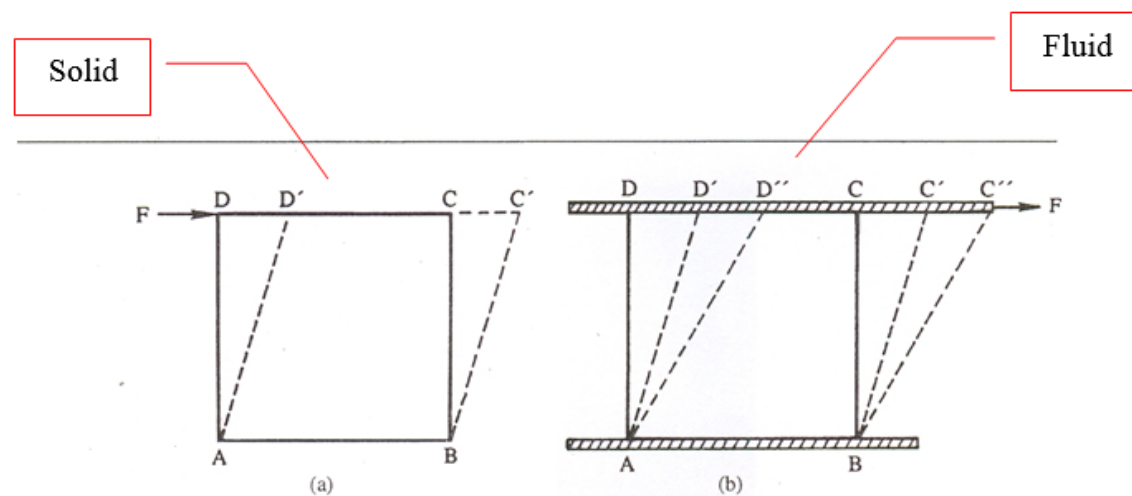
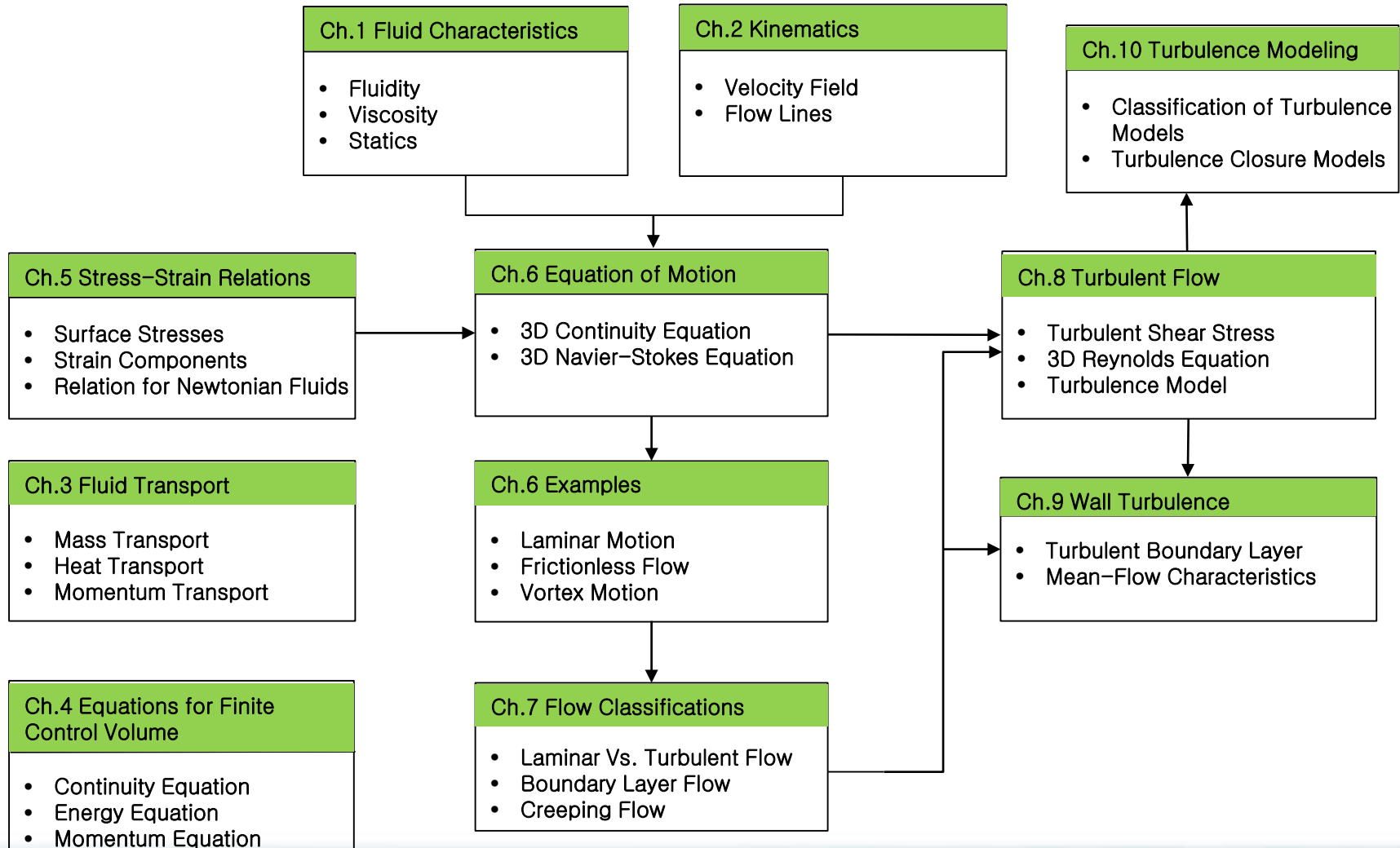


