FUNDAMENTALS OF FLUID MECHANICS

Chapter 1
Basic Properties of Fluids

MAIN TOPICS

- ❖Some Characteristics of Fluids
- ❖Dimensions and Units
- ❖Analysis of Fluid Behaviors
- ❖Ideal Gas Law
- ❖Fluid Properties
- ❖Compressibility of Fluids
- ❖Vapor Pressure
- ❖Surface Tension

謝志誠

Characteristics of Fluids

- What's a Fluid ?
- What's difference between a solid and a fluid ?

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Definition of Fluid

- Fluids comprise the liquid and gas (or vapor) phase of the physical forms.
- A fluid is a substance that deforms continuously under the application of a shear stress no matter how small the shear stress may be.
- A shearing stress is created whenever a tangential force acts on a surface.

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Fluid and Solid 1/3

❖ When a constant shear force is applied:
- ⇨Solid deforms or bends
- ⇨Fluid continuously deforms.

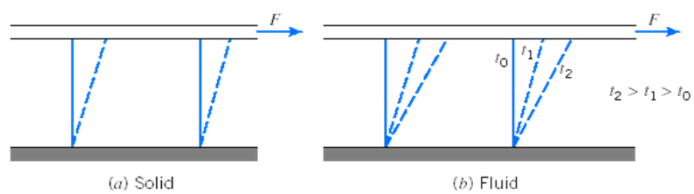

Fig. 1.1 Behavior of a solid and a fluid, under the action of a constant shear force.

謝志誠

Fluid and Solid 2/3

❖ Vague idea: 模糊的觀點
- ⇨Fluid is soft and easily deformed.
- ⇨Solid is hard and not easily deformed.

❖ Molecular structure: 分子結構的觀點
- ⇨Solid has densely spaced molecules with large intermolecular cohesive force allowed to maintain its shape.

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Fluid and Solid 3/3

- ⇨Liquid has further apart spaced molecules, the intermolecular forces are smaller than for solids, and the molecules have more freedom of movement. At normal temperature and pressure, the spacing is on the order of 10^{-6}mm. The number of molecules per cubic millimeter is on the order of 10^{21} .
- ⇨Gases have even greater molecular spacing and freedom of motion with negligible cohesive intermolecular forces and as a consequence are easily deformed. At normal temperature and pressure, the spacing is on the order of 10^{-7}mm. The number of molecules per cubic millimeter is on the order of 10^{18} .

謝志誠

Fluid? Solid ?

- ❖Some materials, such as slurries, tar, putty, toothpaste, and so on, are not easily classified since they will behave as solid if the applied shearing stress is small, but if the stress exceeds some critical value, the substance will flow. The study of such materials is called rheology. 某些物質，如泥漿、瀝青、油灰、牙膏等，在承受微小剪應力作用時，特性近似固體，但當剪應力超過某個臨界值以上時，其特性又近似流體。研究此類物質的學科，稱為流變學。

謝志誠

Fluid Characteristic Description

- Qualitative aspect
  - ⇨ Identify the nature, or type, of the characteristics (such as length, time, stress, and velocity) .
  - ⇨ Given in terms of certain **primary quantities, such as Length,L, time, T, mass, M, and temperature, θ**. The primary quantities are also referred to as basic dimensions.
  - ⇨ Given in terms of other **secondary quantity**, for example, area≒L^2,velocity ≒Lt^{-1} ,density ≒ML^{-3}.
- Quantitative aspect
  - ⇨ Provide a numerical measure of the characteristics.
  - ⇨ Requires both a number and a standard, Such standards are called units.

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Primary and Secondary Quantities

- Primary quantities also referred as basic dimensions.
  - ⇨ Such as Length,L, time, T, mass, M, and temperature, θ.
  - ⇨ Used to provide a qualitative description of any other secondary quantity.
- Secondary quantities
  - ⇨ For example, area≒L^2,velocity ≒Lt^{-1} ,density ≒ML^{-3}.

