Ecole Nationale des Sciences et Technologies Avancées à Borj Cédria

Fluid Mechanics

Chapter 1

Introduction and Fundamental Concepts

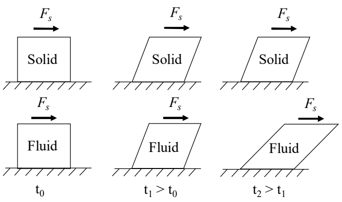
2022-2023

Introduction – Generalities

- All matter exists in one of three phases: liquid, vapor (or gas), and solid.
- The word "fluid" is used as a general term for the first two of these phases, since the basic mechanical behavior of liquids and gases is very similar.
- Perhaps it is easier to define materials in terms of how they respond (i.e., deform or flow) when subjected to an applied force in a specific situation such as the simple shear situation

Introduction – Generalities

- Under shear force, a fluid can be deformed continuously, while a solid cannot.



Introduction – Generalities

Fluid mechanics is the science that deals with the behavior of a fluid either in rest or in motion

The study of fluid mechanics can be devided into 3 branches

- Statics of Fluid (statique des fluides) : mechanics of fluids at rest
- Kinematics (cinématique des fluides): mechanics of fluid in motion, deals with velocity and streamline w/o considering forces or energy
- Fluid Dynamics (dynamique des fluides): deals with the relations between velocities and accelerations and forces exerted by or upon fluids in motion
- Fluids are considered as continuous medium (media)

Dimensions and Units

- There are two primary sets of units:
  1. SI (Système International) units
  2. English units (Imperial system)
- Fundamental dimensions are as follow :
  - mass [M]
  - length [L]
  - time [t]
  - temperature [θ]
  - current
  - luminosity
  - ….
- Other dimensions are combinations of the the fundamental dimensions

Table of Units

Quantity	SI Unit	English Unit	Other common units
Length (L)	Meter (*m*)	Foot (*ft*)	Inch (*in*)
Mass (m)	Kilogram (*kg*)	Slug (slug) = $lb \times sec^2/ft$	Slug
Time (t)	Second (*s*)	Second (*sec*)	Second (*sec*)
Temperature (θ)	Celcius(°*C*)	Farenheit(°*F*)	Kelvin (K), Rankine (°R)
Area (L^2)	m^2	ft^2	in^2
Volume (L^3)	m^3	ft^3	in^3, galon, litre
Velocity (Length/Time)	*m/s*	*ft/sec*	*in/sec*
Acceleration (Length/Time^2)	m/s^2	ft/sec^2	in/sec^2
Force (mass×acceleration)	Newton (*N*)=*kg×m/s2*	Pound (*lb*)	---

Properties of Fluids

Fluid properties can be summarised as follows:

- Density (masse volumique)
- Specific Volume
- Specific weight
- Pressue
- Tempurature
- Viscosity
- Bulk Modulus and Fluid Elasticity
- …

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Properties of Fluids

1 Density ρ (masse volumique)

Is the mass of the fluid per unit volume

$$\rho \equiv \frac{\text{mass}}{\text{Volume}} \left[\frac{\text{kg}}{\text{m}^3}\right]$$

In English units $\rho \left[\frac{\text{lb}_\text{m}}{\text{ft}^3}\right]$ or $\left[\frac{\text{Slug}}{\text{ft}^3}\right]$

$\rho \propto T, P$

Dependence is strong for gases

Dependence is weak for liquids

If dependence is negligible the fluid is called incompressible.

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Properties of Fluids

2 Specific Volume v

Is the volume occupied by the unit mass of the fluid

$$v \equiv \frac{\text{Volume}}{\text{mass}} \left[\frac{\text{m}^3}{\text{kg}}\right]$$

$$v = \frac{1}{\rho}$$

In English units $v \left[\frac{\text{ft}^3}{\text{lb}_\text{m}}\right]$ or $\left[\frac{\text{ft}^3}{\text{Slug}}\right]$

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Properties of Fluids

3 Specific weight γ

Is the weight per unit volume of the fluid

$$\gamma \equiv \frac{\text{weight}}{\text{Volume}} = \frac{mg}{V} = \rho \cdot \mathrm{g}$$

$$\gamma = \rho \mathrm{g} \left[\frac{\mathrm{kg}}{\mathrm{m}^3} \cdot \frac{\mathrm{m}}{\mathrm{sec}^2}\right] = \left[\frac{\mathrm{N}}{\mathrm{m}^3}\right]$$

