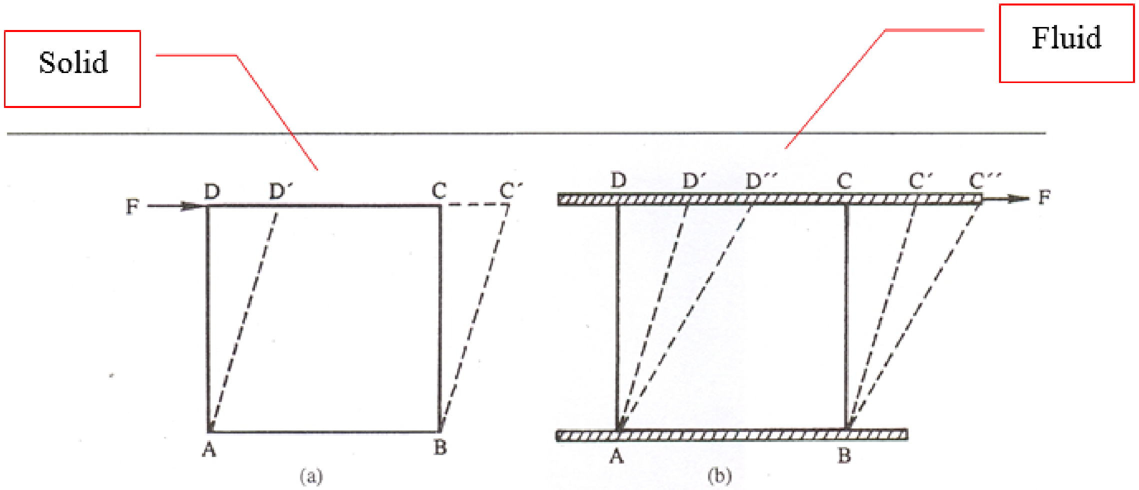
Fluid Dynamics

Chapter 1 Fluid Characteristics



Outline of Course

Ch.1 Fluid Characteristics
- Fluidity
- Viscosity
- Statics

Ch.2 Kinematics
- Velocity Field
- Flow Lines

Ch.10 Turbulence Modeling
- Classification of Turbulence Models
- Turbulence Closure Models

Ch.5 Stress–Strain Relations
- Surface Stresses
- Strain Components
- Relation for Newtonian Fluids

Ch.6 Equation of Motion
- 3D Continuity Equation
- 3D Navier–Stokes Equation

Ch.8 Turbulent Flow
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- 3D Reynolds Equation
- Turbulence Model

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- Heat Transport
- Momentum Transport

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- Vortex Motion

Ch.9 Wall Turbulence
- Turbulent Boundary Layer
- Mean–Flow Characteristics

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- Continuity Equation
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- Momentum Equation

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- Laminar Vs. Turbulent Flow
- Boundary Layer Flow
- Creeping Flow

