Intermediate Fluid Mechanics

Chapter 1: Fluid Properties

Marc Calaf

Department of Mechanical Engineering

University of Utah

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Chapter Overview

Lecture Objectives

- Define some basic properties of Fluids
- Introduce why we think of fluids as a continuum and not as molecules

Chapter Overview

What is a fluid?

- A fluid is a substance (material or quantity of mass) that does not have a preferred shape and that deforms continuously under the application of a shear (tangential stress), no matter how small the shear stress maybe.

- A fluid can also be defined as any substance that cannot sustain a shear stress when at rest.

- Fluids can be divided into two categories: (i) liquids, (ii) gases.

Which one is a fluid?

Can you tell which one of the two illustrations represents a fluid, when shear stress is applied to the top face while the bottom one remains stationary ?

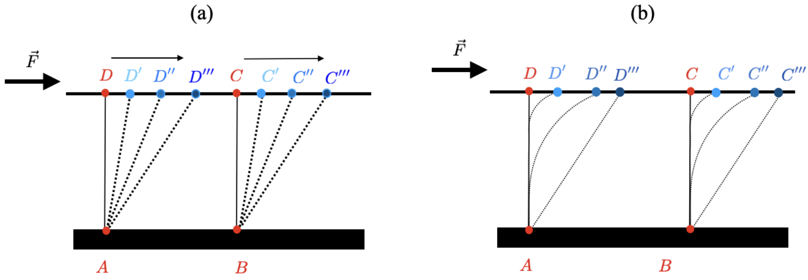

Figure: *Comparison in deformation behavior between an elastic solid (a) and a fluid (b).*

Difference between an Elastic Solid and a Fluid:

A) Elastic Solid:

- A material that deforms linearly through its complete thickness.
- In this case, the magnitude of the applied force and the modulus of elasticity determine the extent of the deformation.
- *i.e* the distance between D-D' and C-C'. The deformation in this case is finite under a continuous applied shear stress. When the shear stress ceases, the material returns to its initial shape.

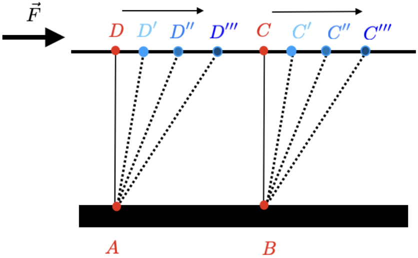

Figure: *Deformation behavior for an elastic solid.*

Difference between an Elastic Solid and a Fluid:

B) Fluid:

- When the shear stress is applied to the top face of the material, points D and C move towards D' and C' respectively but the lower portion of the fluid near the fixed bottom plate does not even know that the top plate has began to move.

- When the shear stress ceases, deformation stops, but the fluid does not return to its original shape.

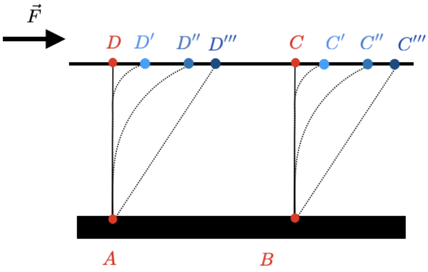

Figure: *Deformation behavior for a fluid (b).*

Examples:

Example 1

See the video included in this link

Example 2

See the video included in this link

For other Fluids Videos and explanations

See the video included in this link

⟹ What causes this fundamental difference in behavior between solids and fluids?

Viscosity:

- Viscosity is the material property that represents the internal resistance of a fluid to motion.
- Viscosity determines the extent of momentum transfer in a fluid due to: (i) molecular collisions in gases, and (ii) cohesive forces between molecules in liquids.

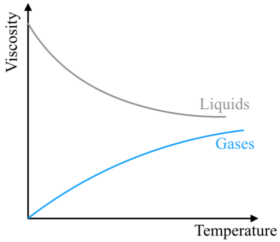

Figure: *Change in viscosity as a function of temperature.*

Viscosity

Characteristics of Viscosity:

- Viscosity depends strongly on temperature but only very weakly on pressure.
- In liquids, viscosity decreases with temperature because molecules possess more energy at higher temperatures, allowing them to oppose intermolecular forces more strongly and move more freely.
- In gases, viscosity increases with temperature because gases move more randomly at higher temperature, which results in more molecular collisions and thus greater resistance to flow.

Chapter Overview

The continuum hypothesis:

Molecular view:

- In principle it should be possible to study fluid dynamics by considering the motion of the individual molecules, as it is done in kinetic theory of gases.
- In this case, one must write a coupled-set of dynamic equations for all molecules.
- But in a single mm^3 of oxygen at 1 atm of pressure and at 20° C there are about 3×10^6 molecules, $\Longrightarrow$ one quickly realizes that this quickly becomes an unmanageable problem.

Note

$\Longrightarrow$ Given that we are generally interested in the *gross* behavior of the fluid, *i.e.* the average motion of a large number of molecules; it is better to approach the problem of fluid dynamics from a more '*macroscopic*' perspective.