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System of Dimensions

- ❖ Mass[M], Length[L], time[t], and Temperature[T] …**MLt system**
- ❖ Force[F], Length[L], time[t], and Temperature[T] …**FLt system**
- ❖ Force[F], Mass[M], Length[L], time[t], and Temperature[T] …**FMLtT system**

謝志誠

Dimensions Associated with Common Physical Quantities

TABLE 1.1
Dimensions Associated with Common Physical Quantities

	FLT System	MLT System
Acceleration	LT^{-2}	LT^{-2}
Angle	$F^0L^0T^0$	$M^0L^0T^0$
Angular acceleration	T^{-2}	T^{-2}
Angular velocity	T^{-1}	T^{-1}
Area	L^2	L^2
Density	$FL^{-4}T^2$	ML^{-3}
Energy	FL	ML^2T^{-2}
Force	F	MLT^{-2}
Frequency	T^{-1}	T^{-1}
Heat	FL	ML^2T^{-2}
Length	L	L
Mass	$FL^{-1}T^2$	M
Modulus of elasticity	FL^{-2}	$ML^{-1}T^{-2}$
Moment of a force	FL	ML^2T^{-2}
Moment of inertia (area)	L^4	L^4
Moment of inertia (mass)	FLT^2	ML^2
Momentum	FT	MLT^{-1}
Power	FLT^{-1}	ML^2T^{-3}
Pressure	FL^{-2}	$ML^{-1}T^{-2}$
Specific heat	$L^2T^{-2}\Theta^{-1}$	$L^2T^{-2}\Theta^{-1}$
Specific weight	FL^{-3}	$ML^{-2}T^{-2}$
Strain	$F^0L^0T^0$	$M^0L^0T^0$
Stress	FL^{-2}	$ML^{-1}T^{-2}$
Surface tension	FL^{-1}	MT^{-2}
Temperature	Θ	Θ
Time	T	T
Torque	FL	ML^2T^{-2}
Velocity	LT^{-1}	LT^{-1}
Viscosity (dynamic)	$FL^{-2}T$	$ML^{-1}T^{-1}$
Viscosity (kinematic)	L^2T^{-1}	L^2T^{-1}
Volume	L^3	L^3
Work	FL	ML^2T^{-2}

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Dimensionally Homogeneous

- All theoretically derived **equations** are ***dimensionally homogeneous***– that is, the dimensions of the left side of the equation must be the same as those on the right side, and all additive separate terms have the same dimensions.
  - ⇨General homogeneous equation: valid in any system of units.
  - ⇨Restricted homogeneous equation : restricted to a particular system of units.

Valid only for the system of units using feet and seconds

$$d = \frac{gt^2}{2} \quad \Rightarrow \quad d = 16.1t^2$$

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System of Units

- British Gravitational System: B.G.
- International System: S.I.
- English Engineering: E.E.

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Dimension and Units

- MLtT
  - International System (kg, m, s, ^oK)
- FLtT
  - British Gravitational (lbf, ft, s, ^oR)
- FMLtT
  - English Engineering (lbf, lbm, ft, s, ^oR)

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British Gravitational System

- Length: ft
- Time: second
- Force: lb
- Temperature: ^oF or ^oR : $^oR = ^oF + 459.67$
- Mass: slug : $1\ \text{lb} = 1\ \text{slug} \times 1\ \text{ft}/\text{sec}^2$
- Gravity: $g = 32.174\ \text{ft}/\text{sec}^2$
- Weight: $W\ (\text{lb}) = m\ (\text{slug}) \times g\ (\text{ft}/\text{sec}^2)$

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International System (SI)

- Length: m
- Time: second
- Mass: Kg
- Temperature : ^oK : $^oK = {}^oC + 273.15$
- Force: Newton: 1 N＝1 Kg×1 m / sec^2
- Work: Joule (J) ; J ＝1 N×m
- Power: Watt (W) ;W＝J / sec＝N×m/sec
- Gravity: g = 9.807 m / sec^2
- Weight: W (N) = m (Kg) × g (m/ sec^2) : 1 kg-mass weights 9.81N

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English Engineering (EE) System

