ME 305 Fluid Mechanics I

Part 1

Fundamental Fluid and Flow Properties

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Mechanics

- Mechanics studies the motion and deformation of material bodies under applied loads (forces, moments).
- It involves loads, energy, motion, deformation and material properties.
- When the material is in solid phase it is called solid mechanics, which you already studied in ME 205, ME 206, ME 208.
- When the material is in liquid or gas phase it is called fluid mechanics.

High School Definition of a Fluid

- Three most common phases of matter are solid, liquid and gas.
- Liquids and gases are together called fluids.

	Intermolecular Attraction Forces	*Molecules*	*Volume and Space*
Solid	Strong	Relative positions are rather fixed	Definite volume Definite shape
Liquid	Medium	Free to change their relative positions	Definite volume Indefinite shape
Gas	Weak	Practically unrestricted	Indefinite volume Indefinite shape

- Later we'll give another definition for ''fluid'', based on its behavior under shear forces.

Exercise : From a technical point of view, what is the difference between gases and vapors?

Exercise : What are the fourth and fifth phases of matter? Do a research on them.

Branches of Science that Study Fluids

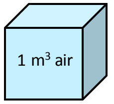
- Mechanics is concerned with both stationary and moving bodies under the influence of loads.
  - Statics is the branch of mechanics that deals with bodies at rest.
  - Dynamics is the branch of mechanics that deals with bodies in motion.
- Fluid mechanics deals with the behavior of fluids at rest (fluid statics) and in motion (fluid dynamics).
  - Hydrodynamics studies liquids (incompressible flow) in motion.
    - Hydraulics studies liquids flowing in pipes, ducts and open channels.
  - Gas dynamics studies compressible flow of gases with high density changes.
  - Aerodynamics is similar to gas dynamics, but also covers low speed flows. It focuses on air flow.

Application Areas of Fluid Mechanics

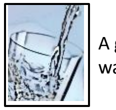
- Too many to list all of them. Some examples are
  - Household appliances : refrigerator, vacuum cleaner, dish washer, washing machine, water meter, natural gas meter, air conditioner, radiator, etc.
  - Turbomachines : pump, turbine, fan, blower, propeller, etc.
  - Military : Missile, aircraft, ship, underwater vehicle, dispersion of chemical agents, etc.
  - Automobile : IC engine, air conditioning, fuel flow, external aerodynamics, etc.
  - Medicine : Heart assist device, artificial heart valve, Lab-on-a-Chip device, glucose monitor, controlled drug delivery, etc.
  - Electronics : Convective cooling of generated heat.
  - Energy : Combustor, burner, boiler, gas, hydro and wind turbine, etc.
  - Oil and Gas : Pipeline, pump, valve, offshore rig, oil spill cleanup, etc.
- Almost everything in our world is either in contact with a fluid or is itself a fluid.

The Concept of Continuum

- At the microscopic scale, fluids are composed of molecules.



~ 2 x 10^{25} molecules



A glass of water

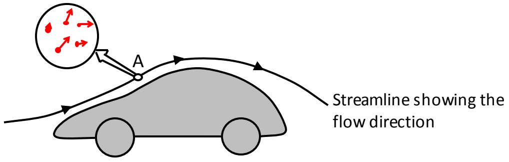
~ 10^{25} molecules

- Question : Is it possible to keep track of all these molecules ?
- Answer : Practically impossible and not necessary for most engineering problems.
- Rather, we study most engineering problems at the macroscopic scale.
- That is we treat fluids as continuum and do not concern with the behavior of individual molecules.

The Concept of Continuum

Microscopic level: Each fluid molecule shown below moves at a different speed in a different direction.

Macroscopic level: The speed at point A is 60 km/h. The direction of air flow at point A is as shown below.



60 km/h is the average speed of molecules in the small volume surrounding point A. We can say that the fluid particle located at point A is moving with a speed of 60 km/h.