# Fluid Dynamics

## Chapter 1 Fluid Characteristics



# Outline of Course



# Chapter 1 Fluid Characteristics

## Contents

1.1 Introduction

1.2 Units of Measurement

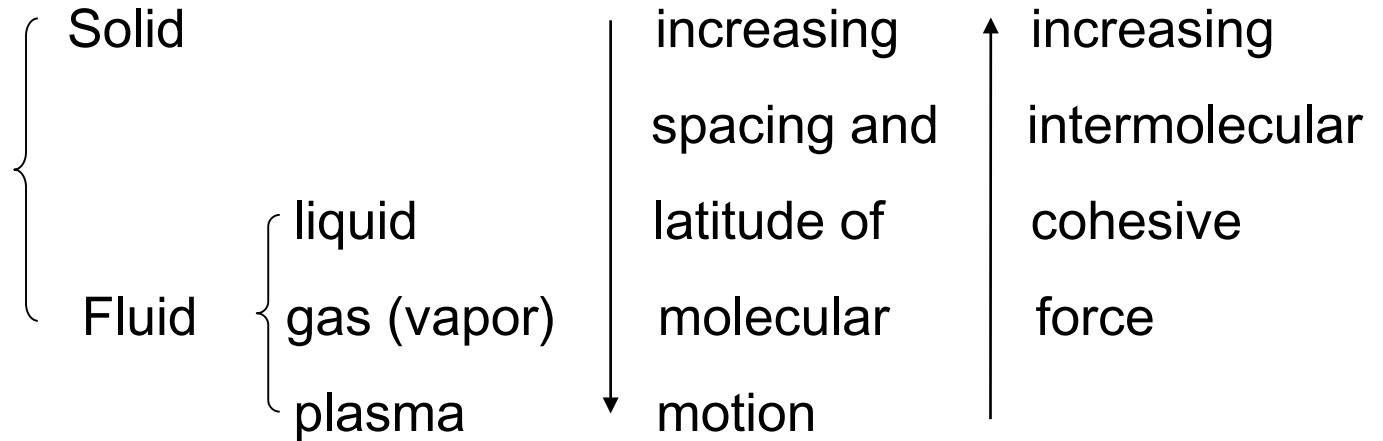
1.3 Properties and States of Fluids

## Objectives

- Define fluidity
- Study fundamental properties of the fluid

# 1.1 Introduction

## 1.1.1 Phases



# 1.1 Introduction

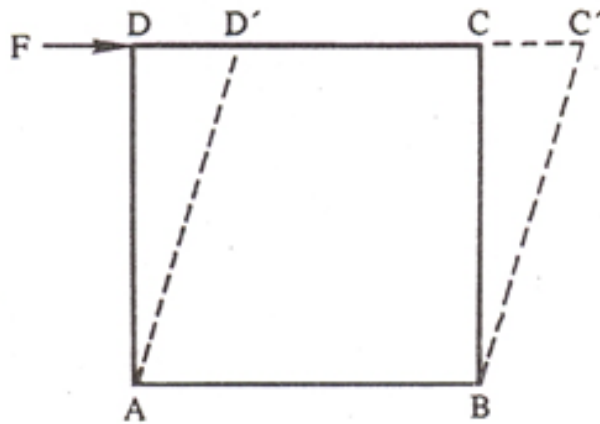
## 1.1.2 Fluidity

Fluid	Solid
<ul style="list-style-type: none"> <li>• deform <u>continuously</u> <u>under shearing (tangential) stresses</u> no matter how small the stress</li> <li>• shear stress <math>\propto</math> <u>time rate</u> of angular deformation (strain, displacement)</li> </ul>	<ul style="list-style-type: none"> <li>• deform by an amount proportional to the shear stress applied</li> <li>• shear stress <math>\propto</math> <u>magnitude</u> of the angular deformation (total strain)</li> </ul>

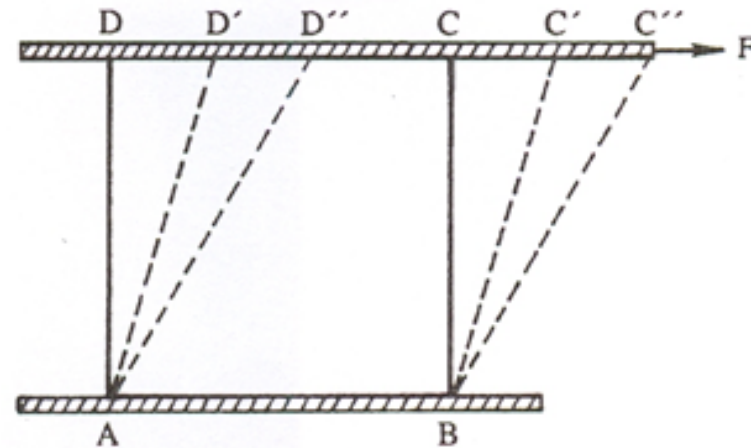
# 1.1 Introduction

Fluid

Solid



(a)



(b)

# 1.1 Introduction

## 1.1.3 Compressibility

- 1) compressible fluid: gases, vapors → thermodynamics
- 2) incompressible fluid: liquid (small compressibility), water

## 1.1.4 Continuum approach

- dimensions in fluid space are large compared to the molecular spacing to ignore discrete molecular structure
- neglect void
- Consider a small volume of fluid  $\Delta V$  containing a large number of molecules, and let  $\Delta m$  and  $v$  be the mass and velocity of any individual molecule

# 1.1 Introduction

$$\rho = \lim_{\Delta V \rightarrow \varepsilon} \frac{\sum \Delta m}{\Delta V}$$

$$\vec{u} = \lim_{\Delta V \rightarrow \varepsilon} \frac{\sum v \Delta m}{\sum \Delta m}$$

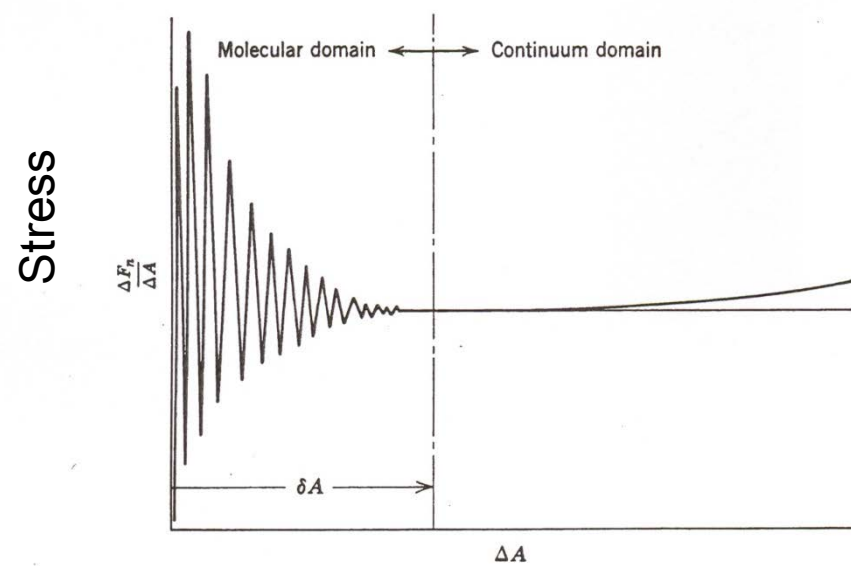
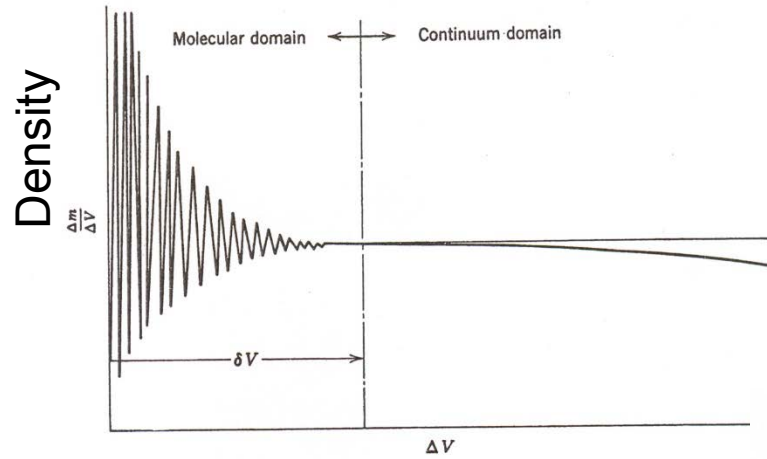
$\varepsilon$  = volume which is sufficiently small compared with the smallest significant length scale in the flow field but is sufficiently large that it contains a large number of molecules