- Mass: lbm
- Force:lbf
- Length: ft
- Time: second
- Temperature: ^oR (absolute temperature)

$F = ma / g_c$ ； g_c : the constant of proportionality

$1\ lbf = (lb_m \times 32.174\ ft / sec^2) / g_c$

$g_c = (lb_m \times 32.174\ ft / sec^2) / lbf$

In E.E., the relationship between weight and mass :

W＝mg / gc Therefore, 1 slug＝32.174 lbm (when $g = g_c$)

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Conversion Factor

■ **TABLE 1.3**
Conversion Factors from BG and EE Units to SI Units[a]

	To Convert from	to	Multiply by
Acceleration	ft/s^2	m/s^2	3.048 E − 1
Area	ft^2	m^2	9.290 E − 2
Density	lbm/ft^3	kg/m^3	1.602 E + 1
	$slugs/ft^3$	kg/m^3	5.154 E + 2
Energy	Btu	J	1.055 E + 3
	ft · lb	J	1.356
Force	lb	N	4.448
Length	ft	m	3.048 E − 1
	in.	m	2.540 E − 2
	mile	m	1.609 E + 3
Mass	lbm	kg	4.536 E − 1
	slug	kg	1.459 E + 1
Power	ft · lb/s	W	1.356
	hp	W	7.457 E + 2
Pressure	in. Hg (60 °F)	N/m^2	3.377 E + 3
	lb/ft^2 (psf)	N/m^2	4.788 E + 1
	$lb/in.^2$ (psi)	N/m^2	6.895 E + 3
Specific weight	lb/ft^3	N/m^3	1.571 E + 2
Temperature	°F	°C	$T_C = (5/9)(T_F - 32°)$
	°R	K	5.556 E − 1
Velocity	ft/s	m/s	3.048 E − 1
	mi/hr (mph)	m/s	4.470 E − 1
Viscosity (dynamic)	$lb \cdot s/ft^2$	$N \cdot s/m^2$	4.788 E + 1
Viscosity (kinematic)	ft^2/s	m^2/s	9.290 E − 2
Volume flowrate	ft^3/s	m^3/s	2.832 E − 2
	gal/min (gpm)	m^3/s	6.309 E − 5

[a]If more than four-place accuracy is desired, refer to Appendix E.

■ **TABLE 1.4**
Conversion Factors from SI Units to BG and EE Units[a]

	To Convert from	to	Multiply by
Acceleration	m/s^2	ft/s^2	3.281
Area	m^2	ft^2	1.076 E + 1
Density	kg/m^3	lbm/ft^3	6.243 E − 2
	kg/m^3	$slugs/ft^3$	1.940 E − 3
Energy	J	Btu	9.478 E − 4
	J	ft · lb	7.376 E − 1
Force	N	lb	2.248 E − 1
Length	m	ft	3.281
	m	in.	3.937 E + 1
	m	mile	6.214 E − 4
Mass	kg	lbm	2.205
	kg	slug	6.852 E − 2
Power	W	ft · lb/s	7.376 E − 1
	W	hp	1.341 E − 3
Pressure	N/m^2	in. Hg (60 °F)	2.961 E − 4
	N/m^2	lb/ft^2 (psf)	2.089 E − 2
	N/m^2	$lb/in.^2$ (psi)	1.450 E − 4
Specific weight	N/m^3	lb/ft^3	6.366 E − 3
Temperature	°C	°F	$T_F = 1.8\,T_C + 32°$
	K	°R	1.800
Velocity	m/s	ft/s	3.281
	m/s	mi/hr (mph)	2.237
Viscosity (dynamic)	$N \cdot s/m^2$	$lb \cdot s/ft^2$	2.089 E − 2
Viscosity (kinematic)	m^2/s	ft^2/s	1.076 E + 1
Volume flowrate	m^3/s	ft^3/s	3.531 E + 1
	m^3/s	gal/min (gpm)	1.585 E + 4

[a]If more than four-place accuracy is desired, refer to Appendix E.

