Basics of Mechanical Engineering-3

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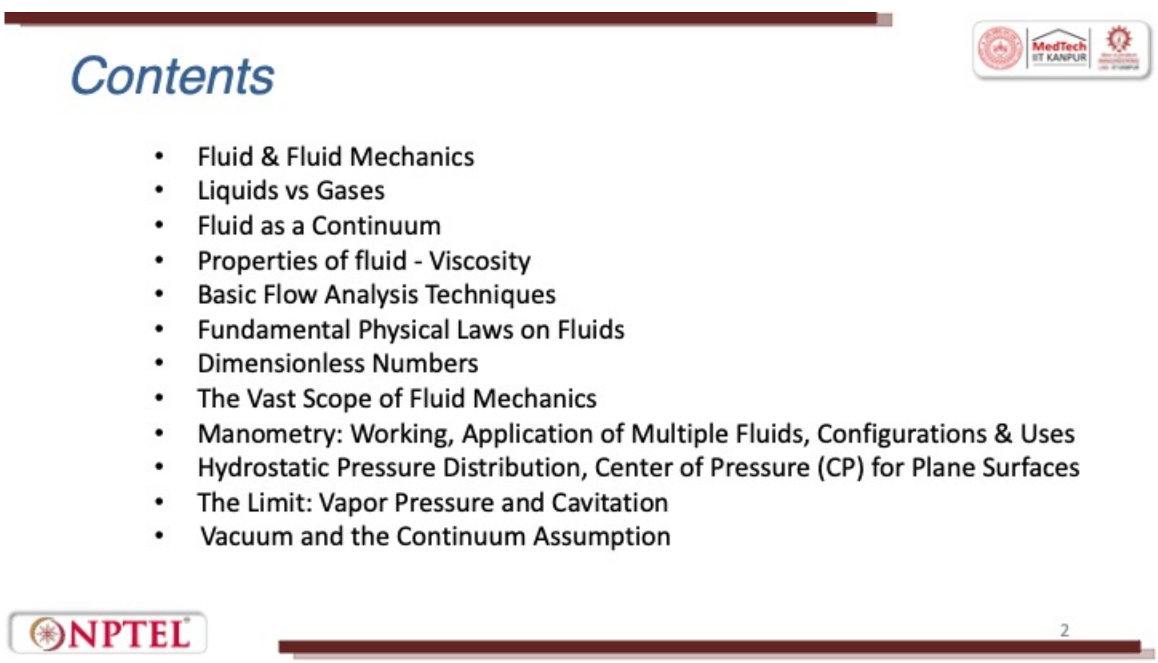
Week 08

Lecture 33: Introduction to Fluid Mechanics

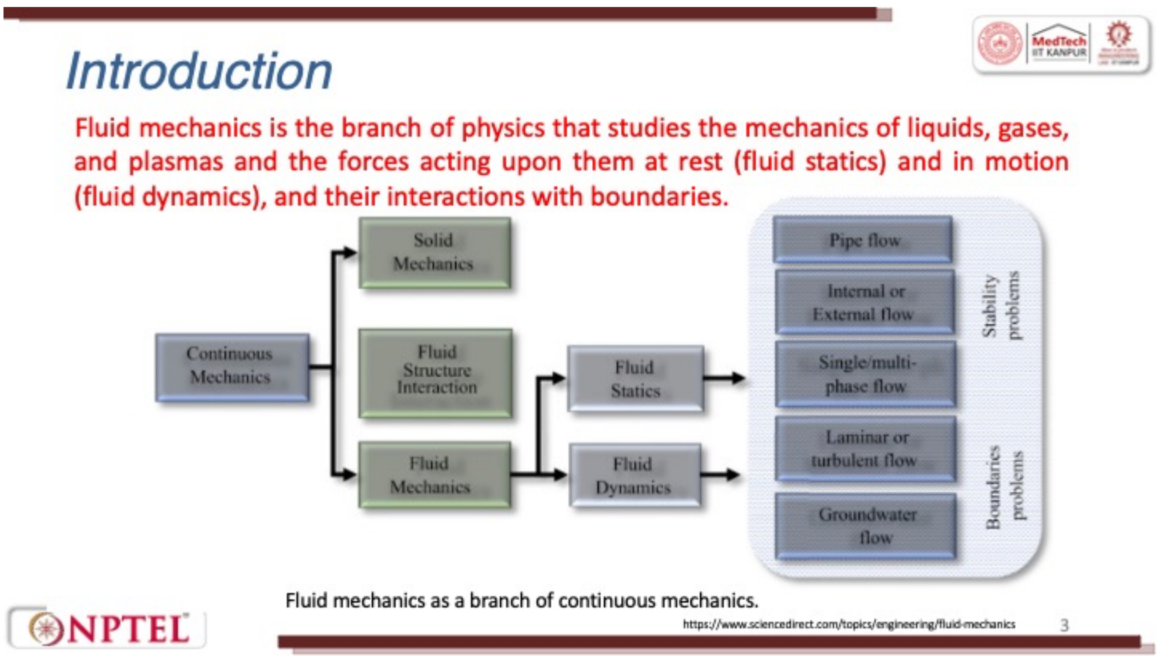
Welcome to the next part of this course, in which we will try to cover topics in Fluid Mechanics. Heat and fluid topics go together. So, that is why these two courses are always taught back-to-back in mechanical engineering, and many of the fundamentals used in fluid mechanics can be applied in thermal studies, and vice versa.



