Chapter 1 Fluid Characteristics

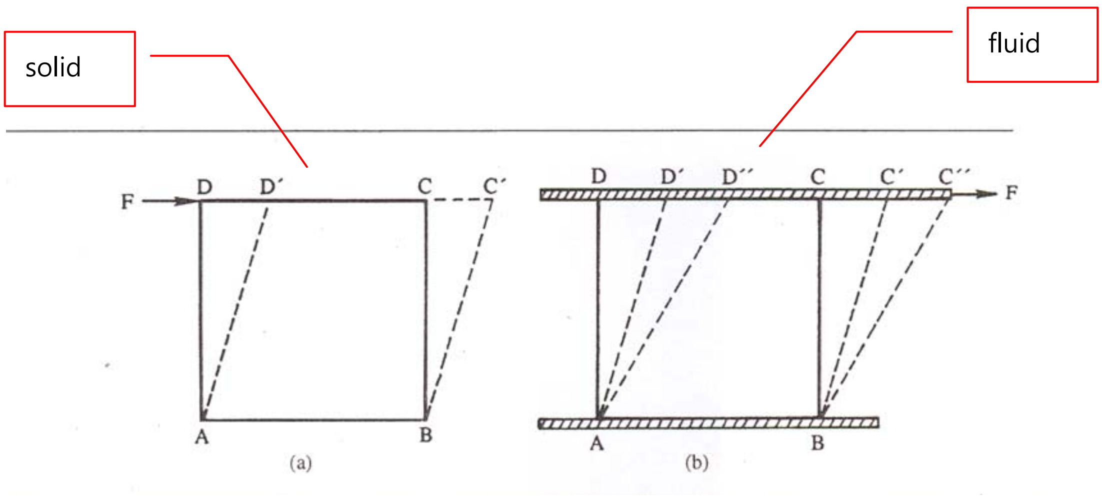
1.1 Introduction

1.1.1 Phases

Solid		↓ increasing spacing and latitude of molecular motion	↑ increasing intermolecular cohesive force
Fluid	liquid gas (vapor) plasma		

1.1.2 Fluidity

Fluid	Solid
● deform continuously under shearing (tangential) stresses no matter how small the stress ● stress ∝ time rate of angular deformation (strain, displacement)	● deform by an amount proportional to the stress applied ● stress ∝ magnitude of the angular deformation (total strain)
Newtonian fluid	**Non-Newtonian fluid**
● shear stress is linearly proportional to rate of angular deformation starting with zero stress and zero deformation ● constant of proportionality $\equiv \mu$, dynamic viscosity → Fig. 1.1 ● water, air [Cf] Analogy between Newtonian fluid and solids obeying Hooke's law of constant modulus of elasticity	● variable (nonlinear) proportionality between stress and deformation rate ● proportionality = f (length of time of exposure to stress, magnitude of stress) ● plastics: paint, jelly, polymer solutions → Rheology



Elastic Solid – perfect memory

Plastic – partial memory

Fluid – zero memory

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 ΔV containing a large number of molecules, and let Δm and v be the mass and velocity of any individual molecule

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

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

ε = 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

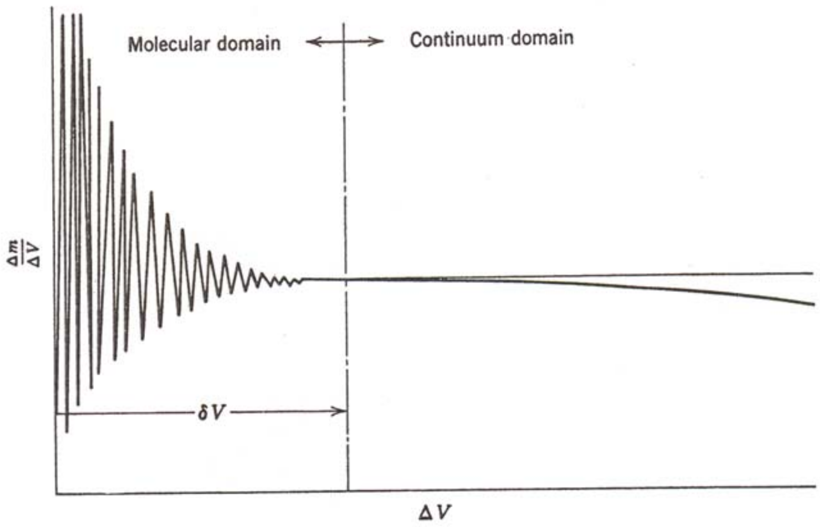


Figure 1.1 Density at a point.