[Cf] Molecular approach

- molecular point of view
- well developed for light gases



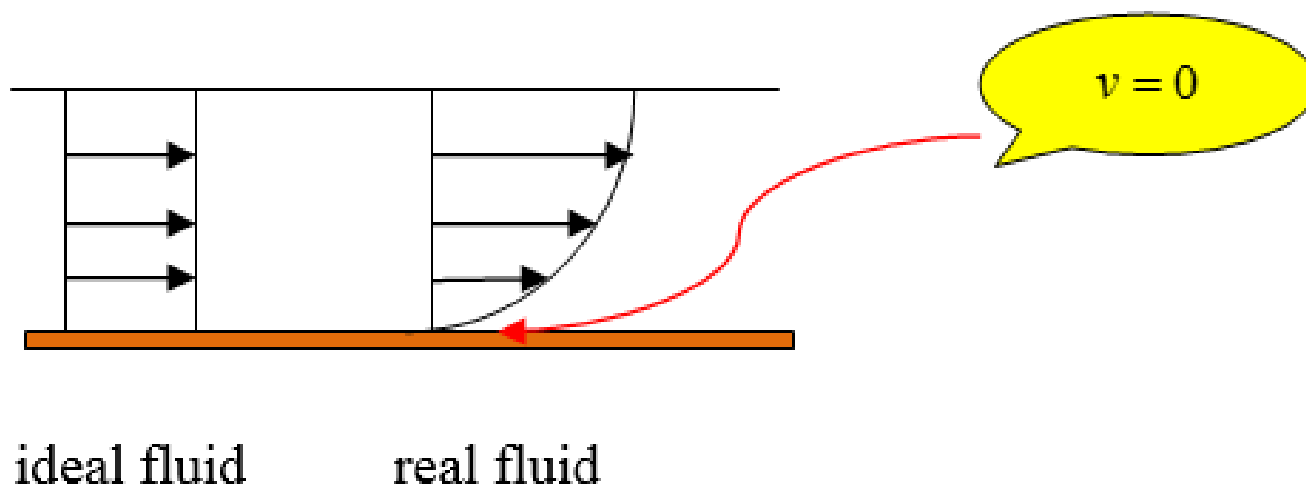
# 1.1 Introduction



# 1.1 Introduction

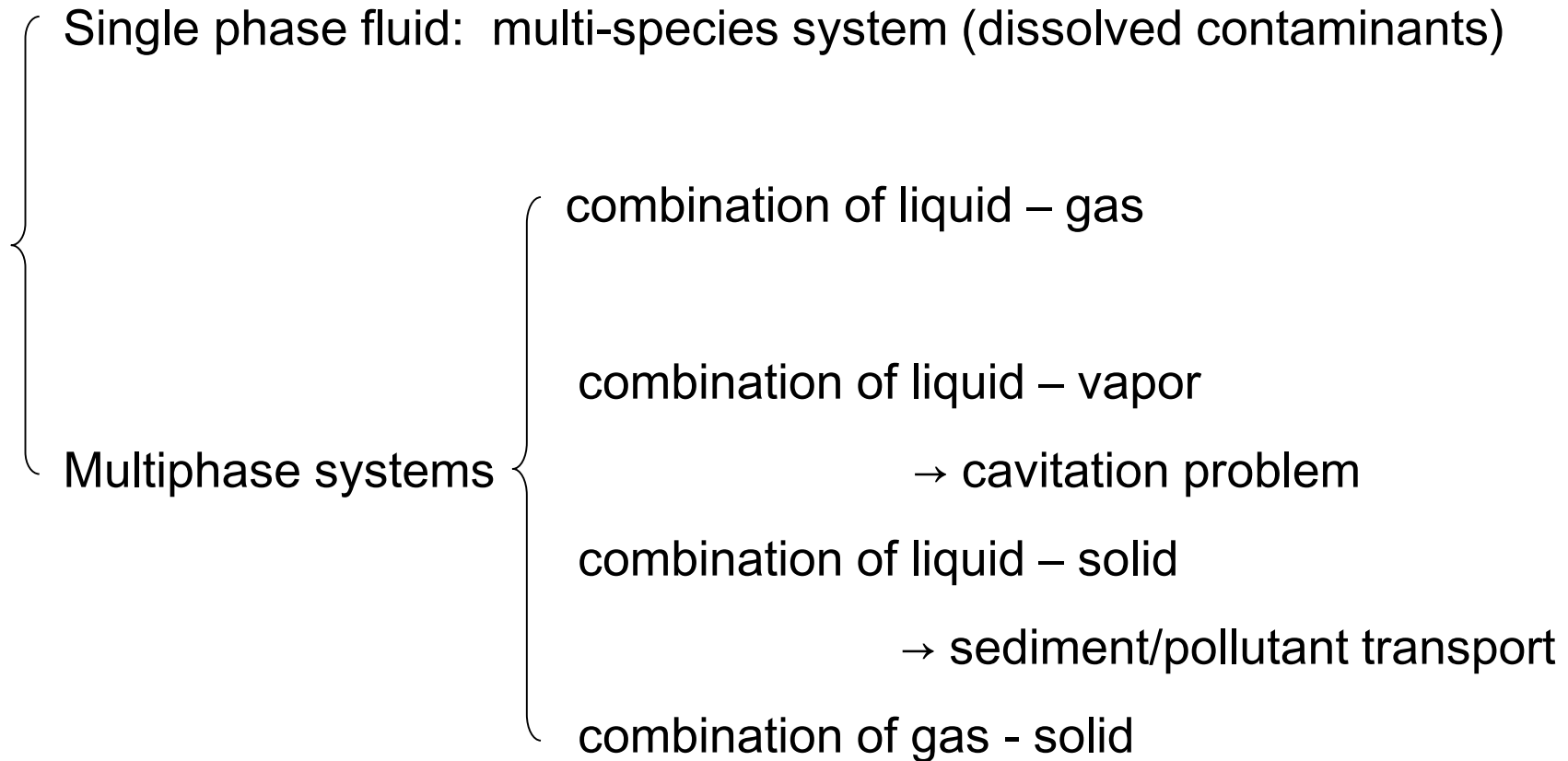
## 1.1.5 No-slip condition at rigid boundary