In this introductory lecture—we will try to cover Fluid and Fluid Mechanics, Liquid versus Gases, Fluid as a Continuum, Properties of the Fluid (Viscosity), Basic Flow Analysis Techniques, and Fundamental Physical Laws on Fluids. What are Dimensionless Numbers?

Vast Scope of Fluid Mechanics. Then, Manometry: Working, Application of Multiple Fluids, Configuration, and Their Uses. Then, Hydrostatic Pressure. Center of Pressure on Plane Surfaces. The Limits: Vapor Pressure and Cavitation.

Cavitation is nothing but bubbles. Then, finally, we will try to see Vacuum and the Continuum Assumptions. Fluid mechanics is a branch of physics that studies the behavior of liquids, gases, and plasmas, as well as the forces acting upon them at rest and in motion, and their interactions with boundaries. When the forces are at rest, it is called fluid statics, and when in motion, it is called fluid dynamics.



So, fluid mechanics is a branch of physics in which liquids and gases are studied. So if you try to take fluid, gas is also a fluid. Mechanics of liquids, gases, and plasma. Plasma is the fourth state of matter. Plasma. So for all three, you can get. Interestingly, friends, you also have cold plasma.

You always think plasma means very hot. Inside the sun, there is plasma. You also have cold plasma, wherein the electron densities are high, but they don't react and create temperature. They can be used for washing. So liquid, gas, and plasma and their forces acting upon them at rest and motion against what?

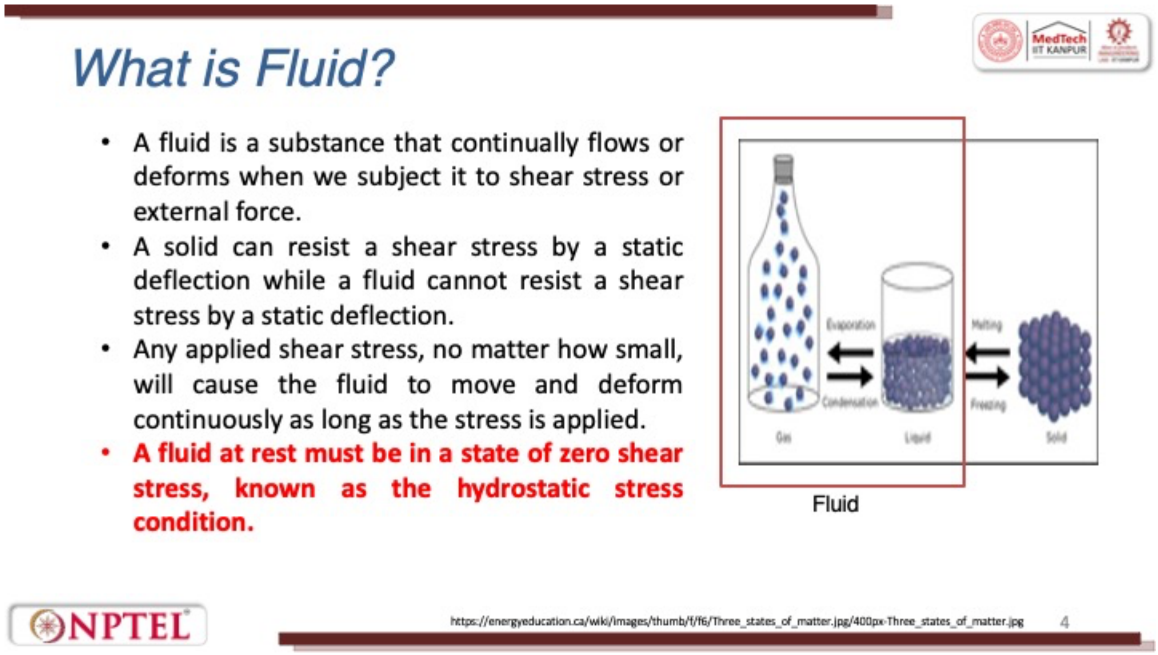
The interaction against their boundaries. So continuum mechanics can be classified as solid mechanics. Fluid-structure interaction and fluid mechanics. Fluid-structure interaction is the interaction with boundaries. When we talk about fluid mechanics, it is called fluid statics and fluid dynamics.