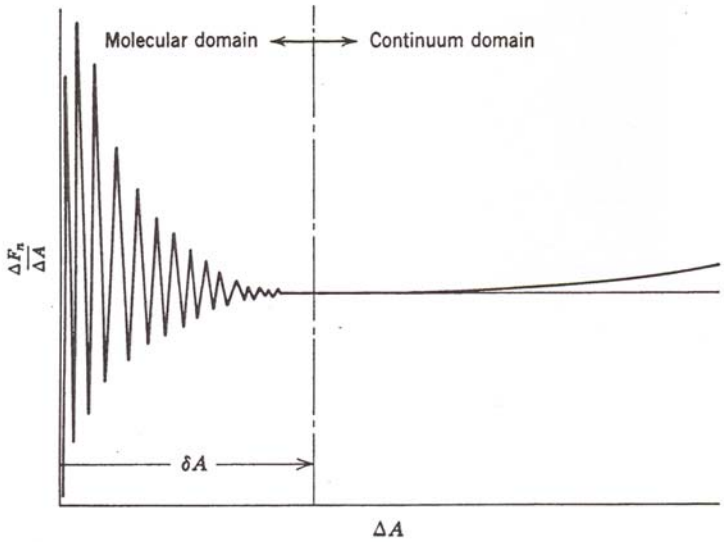
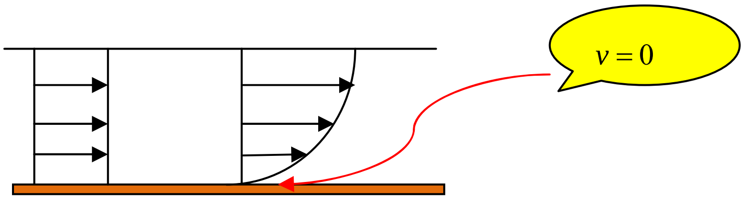


Figure 1.3 Normal stress at a point.

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)



ideal fluid   real fluid

1.1.6 Multiphase system

- Single– phase fluid
- Multiphase systems
  - combination of liquid – gas
  - combination of liquid – vapor
    → cavitation problem
  - combination of liquid – solid
    → sediment/pollutant transport
  - combination of gas - solid

1.2 Units of Measurement

– SI system: metric system

– English system: ft-lb system

* Newton's 2nd law of motion

$$F = ma$$

$F = \text{force(N)}$; $m = \text{mass(kg)}$; $a = \text{acceleration}(\text{m}/\text{sec}^2)$

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

$W = mg$

$W = \text{weight}$; $g = \text{gravitational acceleration}$

1.3 Properties and States of Fluids

1) extensive properties ~ depend on amount of substance

→ total volume, total energy, total weight

2) intensive properties ~ independent of the amount present

→ volume per unit mass, energy per unit mass

weight per unit volume (specific weight, γ)

pressure, viscosity, surface, tension

1.3.1 Properties of importances in fluid dynamics

(1) Pressure, p ~ scalar

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

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

◈ Forces on a fluid element

Body force: act without physical contact

Surface force: require physical contact for transmission

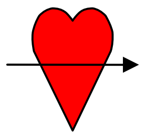
1) body force
- gravity force
- centrifugal force
- Coriolis' force

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

(3) Density, ρ



ρ = mass / volume = $\dfrac{M}{V}$

volume $\propto$ (pressure, temperature)

(4) Specific weight, γ

γ = weight / volume

[Re] Flow of a continuous medium

~ Fluids are treated as homogeneous materials.

~ Molecular effects are disregarded.