- 1) behavior of continuum - type viscous fluids
- 2) zero relative velocity at the boundary surface (proven by experiments)



# 1.1 Introduction

## 1.1.6 Multiphase system



# 1.2 Units of Measurement

- SI system: metric system
- English system: ft-lb system

\* Newton's 2nd law of motion

$$F = ma$$

$F$  = force(N) ;  $m$  = mass(kg) ;  $a$  = acceleration(m / sec<sup>2</sup>)

$$F \rightarrow 1 \text{ kg} \cdot \text{m} / \text{sec}^2 = 1 \text{ N}$$

$$W = mg$$

$W$  = weight ;  $g$  = gravitational acceleration

# 1.3 Properties and States of Fluids

## 1) extensive (external) properties

~ depend on amount of substance

→ total volume, total energy, total weight

## 2) intensive (internal) properties

~ independent of the amount present

→ volume per unit mass, energy per unit mass

weight per unit volume (specific weight,  $\gamma$ )

pressure, viscosity, surface tension

# 1.3 Properties and States of Fluids

## 1.3.1 Properties of importance in fluid dynamics

(1) Pressure,  $p \sim$  scalar

$$p = F / A \text{ (N / m}^2\text{)}$$

$$p_{\text{gauge}} = p_{\text{absolute}} - p_{\text{atm}}$$

◇ Forces on a fluid element

Body force: act without physical contact 질량력

Surface force: require physical contact for transmission 표면력

# 1.3 Properties and States of Fluids

- 1) body force
  - gravity force
  - centrifugal force
  - Coriolis' force
- 2) surface forces
  - normal stress → tensile stress (unusual for fluid)  
pressure
  - tangential stress → shear stress

## (2) Temperature, $T$

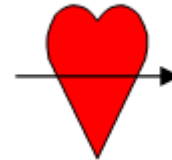
two bodies in thermal equilibrium → same temperature

# 1.3 Properties and States of Fluids

(3) Density,  $\rho$

$$\rho = \text{mass} / \text{volume} = \frac{M}{V}$$

volume  $\propto$  (pressure, temperature)



(4) Specific weight,  $\gamma$

$$\gamma = \text{weight} / \text{volume}$$

[Re] Flow of a continuous medium

- ~ Fluids are treated as homogeneous materials.
- ~ Molecular effects are disregarded.



# 1.3 Properties and States of Fluids

mass density  $\rho(x, y, z, t) = \lim_{\Delta V \rightarrow 0} \frac{\Delta M}{\Delta V}$

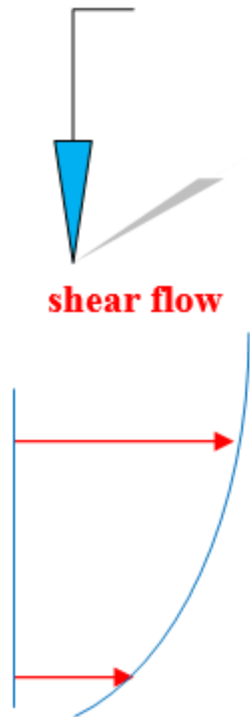
velocity vector  $v = \lim_{\Delta t \rightarrow 0} \frac{\Delta s}{\Delta t}$

(5) Viscosity,  $\mu$

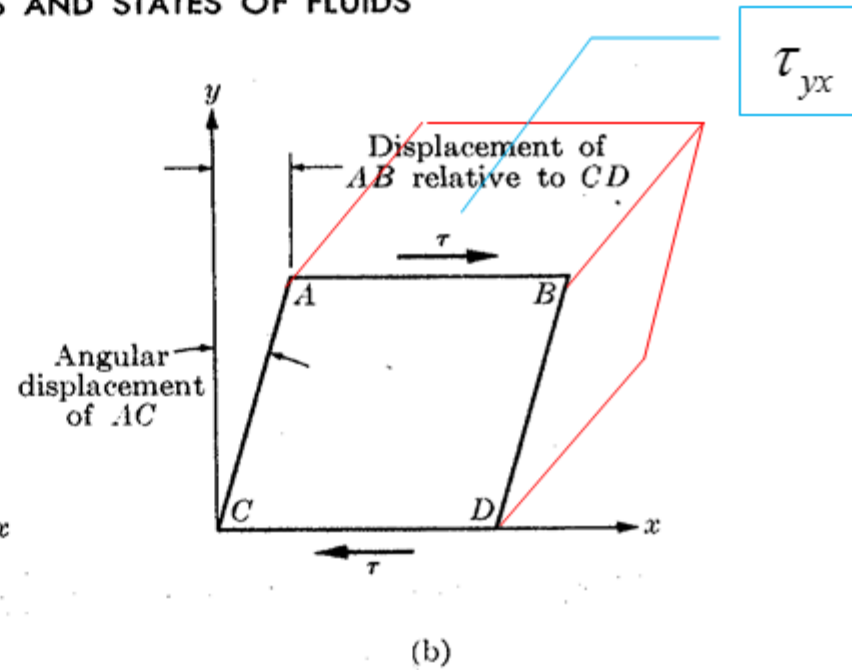
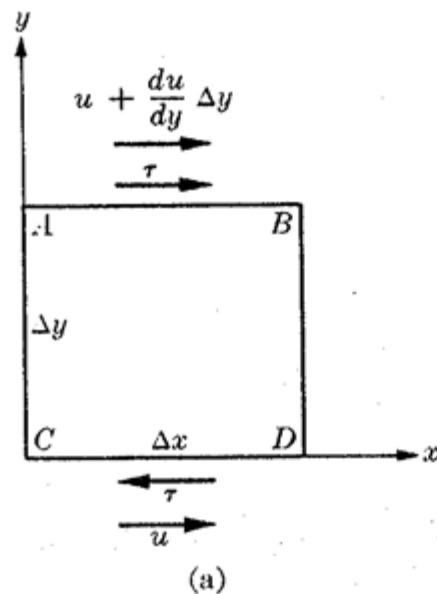
~ due to molecular mobility