謝志誠

Preferred Systems of Units

- ❖SI (kg, m, s, °K)

$$1\ \text{N} \equiv 1\ \text{kg} \cdot \text{m/s}^2$$

- ❖British Gravitational (lb, ft, s, °R)

$$1\ \text{slug} = 1\ \text{lb} \cdot \text{s}^2\text{ft}$$

Example 1.2 BG and SI Units

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Analysis of Fluid Behaviors 1/2

- Analysis of any problem in fluid mechanics necessarily includes statement of the basic laws governing the fluid motion. The basic laws, which applicable to any fluid, are:
  - ⇨Conservation of mass
  - ⇨Newton's second law of motion
  - ⇨The principle of angular momentum
  - ⇨The first law of thermodynamics
  - ⇨The second law of thermodynamics

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謝志誠

Analysis of Fluid Behaviors 2/2

- NOT all basic laws are required to solve any one problem. On the other hand, in many problems it is necessary to bring into the analysis additional relations that describe the behavior of physical properties of fluids under given conditions.
- Many apparently simple problems in fluid mechanics that cannot be solved analytically. In such cases we must resort to more complicated numerical solutions and/or results of experimental tests.

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Ideal Gas Law

- Gases are highly compressible in comparison to fluids, with changes in gas density directly related to changes in pressure and temperature through the equation $p=\rho RT$.
- The ideal gas equation of state $p=\rho RT$ is a model that relates density to pressure and temperature for many gases under normal conditions.
- **The pressure in the ideal gas law must be expressed as an absolute pressure which is measured relative to absolute zero pressure.**
- **The standard sea-level atmospheric pressure is 14.6996 psi (abs) or 101.33kPa (abs).**

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謝志誠

Density

- The density of a fluid, designated by the Greek symbol ρ (rho), is defined as its mass per unit volume.
- Density is used to characterize the mass of a fluid system.
- **In the BG system ρ has units of slug/ft^3 and in SI the units are kg/m^3.**
- The value of density can vary widely between different fluids, but for liquids, variations in pressure and temperature generally have only a small effect on the value of density.

⇨ **The specific volume, v, is the volume per unit mass – that is,**

$$\upsilon = 1/\rho$$

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謝志誠

Specific Weight

- The specific weight of a fluid, designated by the Greek symbol γ (gamma), is defined as its weight per unit volume.

$$\gamma = \rho g$$

- Under conditions of standard gravity (g= 9.807m/ s^2 = 32.174 ft / s^2), water at 60°F has a specific weight of 62.4lb/ft^3 and 9.80kN/m^3. **The density of water is 1.94slug/ft^3 or 999kg/m^3.**

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謝志誠

Specific Gravity

- The specific gravity of a fluid, designated as SG, is defined as the ratio of the density of the fluid to the density of water at some specified temperature.

$$SG = \frac{\rho}{\rho_{H_2O@4°C}}$$

$\rho_{H_2O,\ 4°C}$ = **1.94slug/ft^3 or 999kg/m^3.**

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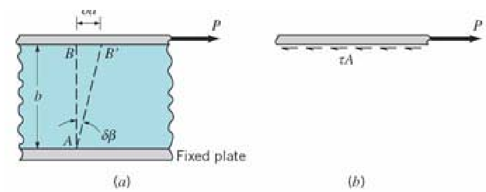
Fluidity of Fluid 1/3

- How to describe the "fluidity" of the fluid?
  - The bottom plate is rigid fixed, but the upper plate is free to move.
  - If a solid, such as steel, were placed between the two plates and loaded with the force *P*, the top plate would be displaced through some small distance, δa.
  - The vertical line AB would be rotated through the small angle, δβ, to the new position AB'.