Continuum (cont'd)

- Continuum assumes that fluid and flow properties, such as density, velocity, pressure, temperature, etc. vary continuously throughout the fluid.
- In continuum, the smallest element of a fluid is NOT a fluid molecule, but rather a fluid particle, which contains enough number of molecules to make meaningful statistical averages.
- Question: Is continuum a reasonable assumption?
- Practical answer: Yes, in many engineering problems.
- Detailed answer: Depends on the Knudsen number.

$$Kn = \frac{\lambda}{L} = \frac{\text{Average distance traveled by molecules between collisions (mean free path)}}{\text{Characteristic dimension of the flow field}}$$

- Continuum is known to be valid for $Kn < 0.01$.
- In this course we will always treat fluids as continuum.

Continuum (cont'd)

Exercise : Is it easier to break the continuum assumption for a gas or a liquid?

Exercise : Air at standard atmospheric conditions has a mean free path of 8×10^{-8} m. What will be the limiting characteristic length that will break the validity of the continuum assumption for an application using standard atmospheric air? Search on the web for micro and nano scale flows to see if there are applications at such small scales.

Exercise : How much the mean free path of air should be increased so that we can start questioning the validity of continuum for flow around a missile with a characteristic length of 10 m? Is it possible to have such high mean free path values at the outermost regions of the atmosphere?

Exercise : Read about ''rarefied gas dynamics''. Find examples where it is encountered.

Exercise : Direct Simulation Monte Carlo (DSMC) is a numerical method that can be used to study high Kn flows. Do a research on general Monte Carlo methods and DSMC is specific.

Dimensions and Units

- In the MLT system basic dimensions are

$$\text{Mass}\,[\mathrm{M}], \quad \text{Length}\,[L], \quad \text{Time}\,[T]$$

- Dimensions of all other quantities can be expressed in terms of these

$$\text{Acceleration}\,[LT^{-2}]$$
$$\text{Energy}\,[???]$$
$$\text{Pressure}\,[???]$$
$$\text{Angular velocity}\,[???]$$
$$\text{Torque}\,[???]$$

- For some problems, Temperature $[\theta]$ also serves as a basic dimension.
- Equations should be dimensionally homogeneous, i.e. dimensions of the left and right sides should be the same.
- Speed of a uniformly accelerated body is given by $V = V_0 + at$

[m/s] [s] [m/s^2]

Dimensions and Units (cont'd)

Exercise: A website claims that the distance travelled by a freely falling body is given by the following formula. Is it dimensionally homogeneous?

$$d = 4.90\,t^2$$

Exercise: The force F, due to the air blowing against a car in a wind tunnel is given by

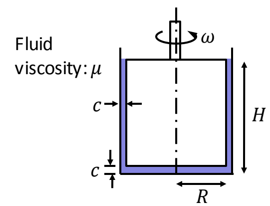
$$F = \frac{C_D \rho V^2 A}{2}$$

where V is the air speed, ρ is the density of air, A is the cross sectional area of the car facing the air, and C_D is a constant called the drag coefficient. Determine the dimensions of C_D.

Dimensions and Units (cont'd)

Exercise: In a previous semester, one ME 305 student provided the following wrong answer for the shown midterm question. The instructor put a comment on the student's paper saying ''You should be able to notice that this answer cannot be correct''. What does the instructor expect from the student?

Question: A concentric cylinder viscometer is formed by rotating the inner cylinder of a pair or closely fitting cylinders. The outer cylinder is kept fixed and the gap between the cylinders is filled with a fluid of unknown viscosity μ. Using the parameters given in the figure, determine the torque that needs to be applied on the inner cylinder to rotate it at a constant speed of ω.