~ whenever a fluid moves such that a relative motion exists between adjacent volumes (different velocity)

# 1.3 Properties and States of Fluids



## PROPERTIES AND STATES OF FLUIDS



# 1.3 Properties and States of Fluids

i) displacement of AB relative to CD in  $\Delta t$

$$\left( u + \frac{du}{dy} \Delta y \right) \Delta t - u \Delta t = \frac{du}{dy} \Delta y \Delta t$$

ii) strain = relative displacement = angular displacement

$$\left[ \frac{du}{dy} \Delta y \Delta t \right] / \Delta y = \frac{du}{dy} \Delta t$$

iii) time rate of strain (= time rate of angular displacement of AC)

$$\frac{du}{dy} \Delta t / \Delta t = \frac{du}{dy}$$

# 1.3 Properties and States of Fluids

$$\tau \propto \frac{du}{dy}$$

$$\tau_{yx} = \mu \frac{du}{dy}$$

where

$\tau_{yx}$  = shear stress acting in the  $x$  - direction on a plane  
whose normal is  $y$  - direction ( $\text{N} / \text{m}^2$ )

$\frac{du}{dy}$  = rate of angular deformation (1 / sec)

$\mu$  = dynamic molecular viscosity

# 1.3 Properties and States of Fluids

$$\mu = \frac{\tau}{\frac{du}{dy}} = \frac{\text{N/m}^2}{\frac{\text{m/s}}{\text{m}}} = \text{N} \cdot \text{s} / \text{m}^2$$

$$= (\text{kg} \cdot \text{m} / \text{s}^2) \cdot \frac{\text{s}}{\text{m}^2} = \text{kg} / \text{m} \cdot \text{sec} = \text{kg} / \text{m} \cdot \text{s}$$

◇ Kinematic viscosity,  $\nu$

$$\nu = \frac{\mu}{\rho} = \frac{\text{kg} / \text{m} \cdot \text{s}}{\text{kg} / \text{m}^3} = \text{m}^2 / \text{s} \quad \rightarrow \quad \text{kinematic dimensions} \rightarrow \text{Fig. 1.4}$$