Chapter 1 Fluid Characteristics

Contents

Objectives

- Define fluidity
- Study fundamental properties of the fluid

1.1 Introduction

1.1.1 Phases

- Solid
- Fluid
  - liquid
  - gas (vapor)
  - plasma

↓ increasing spacing and latitude of molecular motion

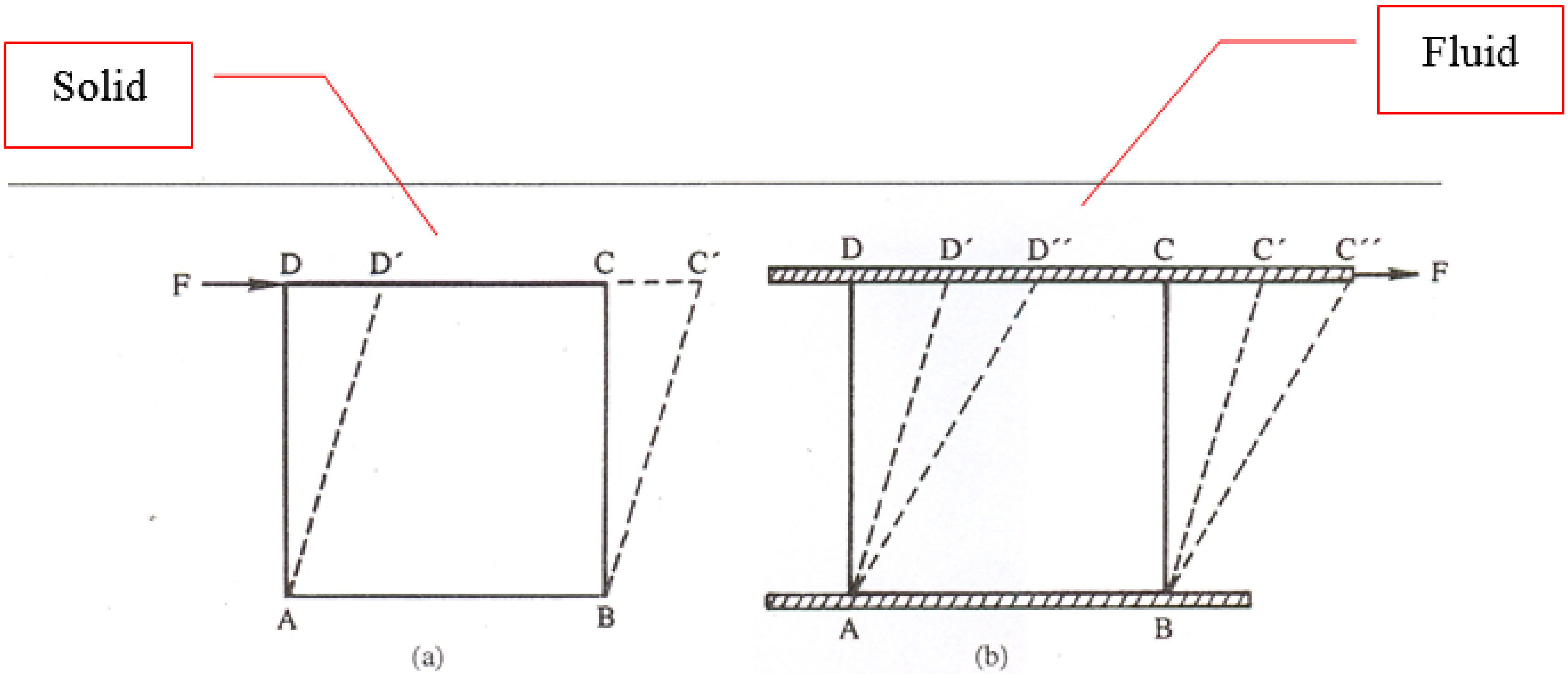
↑ increasing intermolecular cohesive force

1.1 Introduction

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)

1.1 Introduction



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
- <u>neglect void</u>
- 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