Student's wrong answer: $$\text{Torque} = \frac{2\pi\omega H R^3 \mu}{c} + \frac{\pi \omega R^3 \mu}{2c} = \frac{\pi\omega R^3 \mu}{c}\left(2H + \frac{1}{2}\right)$$

Significant Figures

Exercise: In another midterm exam of ME 305 a different version of the previous question was asked. This time numerical values are given for all the parameters, including the viscosity of the fluid, and the required torque is asked. One student provided the following answer and the instructor put a comment on the student's paper saying ''Are you serious?''. What does the instructor expect from the student?

Student's answer: Torque = 15.908633 Nm

- Number of significant figures that need to be used in an answer depends on the significant figures of the numbers that you used to evaluate it.
- For measured quantities, number of significant figures depends on the minimum reading scale of the measuring device.

- Often an engineer needs to use his/her engineering intuition to judge the correct number of significant figures to use.

Fundamental Flow and Fluid Properties

Density	ρ	kg/m³
Velocity	$\vec{V}$	m/s
Pressure	p	Pa , atm , bar , mmHg
Viscosity	μ	Pa·s , poise
Temperature	T	K or ºC
Internal energy	$\check{u}$	J/kg
Enthaply	h	J/kg
Entropy	s	J/(kg K)
Specific heat	c_p , c_v	J/(kg K)
Thermal conductivity	k	W/(m K)

It is common to use p and T to fix the thermodynamic state. Then other properties can be expressed as a function of these two

$$\rho = \rho(p,T)\,, \quad h = h(p,T)\,, \quad \mu = \mu(p,T)\,, \quad \text{etc.}$$

Density

- (ρ) [kg/m³]
- Mass contained in a unit volume of a fluid. $\rho = m/\forall$
- Density determines the inertia of a unit volume of fluid and hence its acceleration when subjected to a given force. Gases are easier to accelerate than liquids.
- Density also determines the amount of gravitational force (weight) acting on a fluid body. Weight of gases are neglected more often than that of liquids.
- Fluids have a very wide range of density.

	Hydrogen Gas	Methane (Natural Gas)	Air	Water	Mercury
Density [kg/m³]	0.084	0.67	1.2	998	13600

(at standart conditions)

Density

- Density in general is a function of p and T, i.e. $\rho = \rho\ (p,T)$
- If a fluid's density is a function of pressure only (not temperature) it is called a barotropic fluid, a simplification mostly used in meteorology.
- Following processes demonstrate how density of an ideal gas ($p = \rho RT$) can change with temperature and pressure.

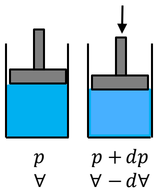
Add heat and allow piston to go up to keep p constant

Remove heat to keep T constant

Density (cont'd)

- Changing p or T may result in a change in ρ

$$\rho = \rho(p,T) \quad \rightarrow \quad \underbrace{d\rho}_{\text{Total change of } \rho} = \underbrace{\left(\frac{\partial \rho}{\partial p}\right)_T dp}_{\text{Change of } \rho \text{ due to the change in } p} + \underbrace{\left(\frac{\partial \rho}{\partial T}\right)_p dT}_{\text{Change of } \rho \text{ due to the change in } T}$$



Used to define bulk modulus of elasticity, E_v

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

Meaning: Amount of differential pressure change (dp) necessary to create a differential change in volume ($d\forall$), of a fluid volume $\forall$.

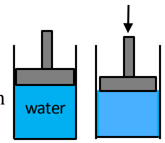
Used to define coefficient of thermal expansion, β

Compressibility

Exercise: Using $m = \rho\forall$, show that E_v can also be written as $\frac{dp}{d\rho/\rho}$.

- Large E_v indicates a relatively incompressible fluid.
- At 1 atm (~100 kPa) pressure and 15 °C temperature, we need to increase pressure to 21.5 MPa to compress a unit volume of water 1 %.