P ＝τA

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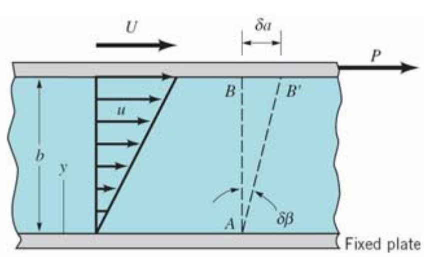
Fluidity of Fluid 2/3

- What happens if the solid is replaced with a fluid such as water?
  - When the force P is applied to the upper plate, it will move continuously with a velocity U.
  - The fluid "sticks" to the solid boundaries and is referred to as the NON-SLIP conditions.
  - The fluid between the two plates moves with velocity u=u(y) that would be assumed to vary linearly, u=Uy/b. In such case, the velocity gradient is **du / dy ＝ U / b.**



謝志誠

Fluidity of Fluid 3/3

- In a small time increment, δt, an imaginary vertical line AB would rotate through an angle, δβ , so that

  tan δβ≒δβ ＝ δa / b

  Sinceδa ＝ U δt it follows that δβ= U δt / b

  δβ ? →δβ＝δβ（P, t）

- Defining the rate of shearing strain, γ, as $\dot{\gamma} = \lim_{\delta t \to 0} \frac{\delta\beta}{\delta t} = \frac{U}{b} = \frac{du}{dy}$
- The shearing stress is increased by P, the rate of shearing strain is increased in direct proportion, $\tau \propto \dot{\gamma}$ or $\tau \propto du/dy$

The common fluids such as water, oil, gasoline, and air the shearing stress and rate of shearing strain can be related with a relationship

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

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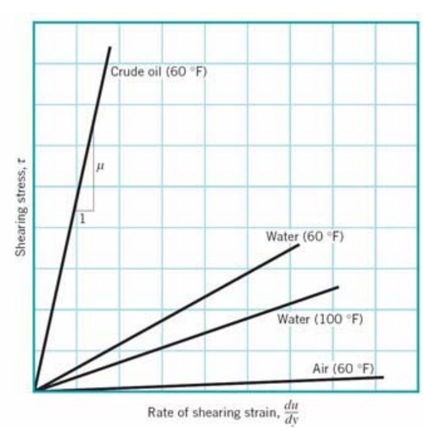
Viscosity

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

- The constant of proportionality is designated by the Greek symbol μ (mu) and is called the absolute viscocity, dynamic viscosity, or simply the viscosity of the fluid.
- The viscosity depends on the particular fluid, and for a particular fluid the viscosity is also **dependent on temperature**.



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謝志誠

Dimension and Unit of μ

- The dimension of μ : Ft/L^2 or M/Lt.
- The unit of μ:
  - ⇨In B.G. : $lbf\text{-}s/ft^2$ or slug/(ft-s)
  - ⇨In S.I. :kg/(m-s) or $N\text{-}s/m^2$ or Pa -s
  - ⇨In the Absolute Metric: poise=1g/(cm-s)

Example 1.4 Viscosity and Dimensionless Quantities

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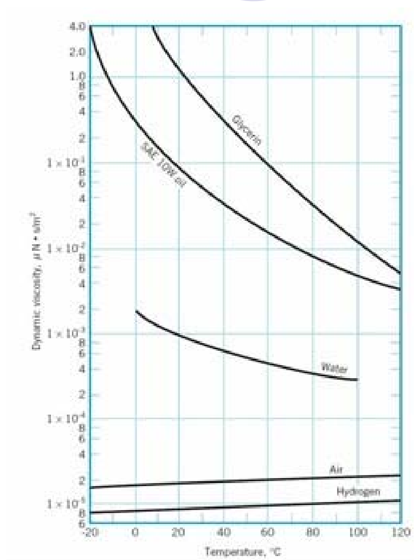
Viscosity and Temperature 1/3

- For fluids, the viscosity decreases with an increase in temperature.
- For gases, an increase in temperature causes an increase in viscosity.

⇨ WHY? molecular structure.