1.1 Introduction

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

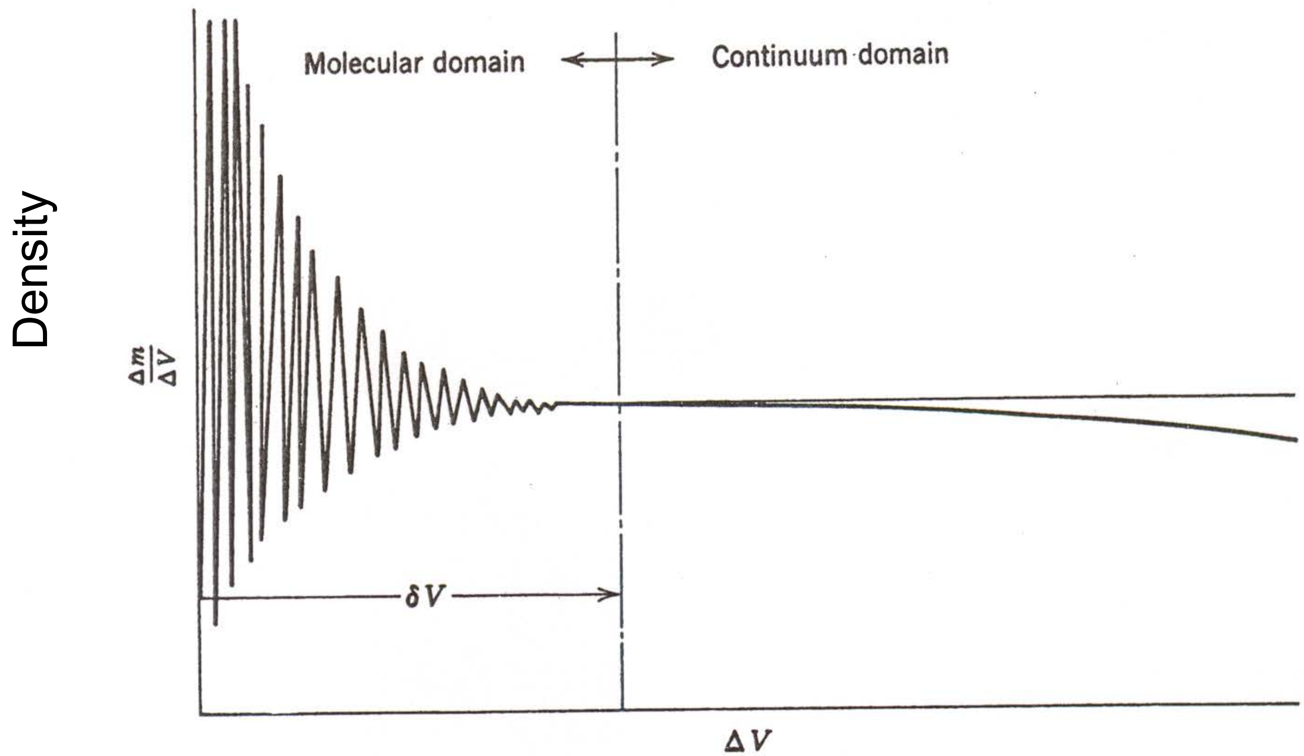
$$\vec{u} = \lim_{\Delta V \to \varepsilon} \frac{\sum v \Delta m}{\sum \Delta m}$$

ε = volume which is sufficiently small compared with the smallest significant length scale in the flow field but is <u>sufficiently large that it contains a large number of molecules</u>