[Cf] dynamics: F, L, T

→ shear stress

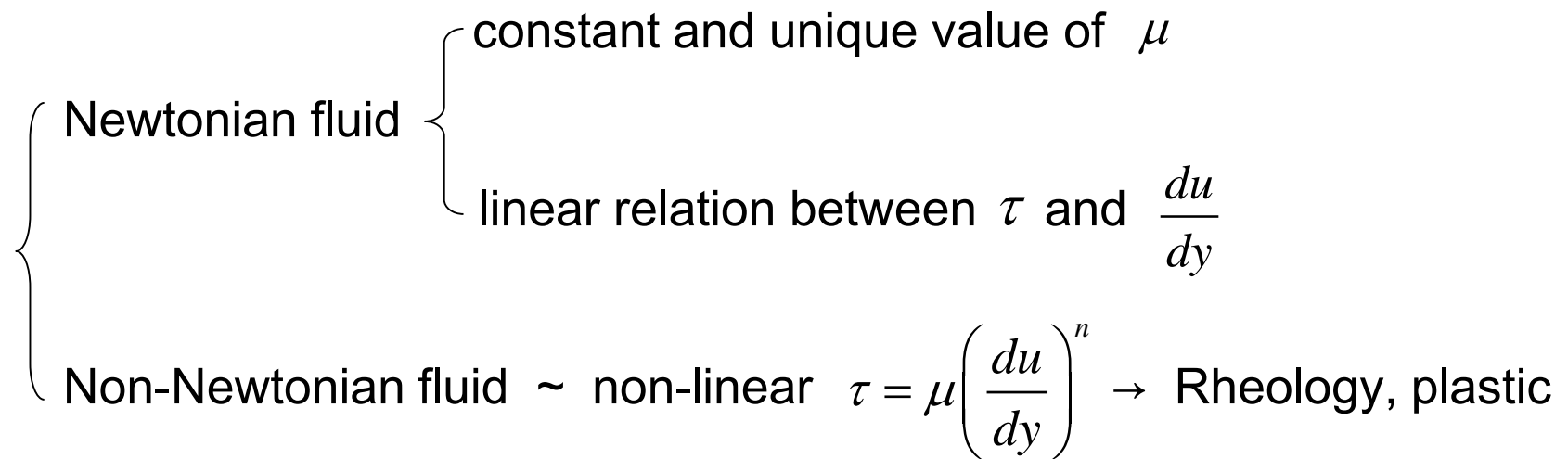
kinematics: L, T

→ deformation

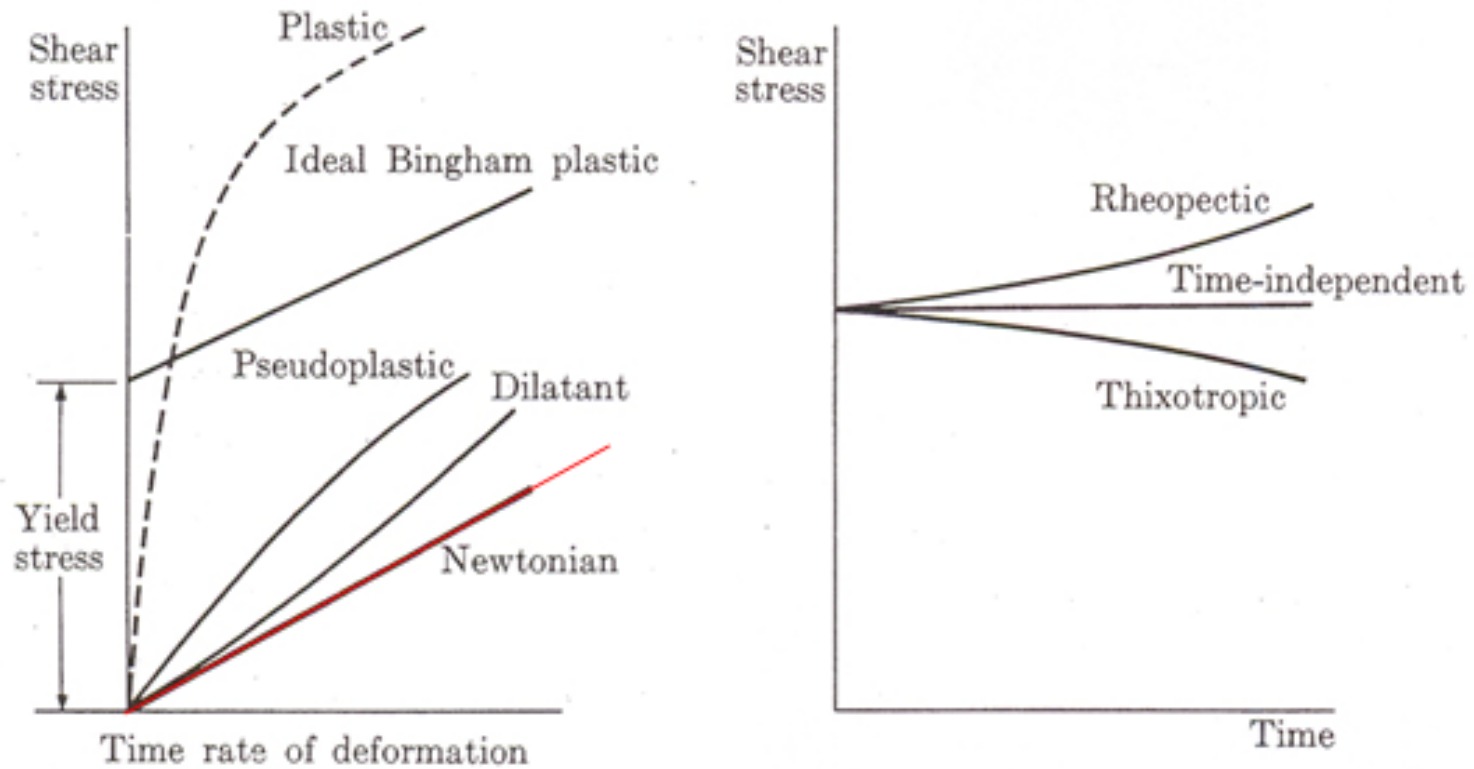
viscosity links two

# 1.3 Properties and States of Fluids

## ◇ Types of Fluid



# 1.3 Properties and States of Fluids



# 1.3 Properties and States of Fluids

Newtonian fluid	Non-Newtonian fluid
<ul style="list-style-type: none"> <li>• shear stress is <u>linearly proportional</u> to rate of angular deformation starting with zero stress and zero deformation</li> <li>• constant of proportionality  <math>\equiv \mu</math>, <u>dynamic viscosity</u> → Fig. 1.1</li> <li>• water, air</li> </ul> <p>[Cf] Analogy between Newtonian fluid and solids obeying Hooke's law of constant modulus of elasticity</p>	<ul style="list-style-type: none"> <li>• variable (<u>nonlinear</u>) proportionality between stress and deformation rate</li> <li>• proportionality            = f (length of time of exposure to stress, magnitude of stress)</li> <li>• plastics: paint, jelly, polymer solutions            → Rheology</li> </ul>



# 1.3 Properties and States of Fluids

[Cf] Stress-strain relationship for solid

$$\tau_{yx} = G \frac{d\xi}{dy}$$

$d\xi$  = relative station displacement of AB

$\frac{d\xi}{dy}$  = angular deformation (shear strain)

$G$  = modulus of elasticity in torsion

# 1.3 Properties and States of Fluids

fluid

$$\frac{du}{dy}$$

velocity

solid

$$\frac{d\xi}{dy}$$

displacement

◇  $\mu$  = function of (temperature, pressure)

# 1.3 Properties and States of Fluids

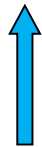
## Viscosity versus temperature

	Liquid	Gas
major factor for viscosity	intermolecular cohesion	exchange of momentum
when temperature is <u>increasing</u>	decrease cohesive force → decrease viscosity	increase molecular activity → increase shear stress

# 1.3 Properties and States of Fluids

[Re] Exchange of momentum

fast-speed layer (FSL)



molecules from FSL speed up molecules in LSL

molecules from LSL slow down molecules in FSL

low-speed layer (LSL)

Two layers tend to stick together as if there is some viscosity between two.

# 1.3 Properties and States of Fluids

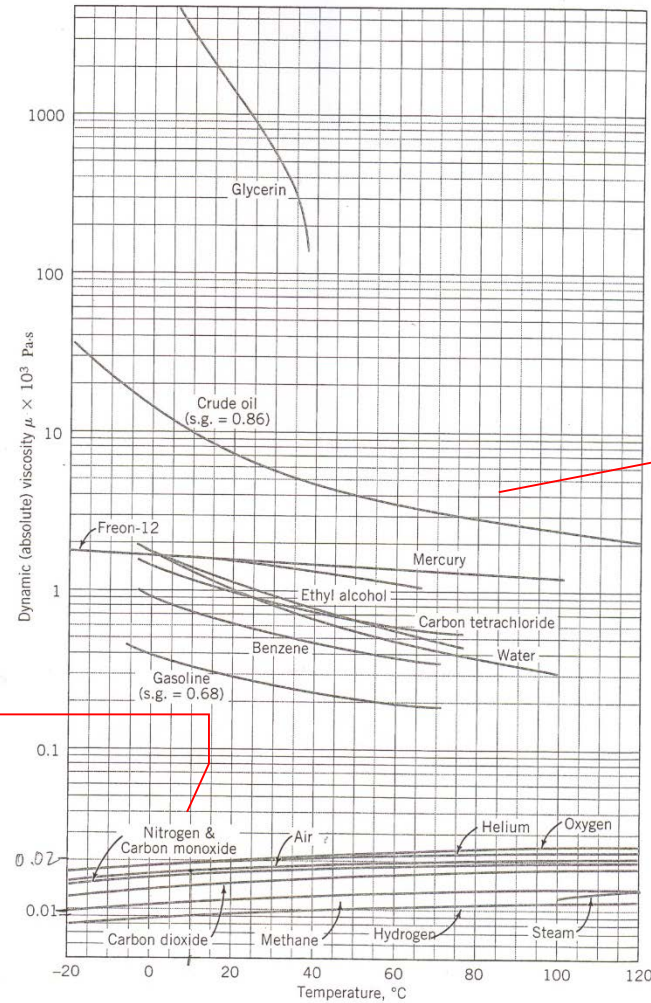
	SI Units						
	$T$ , °C	$\rho$ , kg/m <sup>3</sup>	s.g., —	$E$ , kPa	$\mu \times 10^4$ , Pa · s	$\sigma$ , N/m	$P_{\text{sat}}$ , kPa
Ethyl alcohol	20	788.6	0.79	1,206 625	12.0	0.022	5.86
Freon-12	15.6	1 345.2	1.35	—	14.8	—	—
	-34.4	1 499.8	—	—	18.3	—	—
Gasoline	20	680.3	0.68	—	2.9	—	55.2
Glycerin	20	1 257.6	1.26	4 343 850	14 939	0.063	0.000 014
Hydrogen	-257.2	73.7	—	—	0.21	0.002 9	21.4
Jet fuel (JP-4)	15.6	773.1	0.77	—	8.7	0.029	8.96
Mercury	15.6	13 555	13.57	26 201 000	15.6	0.51	0.000 17
	315.6	12 833	12.8	—	9.0	—	47.2
Oxygen (Liquid)	-195.6	1 206.0	—	—	2.78	0.015	21.4
Sodium	315.6	876.2	—	—	3.30	—	—
	537.8	824.6	—	—	2.26	—	—
Water <sup>b</sup>	20	998.2	1.00	2,170,500	10.0	0.073	2.34
Sea water <sup>b</sup>	20	1024.0	1.03	2,300,000	10.7	0.073	2.34