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

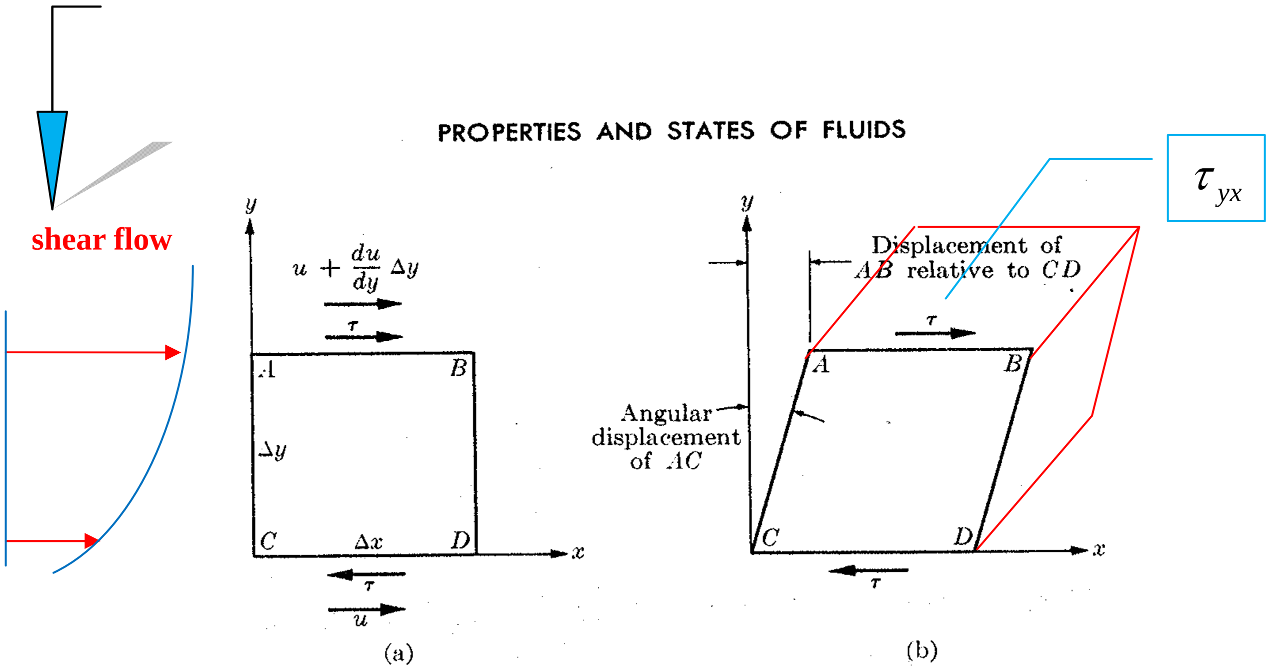
velocity vector $v = \lim_{\Delta t \to 0} \dfrac{\Delta s}{\Delta t}$

(5) Viscosity, μ

~ due to molecular mobility

~ whenever a fluid moves such that a <u>relative motion</u> exists between

adjacent volumes (different velocity)



Stress, $\tau \propto$ **time rate of angular deformation**

i) displacement of AB relative to CD in Δt

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

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)

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

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

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

where

$\tau_{yx} =$ shear stress acting in the x - direction on a plane

whose normal is y - direction $(\mathrm{N/m^2})$

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

$\mu =$ dynamic molecular viscosity

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

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

◈ Kinematic viscosity, ν

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

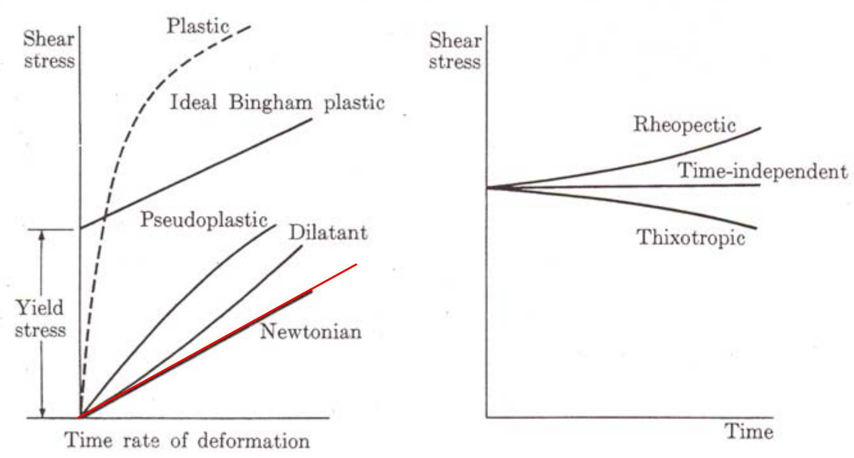
[Cf] dynamic: F, L, T → shear stress

kinematic: L, T → deformation

viscosity links two

◈ Types of Fluid

- Newtonian fluid
  - constant and unique value of μ
  - linear relation between τ and $\dfrac{du}{dy}$
- Non-Newtonian fluid ~ non-linear $\tau = \mu\left(\dfrac{du}{dy}\right)^n$ → Rheology, plastic



[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

<u>fluid</u>   <u>solid</u>

velocity: $\frac{du}{dy}$ $\frac{d\xi}{dy}$: displacement

◈ μ = function of (temperature, pressure)

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

[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.