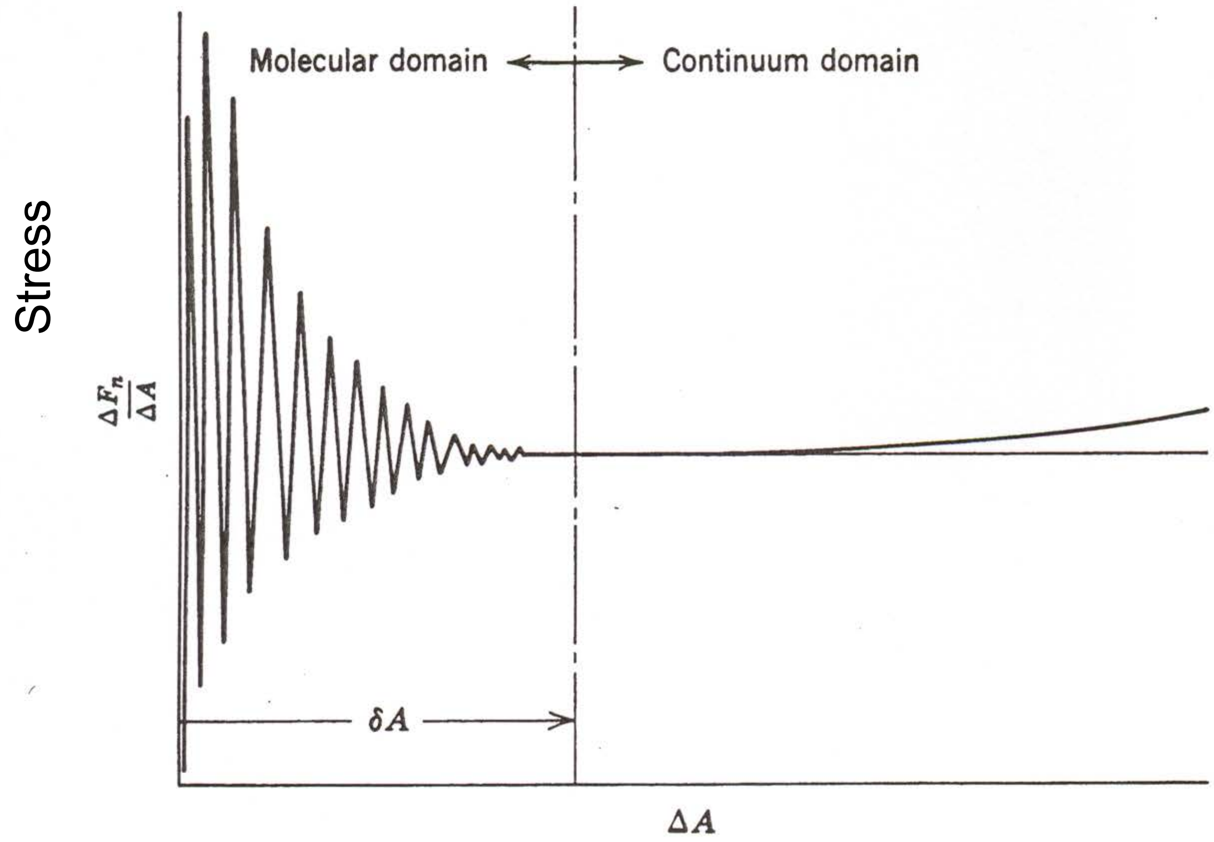
[Cf] Molecular approach

- molecular point of view
- well developed for light gases

1.1 Introduction



1.1 Introduction

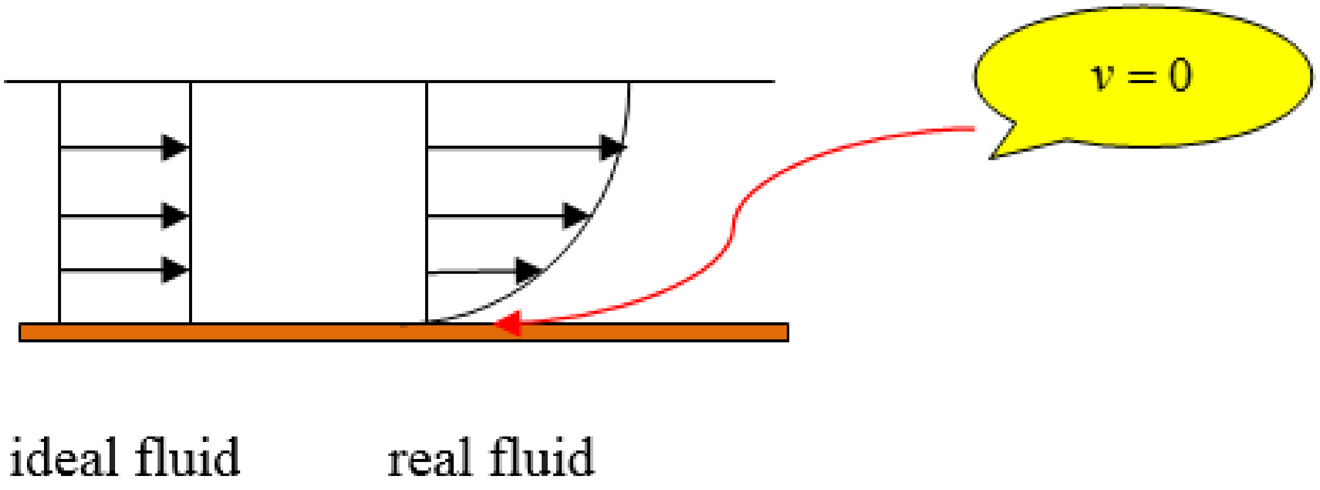


1.1 Introduction

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

- Single– phase fluid: multi-species system (dissolved contaminants)
- 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 (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, γ)