In English units $\gamma = \frac{\rho \mathrm{g}}{\mathrm{g}_c} \left[\frac{\mathrm{lb_m}}{\mathrm{ft}^3} \cdot \frac{\mathrm{ft}}{\mathrm{sec}^2} \cdot \frac{\mathrm{lb_f\,sec}^2}{\mathrm{ft\,lb_m}}\right] = \left[\frac{\mathrm{lb_f}}{\mathrm{ft}^3}\right]$

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Properties of Fluids

4 Specific gravity S (densité)

Is defined as the ratio of mass density of the fluid concerned and the mass density of water at standard pressure and temperature.

$$S \equiv \frac{\rho}{\rho_{\mathrm{ref}}} \left[\frac{kg}{m^3} \cdot \frac{m^3}{kg}\right] = [\ \ ]$$

$$S \equiv \frac{\rho}{\rho_{\mathrm{ref}}} = \frac{\rho\, \mathrm{g}}{\rho_{\mathrm{ref}}\, \mathrm{g}} = \frac{\gamma}{\gamma_{\mathrm{ref}}}$$

For liquids, the reference fluid is water at 4°C and 101.330 kPa; $\rho_{\mathrm{ref}} =$ 1000kg/m^3

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Properties of Fluids

5 Pressure P

Is defined as force per unit area

$$\mathrm{p} \equiv \frac{\text{force}}{\text{area}} \left[\frac{\mathrm{N}}{\mathrm{m}^2}\right] = [\mathrm{Pa}]$$

In english units: $\mathrm{p} \left[\frac{\mathrm{lb_f}}{\mathrm{ft}^2}\right]$ or $\left[\frac{\mathrm{lb_f}}{\mathrm{in}^2}\right]$

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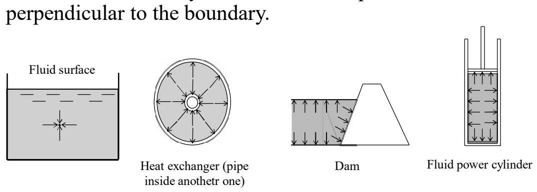
Properties of Fluids

5 Pressure

- Pressure acts uniformly in all directions on a small volume of fluid.
- In a fluid confined by solid boundaries, pressure acts perpendicular to the boundary.



Properties of Fluids

5 Pressure

- Use absolute pressure: relative to zero pressure (vacuum).
- Gauge pressure indicates the pressure relative to local atmospheric pressure.
- *Gauge* and *absolute pressures* are related by:

$$p_{abs} = p_G + p_{atm}$$

- Standard atmospheric conditions

$$P_{atm} = 101.330 \text{ kPa}$$

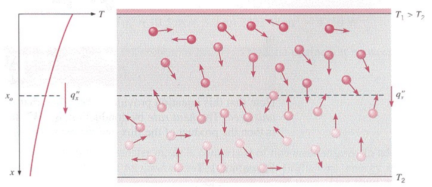
- For relative pressure: pressure difference between two points, no need to indicate whether it is gauge or absolute pressure

Properties of Fluids

6 Temperature

Is a measure of the ability of a substance, or more generally of any physical system, to transfer heat energy to another physical system.

The temperature of a substance is closely related to the average kinetic energy of its molecules at a given point of the fluid.



Properties of Fluids

6 Temperature

There are basically four used temperature scales, Celsius, Kelvin, Fahrenheit, and Rankine

	Kelvin K	Celsius °C	Fahrenheit °F	Rankine °Ra (°R)
Absolute zero	0	−273.15	−459.67	0
Water freezes	273.15	0	32	491.67
Water boils	373.15	100	211.97	671.64

Fahrenheit = Celsius × 9 / 5 + 32

Kelvin = Celsius + 273.15

Rankine = Fahrenheit + 459.6

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Properties of Fluids

7 Viscosity

- Viscosity ≈ the internal stickiness of a fluid
- viscosity ≈ internal friction to fluid motion which can then lead to energy loss.
- Viscosity is a measure of resistance to fluid flow as a result of internal friction forces resulting from cohesion and momentum interchange between molecules.

- Viscosity of a fluid depends on temperature:
  - **In liquids**, viscosity **decreases with increasing temperature** (cohesion decreases with increasing temperature)
  - **In gases**, viscosity **increases with increasing temperature** (molecular interchange between layers increases with temperature setting up strong internal shear)

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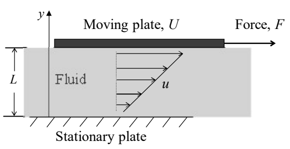
Properties of Fluids

7 Viscosity



The velocity induced by the moving plate is expressed as follows:

$$u(y) = \left(\frac{U}{L}\right) y$$

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Properties of Fluids

7 Viscosity

For a large class of fluids, empirically, $F \propto \frac{AU}{L}$

Where A is the area of the moving plate

More specifically $F = \mu \frac{AU}{L}$

μ is coefficient of viscosity (dynamic viscosity)