The continuum hypothesis:

Continuum view:

- Every '*point*' in the space (identified by its position vector, $\vec{x} = x\,\hat{i} + y\,\hat{j} + z\,\hat{k}$) represents an infinitesimal cube comprised of many, many molecules.
- Hence, the fluid appears as a continuous, homogeneous matter with no voids.
- This allows to treat fluid properties as smoothly varying quantities.
- This idea is called the 'continuum assumption'.
- It is because of the 'continuum assumption' that the fluid density (ρ), and fluid velocity (u) can hence be defined at each point in space.

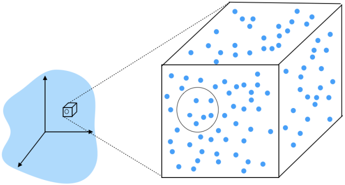

Figure: *Continuum Assumption.*

Density of a Fluid:

As custom, the density of a fluid is defined as: $\rho = \frac{\Delta m}{\Delta V}$

- when ΔV is very small ($\rightarrow 0$), the number of molecules in the volume will vary with time because of the random nature of molecular motion. (Molecules will move in and out of our delimited volume ΔV).
- As the volume increases, the variation in density (ρ) will decrease until ρ' is independent of the measuring volume (ΔV_1 – Vertical line in Figure).
- If the volume is too large (ΔV_2), the value of the density might change due to spatial variations.

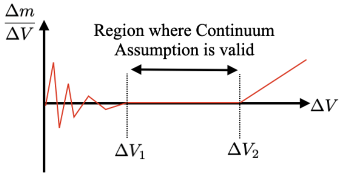

Figure: *Density definition in the continuum assumption.*

Example:

How large does an infinitesimal volume need to be in order for the continuum hypothesis to be valid?

- The continuum hypothesis is valid if the mean free path (λ) between molecules is very small compared to the characteristic length scale (l) of the flow, *i.e.* $\lambda/l \leq 10^{-2}$.
- For the two cases represented in the Figure, $l_1 \approx 5\mu m$, and $l_2 \approx 10m$.

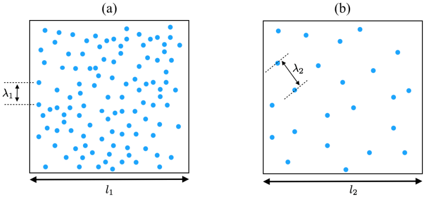

Figure: *(a) Molecular structure of air at standard temperature and pressure, $\lambda_1 \sim 5 \times 10^{-8} m$. (b) Molecular structure of air in the upper atmosphere, $\lambda_2 \sim 1m$.*

Note:

Under the continuum hypothesis, it is not possible to realistically consider any fluid motion on length scales less than l.

Chapter Overview

Transport Phenomena

- In fluid dynamics one is interested in how the fluid motion transports (i) mass, (ii) momentum, (iii) energy, and (iv) concentration, such as pollutants.
- Although the details of molecular motions may be locally averaged to compute fluid temperature, density, or velocity, random molecular motions still lead to diffusive transport of molecular species, temperature or momentum that impact fluid phenomena at macroscopic scales.
- Such diffusive transport is incorporated in the continuum assumption of fluid motion through the specification of transport coefficients (k_m, k, mu, or nu as introduced later).

Mass Transport: Fick's law of diffusion

Fick's law considers the migration of molecules in a mixture (*e.g.* top to bottom in Figure below).

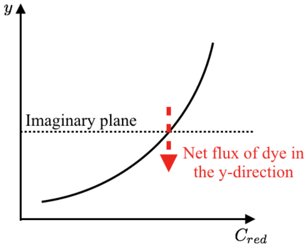

Figure: *Flux of dye from a high concentration region (large y values) to a lower concentration region (small y values).*

- In the y-direction the mass flux of the constituent ($kg/m^2\,s$ in SI) is proportional to the concentration gradient ($q_m \sim \frac{dC}{dy}$).
- Defining k_m as a diffusion coefficient which is a function of the mixture constituency and thermodynamic state,

$$q_m = -k_m \frac{dC}{dy}, \tag{1}$$

Heat Transport: Fourier's law of heat flux

In this case of transport of heat,

$$\vec{q}_H = -k\,\vec{\nabla}\,T, \tag{2}$$

where:

- $\vec{q}_H$ is the heat flux measured in $J/m^2\,s$,
- k is the thermal conductivity.

Momentum flux:

The momentum flux results from the exchange of momentum in intermolecular collisions and/or forces between neighboring molecules.

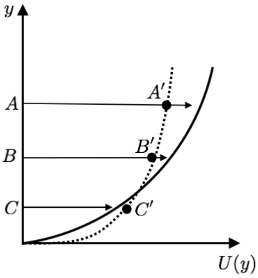

Figure: *Velocity profile and its tendency due to momentum diffusion.*

- The velocity profile will tend to evolve with time towards the '*dashed-line*' profile due to the downward momentum flux.
- As a result a shear stress τ, is generated in the fluid (Newton's law of friction),

$$\tau = \mu \frac{du}{dy}, \tag{3}$$

- μ is the absolute viscosity measured in $kg/m\,s$ in SI system.
- $\mu/\rho = \nu$, the so-called dynamic viscosity ν, measured in m^2/s in SI units.