$p = 1$ atm
$\forall = 1$ unit



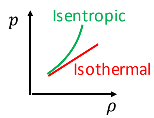
$p = 21.5$ MPa
$\forall = 0.99$unit

- Incompressible fluid is an idealization used mostly for liquids that have constant density over a given range of conditions of a flow problem.
- In this course we'll consider all liquids to be incompressible (constant density) unless otherwise mentioned.
- We'll take ρ_{water} = 1000 kg/m³ (constant) unless otherwise mentioned.

Compressibility (cont'd)

- Gases are much more compressible than liquids.
- E_v of a gas that compresses (or expands) depends on the process.

A perfect gas ($p = \rho RT$) goes through



Isothermal process
(T = constant)
($\frac{p}{\rho}$ = constant)

$$E_v = \rho\frac{dp}{d\rho} = p$$

Isentropic process
($\frac{p}{\rho^k}$ = constant)

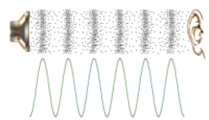
$$E_v = \rho\frac{dp}{d\rho} = kp$$

Exercise: Calculate the isentropic bulk modulus of air ($k = 1.4$) at standard conditions. Compare the compressibility of air and water.

Compressibility (cont'd)

- Due to compressibility, disturbances created in a fluid propagate at a finite speed.
- Sound generated by a speaker is a pressure disturbance and it travels in a medium (e.g. air) with the speed of sound c.
- Considering the motion of sound to be isentropic, for an ideal gas

$$c = \sqrt{\left(\frac{dp}{d\rho}\right)_s} = \sqrt{\frac{E_v}{\rho}} = \sqrt{\frac{kp}{\rho}} = \sqrt{kRT}$$



Movie:
Speeding bullet

- For air at 1 atm pressure and 15 °C temperature

$$c = \sqrt{kRT} = \sqrt{(1.4)(286.9)(288)} = 340.4 \text{ m/s}$$

- For water at 15 °C

$$c = \sqrt{\frac{E_v}{\rho}} \approx \sqrt{\frac{2.15\times 10^9}{1000}} = 1466 \text{ m/s}$$

Coming from slide 1-18

Compressibility (cont'd)

- Speed of sound is higher in less compressible fluids.
- For an incompressible fluid, which is an idealization, speed of sound is infinity.
- Mach number (Ma) is the non-dimensional parameter that can be used to check the importance of compressibility in gas flows.

$$Ma = \frac{V}{c} = \frac{\text{Characteristic speed in a flow problem}}{\text{Speed of sound}}$$

- Although gases are much more compressible than liquids they can also be treated as incompressible (constant density) in many engineering applications.
- As a rule of thumb, flows with $Ma < 0.3$ can be studied as incompressible.

Exercise : In a wind tunnel test air is blown around a car at a speed of 120 km/hr. Calculate Mach number of the flow and decide if compressibility effects are negligible or not.

- In this course we'll take ρ_{air} = 1.2 kg/m³ unless otherwise mentioned.

Density (cont'd)

- Hydrometer is a device used to measure density of a fluid based on Archimedes' principle. It's working principle will be studied in ''Fluid Statics'' chapter and you'll use it in the first experiment of ME 305.

- Specific gravity (Relative density): (s) [unitless]

Ratio of density of a substance to the reference density of water at 4 °C.

$$s = \frac{\rho}{\underbrace{\rho_{\text{water (at 4 °C)}}}_{1000\ \text{kg/m}^3}}$$

- Specific weight: (γ) [N/m³]

Weight per unit volume of a substance.

$$\gamma = \rho g$$

Velocity Field

Fluid velocity: ($\vec{V}$) [m/s]

- In different coordinate systems velocity vector components are

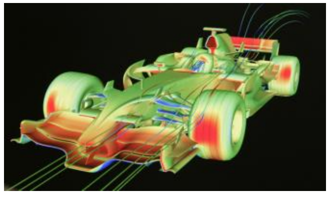
Cartesian : $\vec{V} = u\,\vec{i} + v\,\vec{j} + w\,\vec{k}$

Cylindrical : $\vec{V} = V_r\,\vec{e_r} + V_\theta\,\vec{e_\theta} + V_z\,\vec{e_z}$

- In general velocity field of a flowing fluid is too complicated to be expressed as a closed form equation of space and time.