pressure, viscosity, surface tension

1.3 Properties and States of Fluids

1.3.1 Properties of importance in fluid dynamics

(1) Pressure, p ~ scalar

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

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

◈ Forces on a fluid element

Body force: act without physical contact

Surface force: require physical contact for transmission

1.3 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

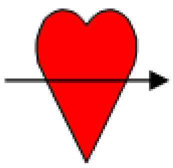
two bodies in thermal equilibrium → same temperature

1.3 Properties and States of Fluids

(3) Density, 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.

1.3 Properties and States of Fluids

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

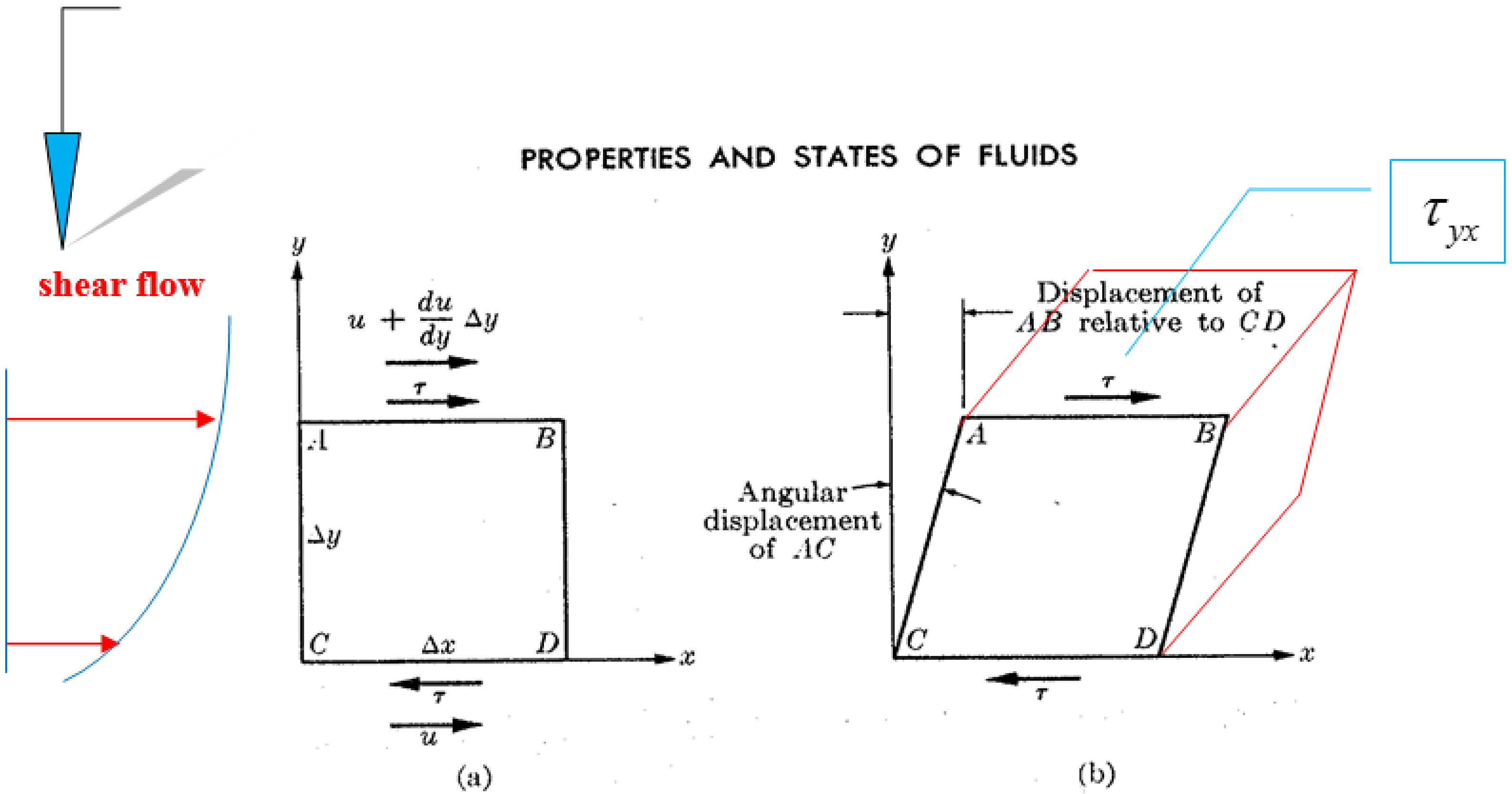
velocity vector $v = \lim_{\Delta t \to 0} \frac{\Delta s}{\Delta t}$