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Viscosity and Temperature 2/3

- The liquid molecules are closely spaced, with strong cohesive forces between molecules, and the resistance to relative motion between adjacent layers is related to these intermolecular force. As the temperature increases, these cohesive force are reduced with a corresponding reduction in resistance to motion. Since viscosity is an index of this resistance, it follows that viscosity is reduced by an increase in temperature.
- **The Andrade's equation $\mu = De^{B/T}$**

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謝志誠

Viscosity and Temperature 3/3

- In gases, the molecules are widely spaced and intermolecular force negligible. The resistance to relative motion mainly arises due to the exchange of momentum of gas molecules between adjacent layers. As the temperature increases, the random molecular activity increases with a corresponding increase in viscosity.
- **The Sutherland equation $\mu = CT^{3/2} / (T+S)$**

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謝志誠

Newtonian and Non-Newtonian Fluid

- Fluids for which the shearing stress is linearly related to the rate of shearing strain are designated as **Newtonian fluids** after I. Newton (1642-1727).
- Most common fluids such as water, air, and gasoline are Newtonian fluid under normal conditions.
- Fluids for which the shearing stress is not linearly related to the rate of shearing strain are designated as **non-Newtonian fluids.**

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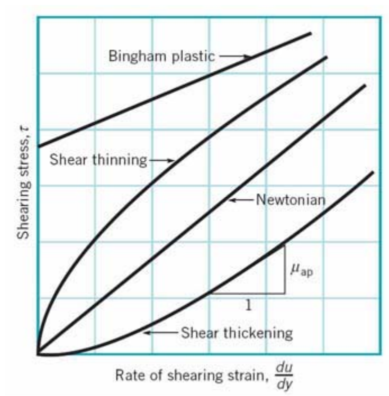
non-Newtonian Fluids 1/2

- Shear thinning fluids: The viscosity decreases with increasing shear rate – the harder the fluid is sheared, the less viscous it becomes. Many colloidal suspensions and polymer solutions are shear thinning. Latex paint is example.（膠質懸浮液及聚合物，如：乳狀塗料 ）



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non-Newtonian Fluids 2/2

- Shear thickening fluids: The viscosity increases with increasing shear rate – the harder the fluid is sheared, the more viscous it becomes. Water-corn starch mixture water-sand mixture are examples.水與玉蜀黍澱粉混合物，水與砂混合物（流沙）。
- Bingham plastic: neither a fluid nor a solid. Such material can withstand a finite shear stress without motion, but once the yield stress is exceeded it flows like a fluid. Toothpaste and mayonnaise are commmon examples.

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謝志誠

Kinematic Viscosity

- Defining kinematic viscosity $\nu = \mu/\rho$ [Ny]
  - ⇨The dimensions of kinematic viscosity are L^2/T.
  - ⇨The units of kinematic viscosity in BG system are ft^2/s and SI system are m^2/s.
  - ⇨In the CGS system, the kinematic viscosity has the units of cm^2/s, is called a stoke, abbreviated St.

Example 1.5 Newtonian Fluid Shear Stress

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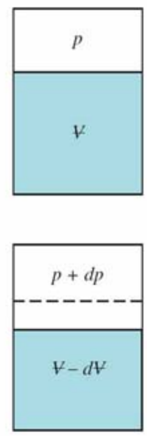
謝志誠

Bulk Modulus

- Liquids are usually considered to be incompressible, whereas gases are generally considered compressible.
- ***Compressible of the fluid?***
- A property, ***bulk modulus Ev***, is used to characterize compressibility of fluid.

$$E_v = -\frac{dp}{d\text{V}/\text{V}} = \frac{dp}{d\rho/\rho}$$

- The bulk modulus has dimensions of pressure. FL^{-2}.



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Compression and Expansion

- When gases are compressed or expanded, the relationship between pressure and density depends on the nature of the process.
  - For isothermal process $\frac{P}{\rho} = constant$

  \>> Ev=P
  - For isentropic process $\frac{P}{\rho^k} = constant$

  \>> Ev=kP

Where k is the ratio of the specific heat at constant pressure, c_p, to the specific heat at constant volume, c_v.

$c_p - c_v$=R=gas constant

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謝志誠

Speed of Sound

❖The velocity at which small disturbances propagate in a fluid is called ***the speed of sound***.