Visualization of flow over an airfoil

http://www.youtube.com/watch?v=gmSKGMSfOcs &NR =1



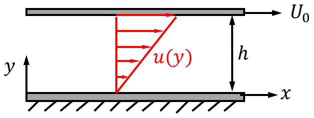
Visualization of flow over an F1 race car

http://www.ecourses.ou.edu

Velocity Field (cont'd)

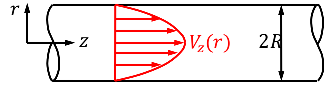
- But there are also simpler flows with easy to express velocity fields.

Couette Flow: Shear driven flow between two wide parallel plates, one is fixed and the other is moving.



$$u = \frac{U_o}{h} y$$
$$v = 0$$
$$w = 0$$

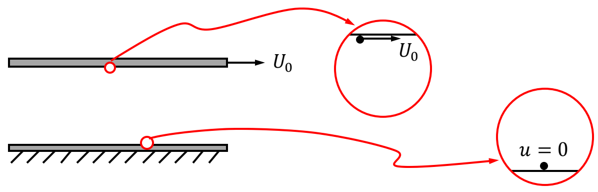
Hagen Poiseuille Flow: Pressure driven, fully developed flow inside a fixed pipe.



$$V_r = 0$$
$$V_\theta = 0$$
$$V_z = V_{\max}\left(1 - \left(\frac{r}{R}\right)^2\right)$$

Velocity Field (cont'd)

- No-slip condition is an important experimental observation that says "A fluid in contact with a solid surface does not slip, i.e. it has the same velocity as the surface".
  - e.g. In Couette flow, fluid speed at the top plate is U_o.
  - e.g. In Couette flow, fluid speed at the bottom plate is zero.
  - e.g. In Hagen-Poiseuille flow, fluid speed at the pipe wall is zero.



- No temperature jump condition is similar to the no-slip condition. It says that "Temperature of fluid particles adjacent to a solid wall is the same as the temperature of the wall".

Forces Acting on a Fluid Body

Force: ($\vec{F}$) [N = kg m/s²] → Body forces / Surface forces

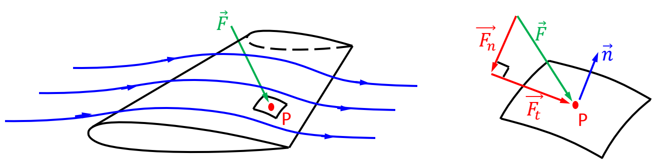
- Body forces are distributed over the volume of a fluid. They arise from "action at a distance".
- They result when a fluid is placed in a gravitational, magnetic, electrostatic or electromagnetic force field. In this course we'll consider only gravitational force.
- Gravitational body force per unit mass is the gravitational acceleration $\vec{g}$.

Exercise: Read about electroosmotic pumps, which pump fluids in micro devices with no moving parts
http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2756694

Exercise: Magnetohydrodynamics (MHD) studies the motion of electrically conducting fluids in magnetic fields. Read more about it at
https://en.wikipedia.org/wiki/Magnetohydrodynamics

Forces (cont'd)

- Surface forces act on the boundaries of a fluid body by the surroundings through direct contact. Fluids also apply a surface force to their surroundings.
- A surface force can be decomposed into a normal force acting perpendicular to the surface and tangential (shear) force acting parallel to the surface.