(5) Viscosity, μ

~ 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



1.3 Properties and States of Fluids

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)

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

1.3 Properties and States of Fluids

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

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

where

τ_{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 $(1/\sec)$

μ = dynamic molecular viscosity

1.3 Properties and States of Fluids

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

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

◈ 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

1.3 Properties and States of Fluids

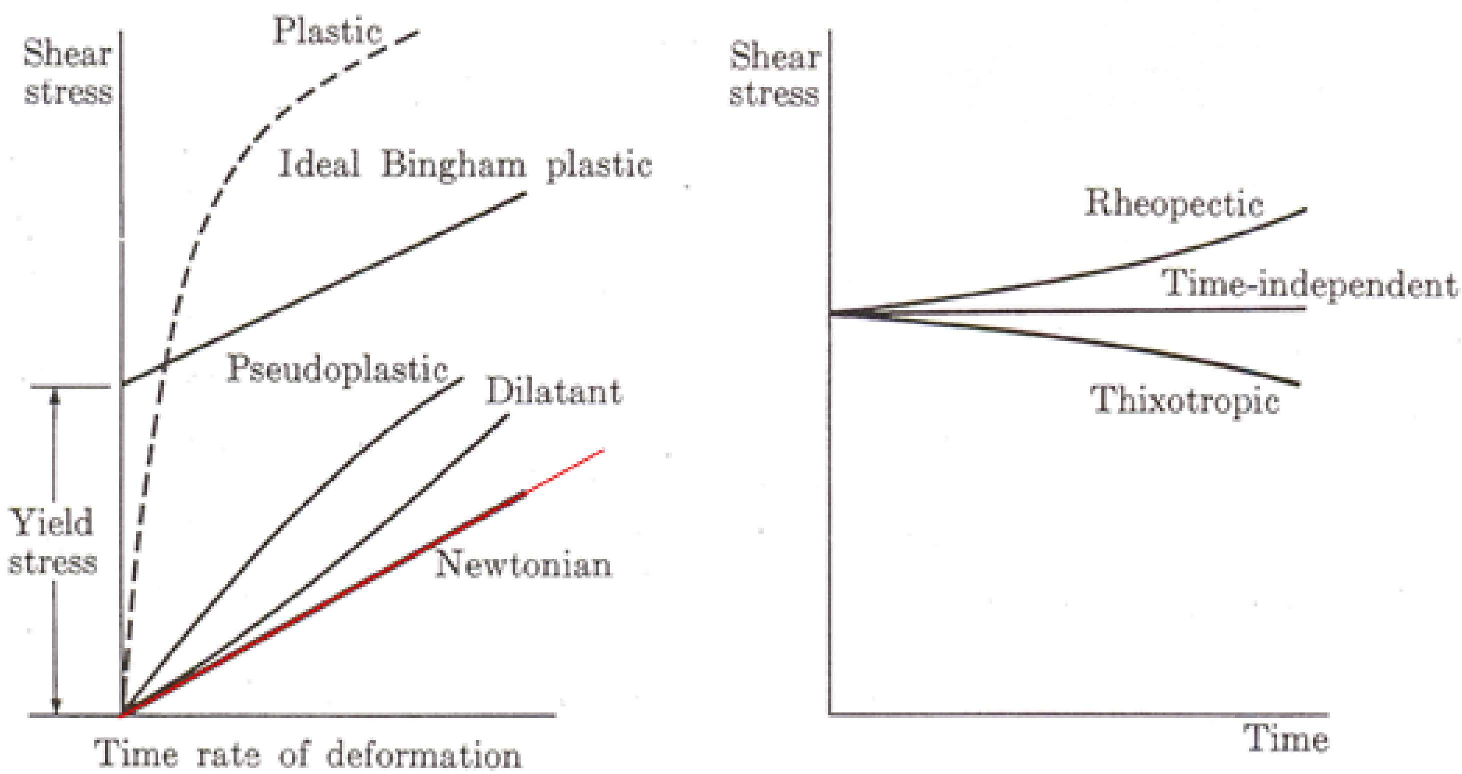
◈ Types of Fluid