<sup>b</sup>The specific heat of liquid water is approximately 25 000 ft·lb/slug·°R or 4 180 J/kg·K.

Water:

$$\mu = 1.0 \times 10^{-3} \frac{N}{m^2 \cdot s}$$

# 1.3 Properties and States of Fluids



$\mu$  decreases  
as  $T$  increases

$\mu$  increases  
as  $T$  increases

# 1.3 Properties and States of Fluids

(6) Specific heat,  $c$  비열  $\frac{cal}{T \cdot g}$

= ratio of the quantity of heat flowing into a substance per unit mass to the change in temperature

(7) Internal energy,  $u$

specific internal energy = energy per unit mass, J/kg

kinetic + potential energy  $\rightarrow$  internal energy

(8) Enthalpy

specific enthalpy =  $u + p / \rho$

# 1.3 Properties and States of Fluids

## (9) Bulk modulus of elasticity and Compressibility

### 1) Compressibility, $C$

= measure of change of volume and density when a substance is subjected to normal pressures or tensions

= % change in volume (or density) for a given pressure change

$$C = -\frac{dvol}{vol} \frac{1}{dp} = +\frac{d\rho}{\rho} \frac{1}{dp}$$

### 2) Bulk modulus of elasticity, $E_v$

$$E_v = \frac{1}{C} = -\frac{dp}{dvol / vol} = \frac{dp}{d\rho / \rho}$$



# 1.3 Properties and States of Fluids

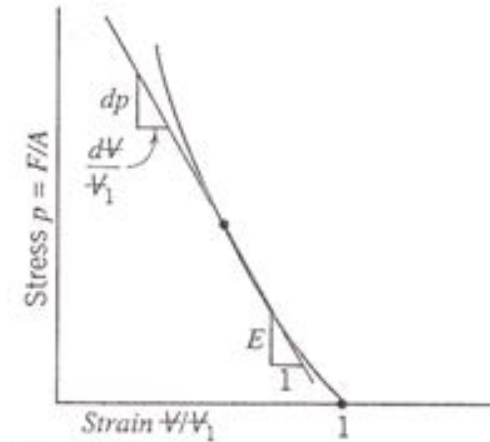
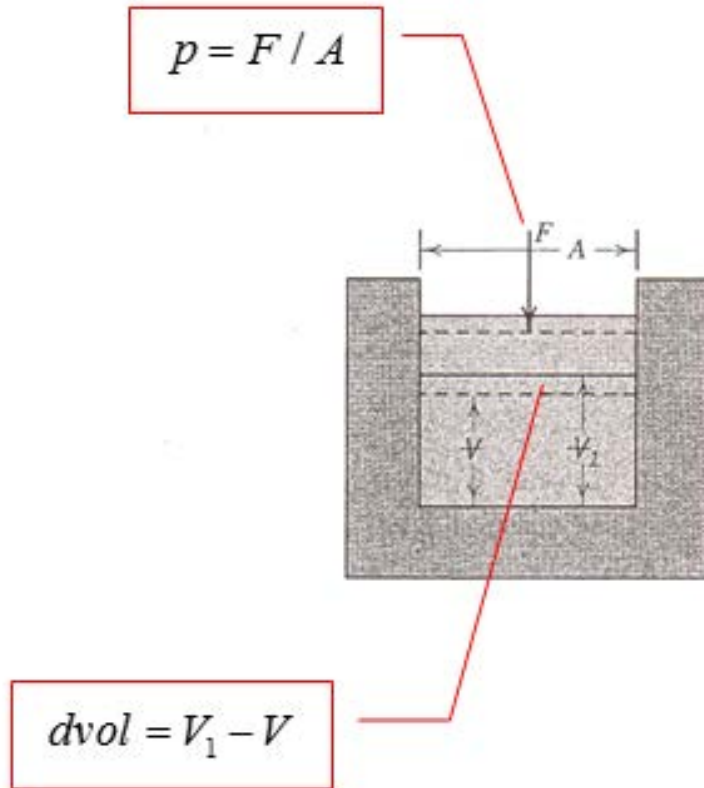


Fig. 1.3

# 1.3 Properties and States of Fluids

(10) Vapor pressure,  $p_v$

Liquids tend to evaporate

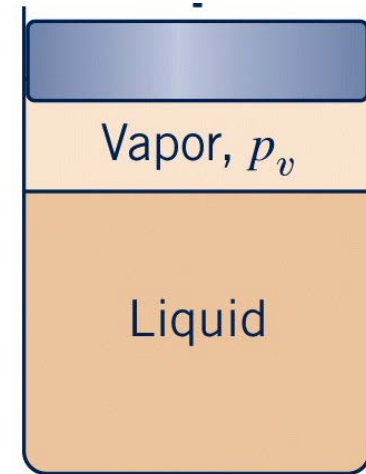
Vapor pressure = pressure at which liquids boil

= equilibrium partial pressure which escaping liquid molecules will exert above any free surface

- Dynamic equilibrium: liquid - vapor

~ increases with temperature

~ The more volatile the liquid, the higher its vapor pressure.