Water:

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

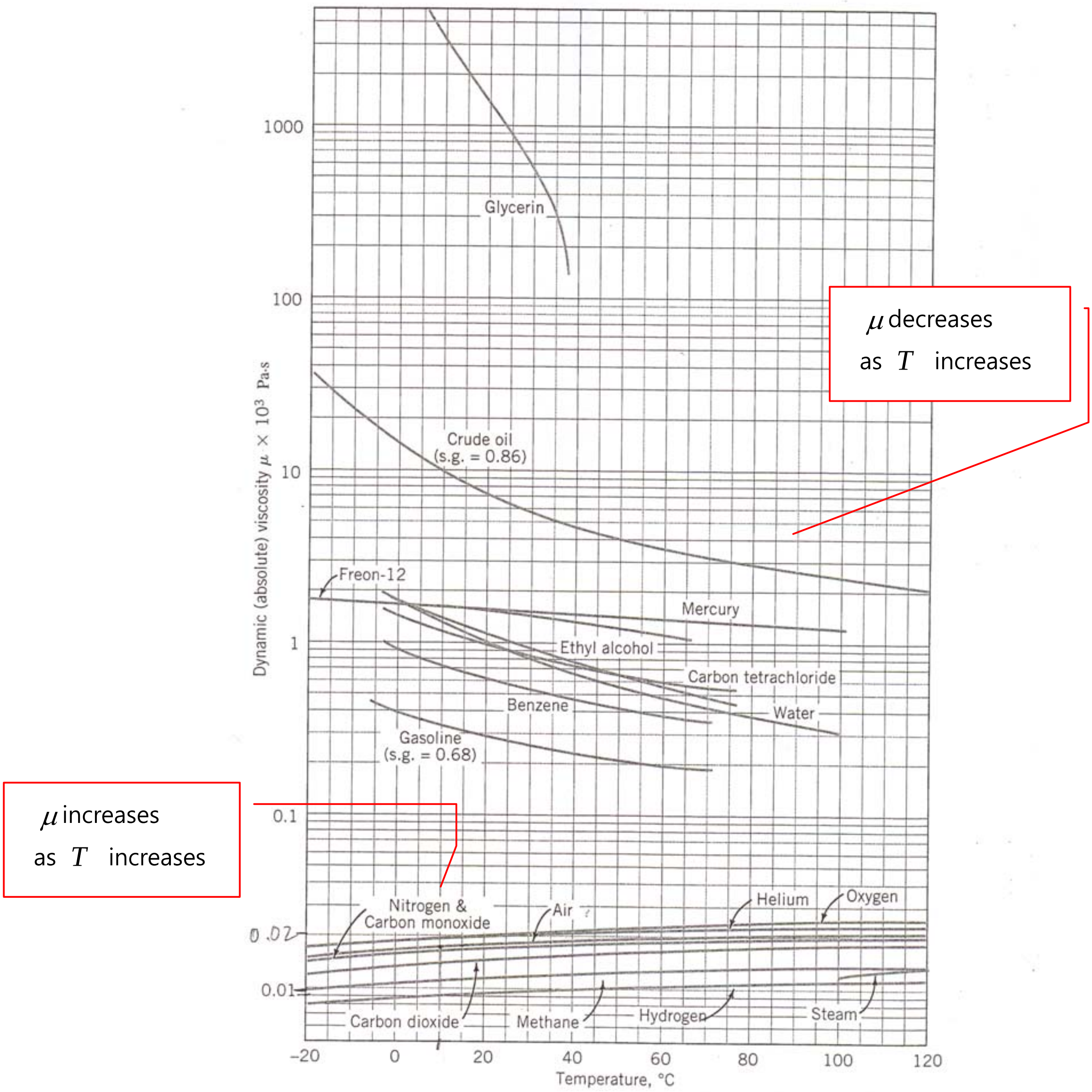
TABLE A2.1 Approximate Properties of Some Common Liquids at Standard Atmospheric Pressure (cont.)

SI Units

	T, °C	ρ, kg/m^3	s.g., —	E, kPa	$\mu \times 10^4$ Pa · s	σ, N/m	p_v, 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[b]	20	998.2	1.00	2 170 500	10.0	0.073	2.34
Sea water[b]	20	1024.0	1.03	2 300 000	10.7	0.073	2.34

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

TABLE A2.3*b* Viscosities of Some Common Fluids (SI Units)