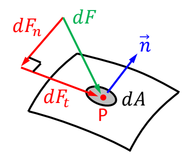
$\vec{F}$: Force acting by the fluid on the wing at point P

$\vec{n}$: Surface normal at point P

$\vec{F_n}$, $\vec{F_t}$: Normal and tangential (shear) components of $\vec{F}$

Stress Acting on Fluid Body

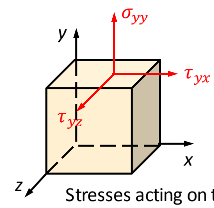
- (σ, τ) [Pa = N/m²]
- Normal stress at point P : $\sigma = \lim_{dA \to 0} \frac{dF_n}{dA}$
- Shear stress at point P : $\tau = \lim_{dA \to 0} \frac{dF_t}{dA}$



- Stress field at a point is a tensor quantity. Complete definition of it requires nine components.
- Cartesian stress tensor : $\begin{bmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{bmatrix}$

Direction of surface normal

Direction of force



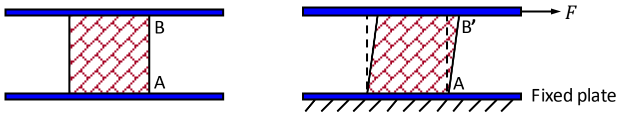
Stresses acting on the top surface of a fluid element are shown

Viscosity

Greek letter "mu"

- (μ) [Pa·s] or [poise]
- Measure of a fluid's resistance to shear or angular deformation.
- It is about the "fluidity" of a fluid. It shows a fluid's resistance to change shape.
- Experiment: Consider a solid block firmly attached to two parallel plates.

Movie : Viscous fluids



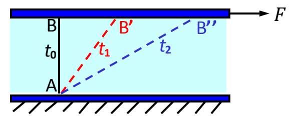
- The block deforms elastically if a force F is appiled to the upper plate.

Shear stress $\propto$ Angular deformation

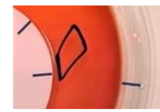
- If we gradually increase the force, the block will break apart at some point.

Viscosity (cont'd)

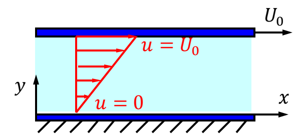
- Think of a similar experiment with a layer of fluid between the parallel plates.
- Vertical fluid element AB will deform continuously as long as the shear force is applied by moving the top plate.



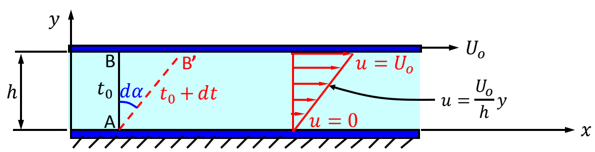
Movie : Shear deformation



- First observation: After an initial transition, velocity of the top plate will be constant (U_0) and the velocity profile within the fluid will be linear (It is possible to mathematically show that this is the case, but for now we will take it as an experimental observation).



Viscosity (cont'd)



- Angular deformation rate of line AB is $\frac{d\alpha}{dt}$ (How fast the angle $d\alpha$ changes in time)

Exercise : Show that this deformation rate is equal to $\frac{du}{dy}$ which is also equal to $\frac{U_o}{h}$

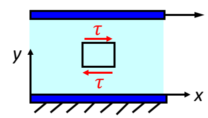
- Second observation: Shear stress acting on a surface parallel to the flow (such as the surface of the top plate) will be proportional to deformation rate

Shear stress $\propto$ Rate of angular deformation or $\tau \propto \frac{d\alpha}{dt}$

Viscosity (cont'd)

$\tau \propto \frac{d\alpha}{dt}$ or $\tau \propto \frac{du}{dy}$

- Newton's Law of Viscosity: Shear stress on a surface tangent to the flow direction is proportional to the
  - rate of shear strain (rate of angular deformation)
  - or to the velocity gradient on the surface (change of velocity in a direction normal to the surface).
- For Newtonian fluids (air, water, gasoline, oils, etc.) the above proportionality is linear and the proportionality constant is known as viscosity.



$$\tau_{yx} = \mu \frac{d\alpha}{dt} = \mu \frac{du}{dy}$$

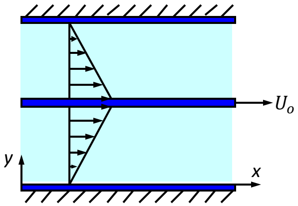
Shear force acts in the $\pm x$ direction and normal of the surface on which the force acts is in $\pm y$ direction.

