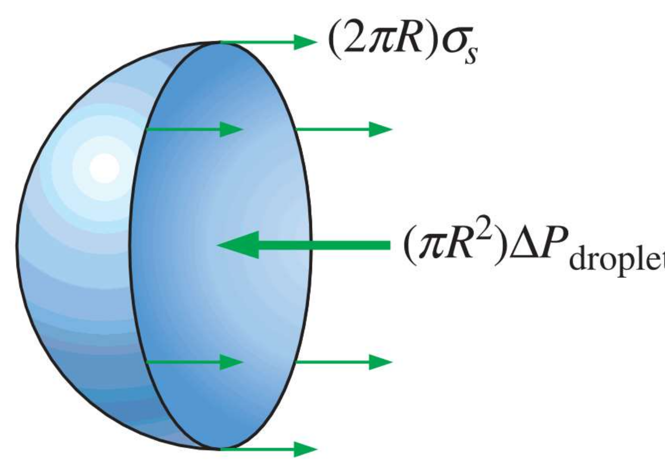
Surface Tension and Capillary Effect

Surface Tension (σ_s) is the intensity of the molecular attraction per unit length along any line in the surface.



Note : The dimension of surface tension in SI units is N/m.



Forces acting on one-half of a liquid drop.

$$2\pi R\sigma_s = \Delta p \pi R^2$$

$$\Rightarrow \Delta p = p_i - p_o = \frac{2\sigma_s}{R}$$

p_i **:** Inside pressure.

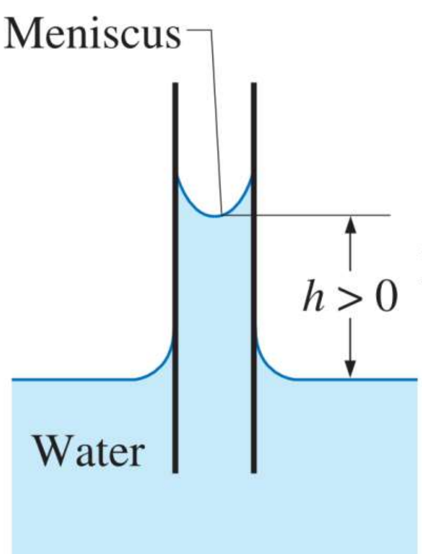
p_o **:** Outside pressure.

R **:** Sphere radius.

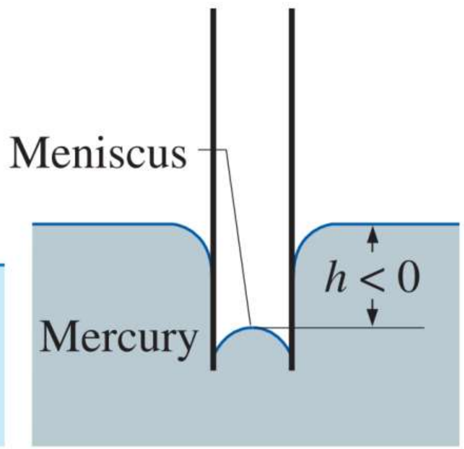
Surface Tension and Capillary Effect

Capillary effect is the rise or fall of a liquid in a small-diameter tube inserted into the liquid.

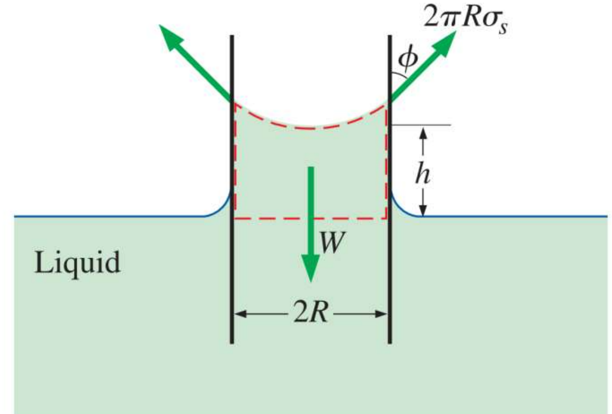
Capillaries are small-diameter tubes or narrow tubes.



The capillary rise of water
(Wetting fluid)



The capillary fall of mercury
(nonwetting liquid.)



The forces acting on a liquid column that has risen in a tube due to the capillary effect.

$$h = \frac{2\sigma_s \cos\phi}{\gamma R}$$

ϕ : Contact angle.

γ : Specific weight.

NOTE: The contact angle in air is
$\phi \approx 0°$ for water-glass
$\phi = 130°$ for mercury-glass
$\phi = 26°$ for kerosene-glass

Surface Tension and Capillary Effect

Physical Properties of Water (SI Units) (Munson et. al., 2016)

Temperature (°C)	Density, ρ (kg/m^3)	Specific Weight[b], γ (kN/m^3)	Dynamic Viscosity, μ (N·s/m^2)	Kinematic Viscosity, ν (m^2/s)	Surface Tension[c], σ (N/m)	Vapor Pressure, p_v [N/m^2(abs)]	Speed of Sound[d], c (m/s)
0	999.9	9.806	1.787 E − 3	1.787 E − 6	7.56 E − 2	6.105 E + 2	1403
5	1000.0	9.807	1.519 E − 3	1.519 E − 6	7.49 E − 2	8.722 E + 2	1427
10	999.7	9.804	1.307 E − 3	1.307 E − 6	7.42 E − 2	1.228 E + 3	1447
20	998.2	9.789	1.002 E − 3	1.004 E − 6	7.28 E − 2	2.338 E + 3	1481
30	995.7	9.765	7.975 E − 4	8.009 E − 7	7.12 E − 2	4.243 E + 3	1507
40	992.2	9.731	6.529 E − 4	6.580 E − 7	6.96 E − 2	7.376 E + 3	1526
50	988.1	9.690	5.468 E − 4	5.534 E − 7	6.79 E − 2	1.233 E + 4	1541
60	983.2	9.642	4.665 E − 4	4.745 E − 7	6.62 E − 2	1.992 E + 4	1552
70	977.8	9.589	4.042 E − 4	4.134 E − 7	6.44 E − 2	3.116 E + 4	1555
80	971.8	9.530	3.547 E − 4	3.650 E − 7	6.26 E − 2	4.734 E + 4	1555
90	965.3	9.467	3.147 E − 4	3.260 E − 7	6.08 E − 2	7.010 E + 4	1550
100	958.4	9.399	2.818 E − 4	2.940 E − 7	5.89 E − 2	1.013 E + 5	1543

[a]Based on data from *Handbook of Chemistry and Physics*, 69th Ed., CRC Press, 1988.

[b]Density and specific weight are related through the equation $\gamma = \rho g$. For this table, $g = 9.807$ m/s^2.

[c]In contact with air.

[d]From R. D. Blevins, *Applied Fluid Dynamics Handbook*, Van Nostrand Reinhold Co., Inc., New York, 1984.

Surface Tension and Capillary Effect

Example 1.6

What diameter of clean glass tubing is required so that the rise of water at 40°C in a tube due to capillary action (as opposed to pressure in the tube) is less than h = 2 mm?

References

[1] Cengel Y., Cimbala, J. (2014). Fluid Mechanics: Fundamentals and Applications (3th Edition). New York: NY: McGraw-Hill Co.

[2] Munson, B.R., Young, D.F., Okiishi, T.H., and Huebsch, W.W. (2016). Fundamentals of Fluid Mechanics (8th Edition). John Wiley & Sons. ISBN 1119080703.