- μ [kg/m.s]
- It is a property of fluid
- It is function of T and P of the fluid
  - gas: viscosity is affected by very high P only
  - liquids: depends exponentially on P. Importance is function of fluid nature

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Properties of Fluids

7 Viscosity

The shear stress induced by F is then, $\tau = \frac{F}{A} = \mu \frac{U}{L}$

From previous slides, the variation of the velocity along the y-axis can be written

$$\frac{du}{dy} = \frac{U}{L}$$

Thus, the shear stress is $\tau = \mu \frac{du}{dy}$

The kinematic viscosity is defined as $\nu = \frac{\mu}{\rho}$ $[m^2/s]$

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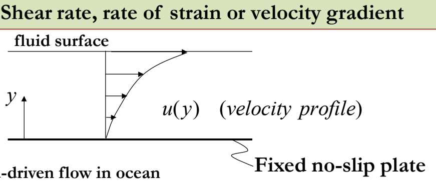
Properties of Fluids

7 Viscosity

Newton's Law of viscosity

Shear stress due to viscosity at a point: $\tau = \mu \frac{du}{dy}$

τ = Shear stress
μ = Viscosity - Absolute viscosity - Dynamic viscosity
du/dy = Shear rate, rate of strain or velocity gradient



e.g.: wind-driven flow in ocean

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Properties of Fluids

7 Viscosity

➢ Fluids for which the shearing stress is linearly related to the rate of shearing strain (rate of angular deformation) are designated as ***Newtonian fluids***.

➢Fortunately most common fluids, both liquids and gases, are Newtonian. Example: Air, Water, Oil, Gasoline, Alcohol, Kerosene, Benzene, Glycerine

- The viscosity μ is a function only of the condition of the fluid, particularly its temperature.
- The magnitude of the velocity gradient (du/dy) has no effect on the magnitude of μ

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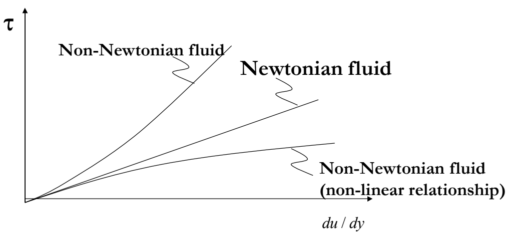
Properties of Fluids

7 Viscosity

➢ Fluids which do not follow the linear law of Newton's, are called Non-Newtonian. Example : blood, paints, toothpaste…

➢The viscosity of the non-Newtonian fluid is dependent on the velocity gradient as well as the condition of the fluid



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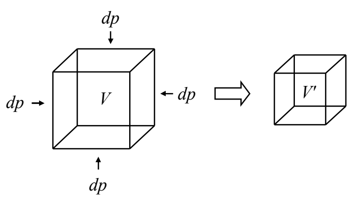
Properties of Fluids

8 Bulk Modulus and Fluid Elasticity *E*

The Bulk Modulus Elasticity is a material property characterizing the compressibility of a fluid. It measures the substance's resistance to uniform compression.



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Properties of Fluids

8 Bulk Modulus and Fluid Elasticity E

$$E \equiv -V\left(\frac{dp}{dV}\right)$$

Where :

- dp is the differential change in pressure on the object
- dV is the differential change in volume of the object
- V is the initial volume of the object

$$E\ [Pa] \text{ or } [N/m^2]$$

In english units: $E\ [lb_f/ft^2]$ or $[lb_f/in^2]$ or $[psi]$

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Properties of Fluids

9 Coefficient de compressibilité isotherme χ

$$\chi = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_T$$

χ est l'inverse d'une pression en Pa^{-1}.

Pour une masse constante m = ρV= Cte.

dm= ρdV+ Vdρ=0 → dV/V = -d ρ/ ρ

Ainsi $\chi = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial P}\right)_T$

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Properties of Fluids

10 Vapor pressure

- Vapour pressure is the partial pressure produced by fluid vapour in an open or a closed container, which reaches its saturated condition, or the transfer of fluid molecules is at equilibrium along its free surface.
- In a closed container, the vapour pressure is solely dependent on temperature. In a saturated condition, any further reduction in temperature or atmospheric pressure below its dew point will lead to the formation of water droplets.
- On the other hand, boiling occurs when the absolute fluid pressure is reduced until it is lower than the vapour pressure of the fluid at that temperature.

For a network of pipes, the pressure at a point can be lower than the vapour pressure, for example, at the suction section of a pump. Otherwise, vapour bubbles will start to form, and this phenomenon is termed as cavitation.

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