Coefficient of viscosity
Absolute viscosity
Dynamic viscosity
Viscosity

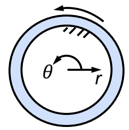
Viscosity (cont'd)

Exercise : a) What is the sign convention for stress? b) Are the stresses shown in the previous figure negative or positive?

Exercise : For the problem shown on the right, determine the sign of the shear stress in the lower and upper fluids. Show the direction of shear forces acting by the fluid on the plates?



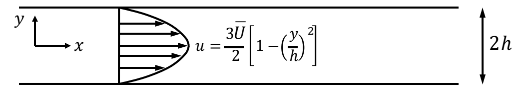
- For problems in the cylindrical coordinate system it is important to write Newton's law of viscosity in correct form. Here we see two cylinders, inner one is fixed and outer one is rotating.



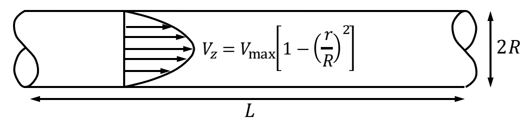
$$\tau_{cyl} = \tau_{r\theta} = \mu \frac{dV_\theta}{dr}$$

Viscosity (cont'd)

Exercise : Velocity distribution of the pressure driven flow of a Newtonian fluid between two fixed, wide parallel plates is as shown. $\overline{U}$ is the mean velocity. The fluid has a viscosity of 2 Pa·s. For $\overline{U} = 0.6$ m/s and $h = 5$ mm, determine the a) shear stress at the bottom wall, b) shear stress at the top wall, c) shear stress acting on a plane parallel to the walls and passing through the centerline.

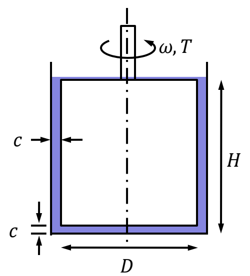


Exercise : Fully developed, pressure driven flow inside a constant diameter pipe has the shown parabolic velocity profile. For a Newtonian fluid with viscosity μ and centerline velocity of V_{max}, calculate the force exerted by the fluid on the pipe wall over a pipe section of length L.



Viscosity (cont'd)

Exercise : A concentric cylinder viscometer may be formed by rotating the inner cylinder of a pair or closely fitting cylinders. A torque of 15 Nm is required to turn the inner cylinder at 10 rad/s while keeping the outer cylinder fixed. Determine the viscosity of the Newtonian fluid in the clerance gap of the viscometer. Assume that the velocity distribution inside the gaps is linear. Neglect the corner effects.



$c = 0.5$ mm
$H = 0.2$ m
$D = 0.1$ m
$\omega = 10$ rad/s
$T = 15$ Nm

$\mu = ?$

Viscosity (cont'd)

- Definition of fluid : A fluid deforms continuously under the application of a shear (tangential) force, no matter how small the force is.

- It is more difficult to deform highly viscous fluids.

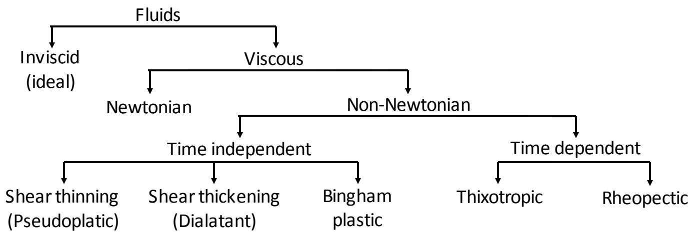
Air	Water	SAE 30 oil	Glycerin	Thick Molasses
μ_{air}	50 μ_{air}	15,000 μ_{air}	75,000 μ_{air}	375,000 μ_{air}