- 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

1.3 Properties and States of Fluids

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

1.3 Properties and States of Fluids



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

◈ μ = 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 increasing	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

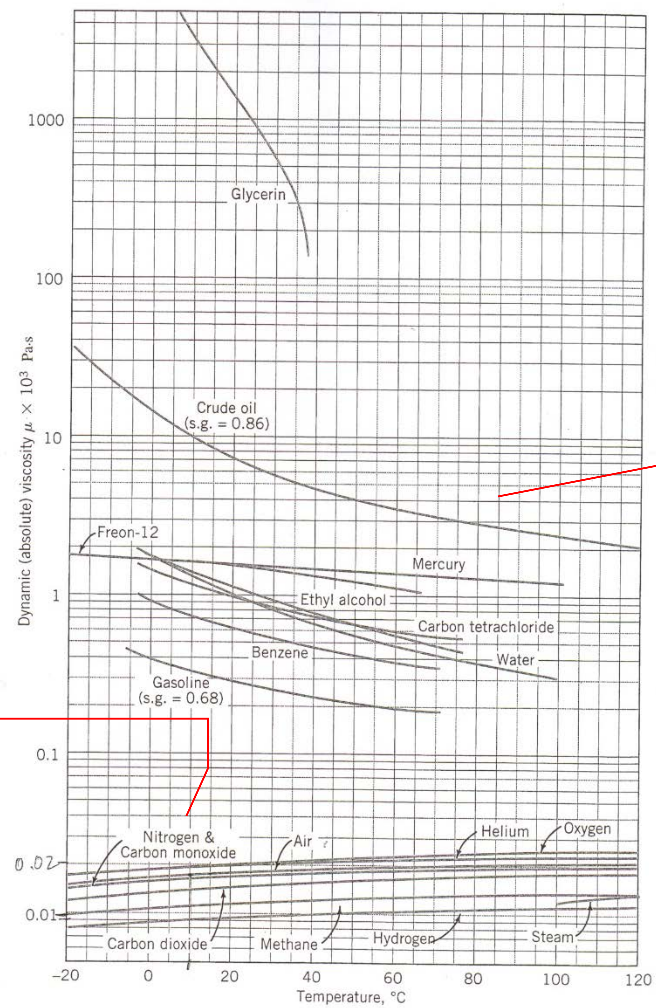
	SI Units						
	T, °C	ρ, kg/m^3	s.g., —	E, kPa	$\mu \times 10^4$ Pa · s	σ, N/m	p_v, kPa
Ethyl alcohol	20	788.6	0.79	1 206 625	12.0	0.022	5.86
Freon-12	15.6	1 345.2	1.35	—	14.8	—	—
	−34.4	1 499.8	—	—	18.3	—	—
Gasoline	20	680.3	0.68	—	2.9	—	55.2
Glycerin	20	1 257.6	1.26	4 343 850	14 939	0.063	0.000 014
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.