❖The speed of sound is related to change in pressure and density of the fluid medium through

$$c = \sqrt{\frac{dp}{d\rho}} = \sqrt{\frac{E_v}{\rho}}$$

⇨For isentropic process $c = \sqrt{\frac{kP}{\rho}}$

⇨For ideal gas $c = \sqrt{kRT}$

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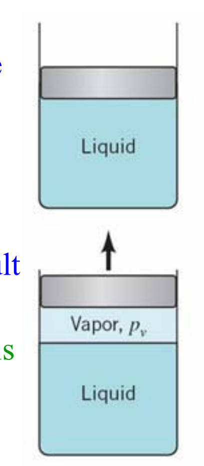
Vapor Pressure and Boiling 1/2

❖ If liquids are simply placed in a container open to the atmosphere, some liquid molecules will overcome the intermolecular cohesive forces and escape into the atmosphere.

❖ If the container is closed with small air space left above the surface, and this space evacuated to form a vacuum, a pressure will develop in the space as a result of the vapor that is formed by the escaping moleculs.

❖ When an equilibrium condition is reached, the vapor is said to be saturated and the pressure that the vapor exerts on the liquid surface is termed the VAPOR PRESSURE, p_v.



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Vapor Pressure and Boiling 2/2

- Vapor pressure is closely associated with molecular activity, the value of vapor pressure for a particular liquid depends on temperature.
- Boiling, which is the formation of vapor bubbles within a fluid mass, is initiated when the absolute pressure in the fluid reaches the vapor pressure.
- The formation and subsequent collapse of vapor bubbles in a flowing fluid, called **cavitation**, is an important fluid flow phenomenon.

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Surface Tension 1/3

- At the interface between a liquid and a gas, or between two immiscible liquids, forces develop in the liquid surface which cause the surface to behave as if it were a "skin" or "membrane" stretched over the fluid mass.
- Although such a skin is not actually present, this conceptual analogy allows us to explain several commonly observed phenomena.
- 在液體與氣體的界面或兩不相容的液體界面間會有「力」產生，且在界面上形成類似「表皮」或「薄膜」的延伸面。雖然這種「表皮」或「薄膜」實際上並不存在，但卻可以透過一些現象來加以推論，例如將鋼針輕放可以浮在水面上、小水銀滴在光滑的表面形成球狀，以及毛細管中液體的上升或向降（毛細管效應）。這種作用在液體表面上，沿著表面任何線的作用力稱為「張力」。

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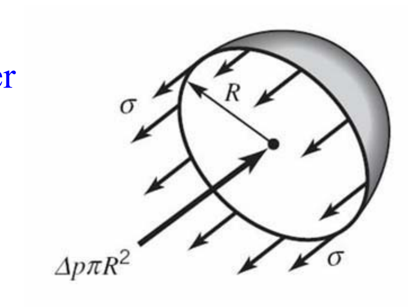
Surface Tension 2/3

❖ Surface tension: the intensity of the molecular attraction per unit length along any line in the surface and is designated by the Greek symbol σ (sigma).



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

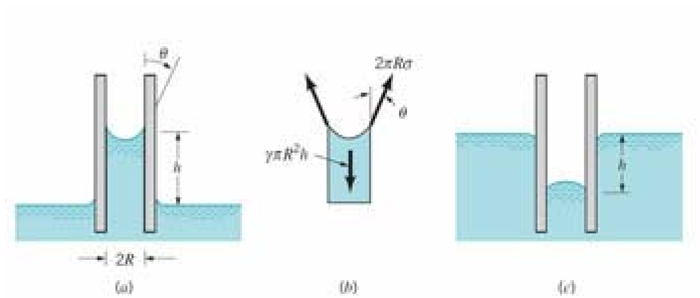
$$\Delta p = p_i - p_e = \frac{2\sigma}{R}$$

Where p_i is the internal pressure and p_e is the external pressure

謝志誠

Surface Tension 3/3

❖ A common phenomena associated with surface tension is the rise or fall of a liquid in a capillary tube.



$$\gamma\pi R^2 h = 2\pi R\sigma\cos\theta \qquad h = \frac{2\sigma\cos\theta}{\gamma R}$$