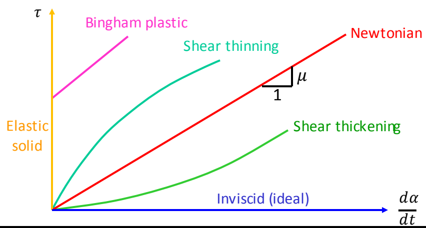
- Viscosity can be measured using
  - capillary tube viscometer
  - falling sphere viscometer
  - concentric cylinder viscometer
  - Saybolt viscometer that you'll be using in the first experiment of ME 305

Movie : Capillary tube viscometer

- Kinematic viscosity: (ν) [m²/s] $\nu = \mu/\rho$ Greek letter "nu"

Viscous Behavior of Fluids





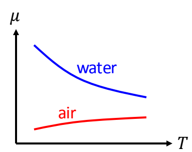
Movie : Non-Newtonian fluid pool
http://www.youtube.com/watch?v=f2XO97XHjVw

Viscous Behavior of Fluids (cont'd)

- Newtonian behavior simple (it is linear). Common fluids such as water, air, oils behave as Newtonian.
- Inviscid (ideal) fluids have $\mu = 0$ and they do not exist in real world. It is an idealization.
- Bingham plastics do not flow below a certain amount of shear stress. (toothpaste, mayonnaise).
- Shear thinning fluid become thinner under increased shear stress. (wall paint, blood).
- Shear thickening fluids become thicker under increased shear stress. (printing ink, corn starch-water mixture, quicksand).
- For thixotropic fluids viscosity decreases with time (the longer the shear force is applied) (lipstick).
- For rheopectic fluids viscosity increases with time (solidifying concrete).

Viscosity (cont'd)

- Effect of pressure on viscosity is small and often neglected.
- Viscosity of liquids decrease with increasing temperature.
- Viscosity of gases increase with increasing temperature.



- General $\mu(T)$ relations
  - For liquids: Andrade equation $\mu = Ae^{BT}$
  - For gases: Sutherland equation $\mu = \frac{CT^{1.5}}{T+D}$

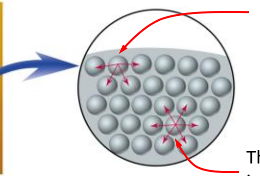
with A, B, C, D being fluid dependent constants

Exercise : As mentioned above, viscosities of liquids and gases change with temperature in different ways due to two different mechanisms that affect their viscosities. What are these mechanisms ?

Hint: Think about temperature's effect on the level of molecular activity and on magnitude of intermolecular attraction separately.

Surface Tension

- (σ) [N/m]
- Surface tension is due to the asymmetric cohesive forces acting on the molecules at a free surface (interface between a liquid and a gas).
- This asymmetry will result in a hypothetical skin (membrane) all around the surface with a surface tension force acting tangential to it.

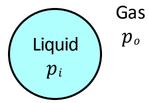


For this molecule on the surface, cohesive forces are not symmetric. It is being pulled inward.

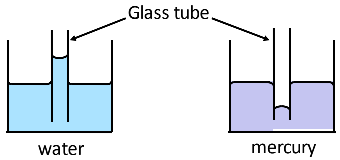
This non-surface molecule is being attracted equally by the molecules all around it.

Surface Tension (cont'd)

Exercise : Surface tension is known to create a pressure difference across a curved interface of two fluids. Consider a spherical liquid droplet in a gas. Compute the pressure difference $p_i - p_o$ in terms of the uniform surface tension (σ) on droplet's surface and the diameter of the droplet (D).



- Capillary rise (or drop), observed when an open ended tube is immersed into a liquid, is also related to surface tension. It'll be studied in ''Fluid Statics'' chapter.



Movie :
Contact angle

Movie :
Floating razor blade