Water:

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

1.3 Properties and States of Fluids



μ decreases as T increases

μ increases as T increases

1.3 Properties and States of Fluids

(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 $= u + p / \rho$

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

$$p = F / A$$

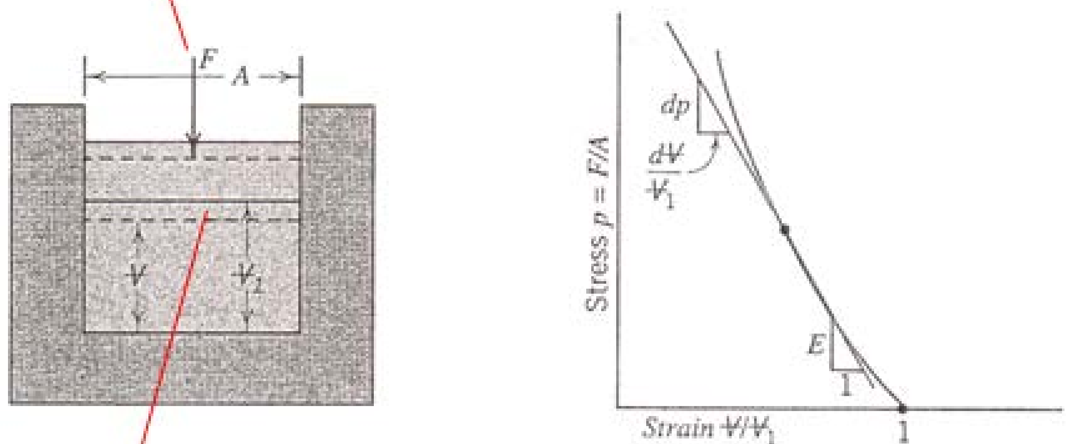


Fig. 1.3

$$dvol = V_1 - V$$

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

~ increases with temperature

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

σ

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)[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

1.3 Properties and States of Fluids

[Appendix 1] Coordinate Systems

i) Cartesian (x, y, z)

ii) Cylindrical (R, θ, z)

$$x = R\cos\theta$$

$$y = R\sin\theta$$

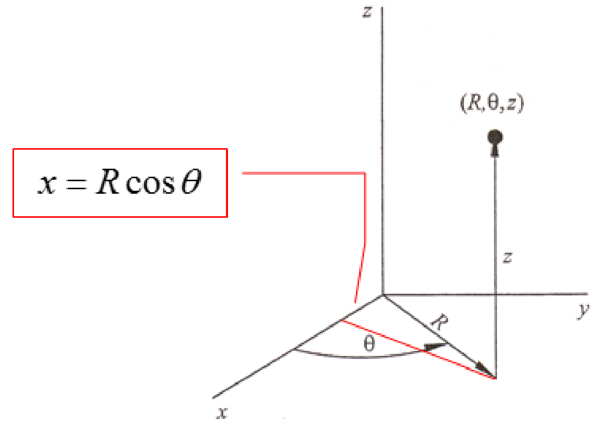
$$z = z$$

iii) Spherical (r, θ, ω)

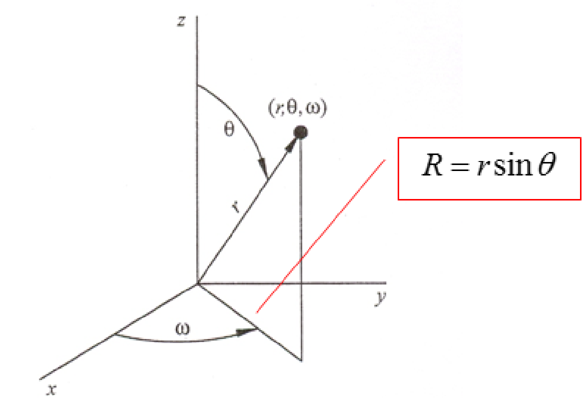
$$x = r\sin\theta\cos\omega$$

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

$$z = r\cos\theta$$



(a)



(b)

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

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

σ = normal stress,

τ = shear stress

1.3 Properties and States of Fluids

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

STRESS-STRAIN RELATIONS