- volatile liquids (휘발성 액체):

gasoline:  $p_v = 55.2 \text{ kPa}$  at  $20 \text{ }^\circ\text{C}$

water:  $p_v = 2.34 \text{ kPa}$  at  $20 \text{ }^\circ\text{C}$

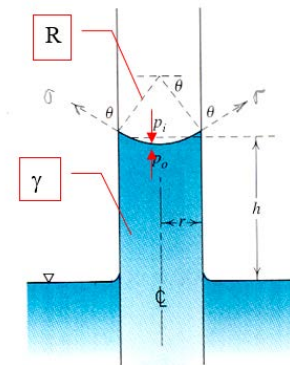
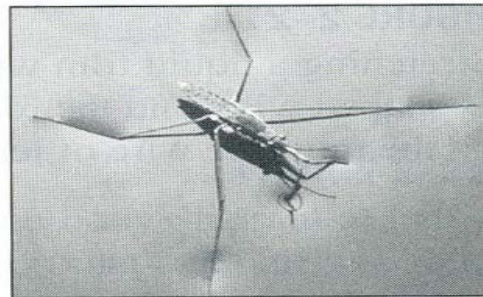
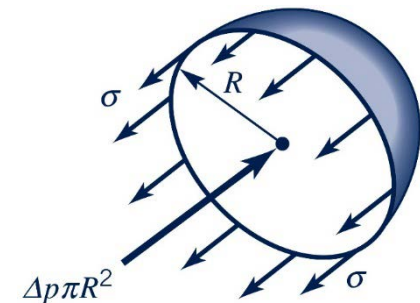
# 1.3 Properties and States of Fluids

(11) Surface energy and surface tension,

At boundaries between gas and liquid phase, molecular attraction introduce forces which cause the interface to behave like a membrane under tension.

$$\sigma = \frac{(\text{force}) \times (\text{distance})}{\text{area}} = \frac{\text{work}}{\text{area}} = \frac{\text{force}}{\text{length}}$$

~ water: decrease with temperature



# 1.3 Properties and States of Fluids

Increase then decrease

Decrease

PHYSICAL PROPERTIES OF WATER (SI UNITS)<sup>f</sup>

Temperature, °C	Specific Weight, <sup>a</sup> $\gamma$ , kN/m <sup>3</sup>	Density, <sup>a</sup> $\rho$ , kg/m <sup>3</sup>	Modulus of Elasticity, <sup>b,c</sup> $E \times 10^{-6}$ , kPa	Viscosity, <sup>a</sup> $\mu \times 10^3$ , Pa·s	Kinematic Viscosity, <sup>a</sup> $\nu \times 10^6$ , m <sup>2</sup> /s	Surface Tension, <sup>a,d</sup> $\sigma$ , N/m	Vapor Pressure, <sup>e</sup> $p_v$ , kPa
0	9.805	999.8	1.98	1.781	1.785	0.075 6	0.61
5	9.807	1 000.0	2.05	1.518	1.518	0.074 9	0.87
10	9.804	999.7	2.10	1.307	1.306	0.074 2	1.23
15	9.798	999.1	2.15	1.139	1.139	0.073 5	1.70
20	9.789	998.2	2.17	1.002	1.003	0.072 8	2.34
25	9.777	997.0	2.22	0.890	0.893	0.072 0	3.17
30	9.764	995.7	2.25	0.798	0.800	0.071 2	4.24
40	9.730	992.2	2.28	0.653	0.658	0.069 6	7.38
50	9.689	988.0	<u>2.29</u>	0.547	0.553	0.067 9	12.33
60	9.642	983.2	2.28	0.466	0.474	0.066 2	19.92
70	9.589	977.8	2.25	0.404	0.413	0.064 4	31.16
80	9.530	971.8	2.20	0.354	0.364	0.062 6	47.34
90	9.466	965.3	2.14	0.315	0.326	0.060 8	70.10
100	9.399	958.4	2.07	0.282	0.294	0.058 9	101.33

Decrease

Decrease

Increase

# 1.3 Properties and States of Fluids

## [Appendix 1] Coordinate Systems

- i) Cartesian  $(x, y, z)$
- ii) Cylindrical  $(R, \theta, z)$

$$x = R \cos \theta$$

$$y = R \sin \theta$$

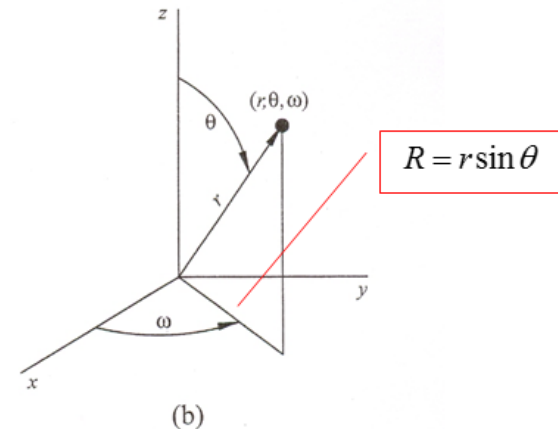
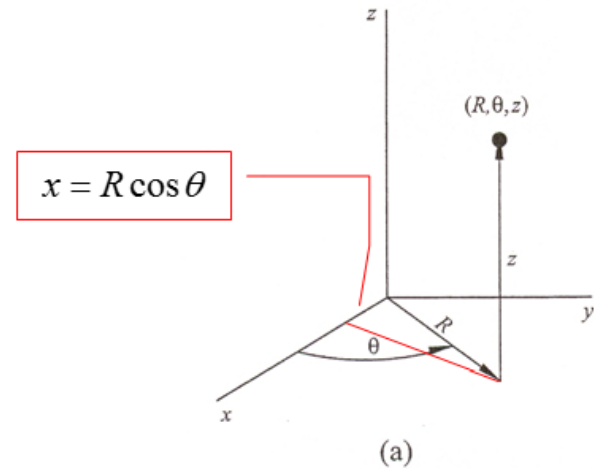
$$z = z$$

- iii) Spherical  $(r, \theta, \omega)$

$$x = r \sin \theta \cos \omega$$

$$y = r \sin \theta \sin \omega$$

$$z = r \cos \theta$$



# 1.3 Properties and States of Fluids

[Appendix 2] Tensor

Scalar – quantity with magnitude only

Vector – quantity with magnitude and direction

Tensor – an order array of entities which is invariant under coordinate transformation, this includes scalars and vectors

- Rank (order) of tensors –  $3^p$

0th order – 1 component, scalar (e.g., mass, length, pressure)

1st order – 3 components, vector (e.g., velocity, force, acceleration)

2nd order – 9 components, (e.g., stress, rate of strain, turbulent diffusion coeff.)

# 1.3 Properties and States of Fluids

- Example of 2nd order tensor  
~ stress acting on a fluid element

$$\text{Stress tensor} = \begin{bmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{bmatrix}$$

$\sigma$  = normal stress,

$\tau$  = shear stress

# 1.3 Properties and States of Fluids

$\tau_{yx}$  = shear stress in  $xz$  - plane  
and in  $x$  - direction.

STRESS-STRAIN RELATIONS