(6) Specific heat, c

= 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, $\mathrm{J/kg}$

kinetic + potential energy → internal energy

(8) Enthalpy

specific enthalpy $= u + p/\rho$

(9) Bulk modulus of elasticity and Compressibility

1) Compressibility, C

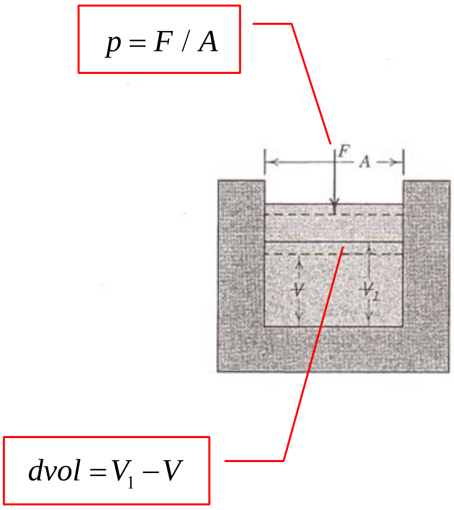
= measure of change of volume and density when a substance is subjected to normal pressures or tensions

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

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

2) Bulk modulus of elasticity, E_v

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



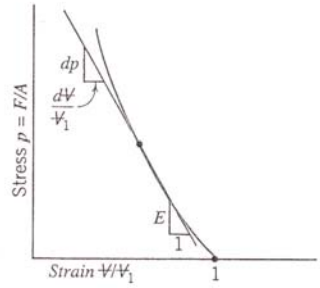


Fig. 1.3

(10)Vapor pressure, p_v

= pressure at which liquids boil

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

~ increases with temperature

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

(11) Surface energy and surface tension, σ

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

Increase then decrease

decrease

PHYSICAL PROPERTIES OF WATER (SI UNITS)[f]

Temperature, °C	Specific Weight,[a] γ, kN/m^3	Density,[a] ρ, kg/m^3	Modulus of Elasticity,[b,c] $E \times 10^{-6}$, kPa	Viscosity,[a] $\mu \times 10^3$, Pa·s	Kinematic Viscosity,[a] $\nu \times 10^6$, m^2/s	Surface Tension,[a,d] σ, N/m	Vapor Pressure,[e] 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	2.29	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

[Appendix 1] Coordinate Systems

i) Cartesian (x, y, z)

ii) Cylindrical (R, θ, z)

$$x = R\cos\theta$$

$$y = R\sin\theta$$

$$z = z$$

iii) Spherical (r, θ, ω)

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

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

$$z = r\cos\theta$$

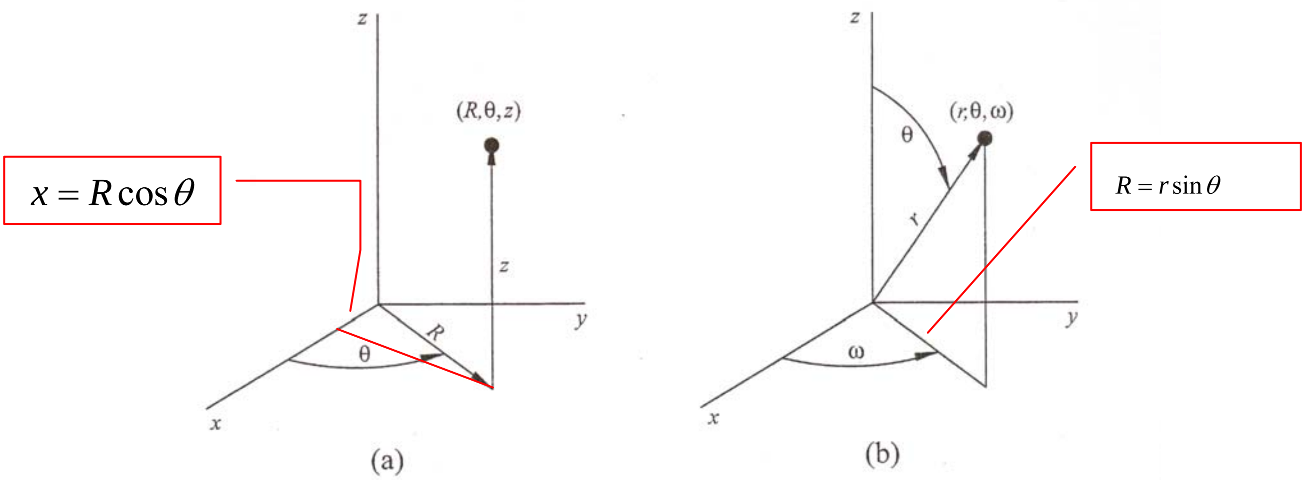


FIGURE A.1 Relationship between cartesian coordinates and (a) cylindrical coordinates and (b) spherical coordinates.

[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

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.)

- Example of 2nd order tensor

~ stress acting on a fluid element

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

σ = normal stress, τ = shear stress

τ_{yx} = shear stress in xz - plane and in x - direction