So dynamic is motion. Here it is at rest. Then we can try to see what happens when the fluid flows through a pipe. What are the internal and external flows that can happen? Then single or multiple phase flow.

Single phase is only water. Multiple is when you have bubbles in it. Then you can have laminar and turbulent flow. In thermodynamics, we studied boiling. We thought that first there would be discrete films formed.

And then a continuous film would be made. So the next one is going to be laminar and turbulent flow. Laminar is a smooth film. Getting formed on top of a flat plate is laminar, and turbulent is when you have roughness on the surface or any undulation, there is going to be a turbulent flow created. And then finally, groundwater flow.

All these things are related to statics and fluid dynamics. So, the stability problem will come here, and the boundary problems will come here. So, the stability problem is pipe flow—a fluid flowing through a pipe, internal or external flow, inside a pipe or outside a pipe. Heat exchangers have many applications, including single and multiple flows. These are all stability problems. Then, laminar and turbulent flows and groundwater depend upon the boundary problem.



What is a fluid? A fluid is a substance that continually flows or deforms when subjected to shear stress or an external force. It continually flows or deforms. When we subject it to shear stress, what is shear stress? Shear stress or external force acts on a fluid.

A solid can resist shear stress by static deflection, while a fluid cannot resist shear stress by static deflection. So, when we have a body where shear force is applied, a solid can resist the shear stress by static deflection, while a fluid cannot resist the shear stress by static deflection. Any applied shear stress, no matter how small, will cause the fluid to move and deform continuously as long as the stress is applied. So, if you try to apply some stress, as long as the stress is applied—no matter how small—it will cause the fluid to move and deform continuously as long as the stress is applied. A fluid at rest must be in a state of zero shear stress, known as the hydrostatic stress condition.

This is important. A fluid at rest in a state of zero shear stress is known as hydrostatic stress conditions. So, you can see a fluid; there is a bottle, and the bottle is filled with gas, right? So, when we try to condense this gas, how do you condense it? You can try to apply very high pressure. Under very high pressure, it gets condensed. That is how they produce liquefied petroleum; they do the same. So, they will pressurize it, and then they get it condensed.

So, when this tries to evaporate, when you try to heat it, it gets evaporated and forms this. So, condensation, evaporation—this is gas, and when it is compressed, it becomes a liquid. When you further try to push it, when we freeze it, it forms a solid. When the solid melts, it forms a liquid. This is solid.

What is Fluid Mechanics?

- Fluid mechanics is the study of fluids either in motion (fluid dynamics) or at rest (fluid statics).
- Both gases and liquids are classified as fluids.
- The field encompasses an enormous number of engineering applications, such as breathing, blood flow, pumps, turbines, airplanes and rivers.
- Almost everything on this planet either is a fluid or moves within or near a fluid.

Newtonian Fluid (water)   Non-Newtonian Fluid (Ketchup)

https://psiberg.com/wp-content/uploads/2023/09/Newtonian-vs-non-newtonian-1st.svg 5

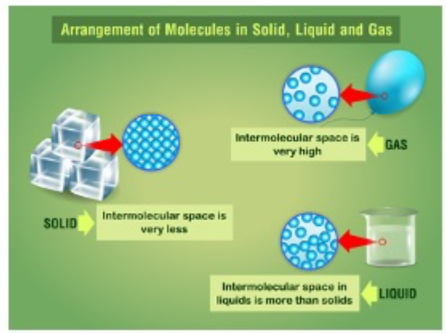
Fluid Mechanics is the study of fluid either in motion or at rest. So, a bottle of water is a static one. If I have a bottle through which water is pushed inside on one side and taken outside on the other, then the fluid is in motion. The blood flowing through the vein is in motion. Many times, it will be difficult for us to calculate.

So, what we do is we try to convert it, simplify it, assume it at rest, and then try to solve. So, both gases and liquids are classified as fluids. Fluids encompass an enormous number of engineering applications, such as breathing, blood flow, pumps, turbines, airplanes, and rivers. Almost everything on this planet is either a fluid or moves within or near a fluid. In fluid mechanics, we have two classifications.

We call them Newtonian fluids and Non-Newtonian fluids. If the shear stress is directly proportional to the shear strain and if the line remains linear, it is called a Newtonian fluid. Non-Newtonian fluids are those that do not follow these characteristics and are called Non-Newtonian fluids. For example, ketchup is one, and you can have paste, toothpaste is another, blood—all these are Non-Newtonian fluids.

Liquids vs Gases

- Within fluids, there are two classes: liquids and gases.
- This distinction relates to the effect of cohesive forces between their molecules.
- A liquid, with strong cohesive forces, tends to retain its volume and will form a free surface in a gravitational field if unconfined from above. Free-surface liquid flows are dominated by gravitational effects.
- A gas, with negligible cohesive forces, expands to fill its container and has no definite volume.
- Gases cannot form a free surface.



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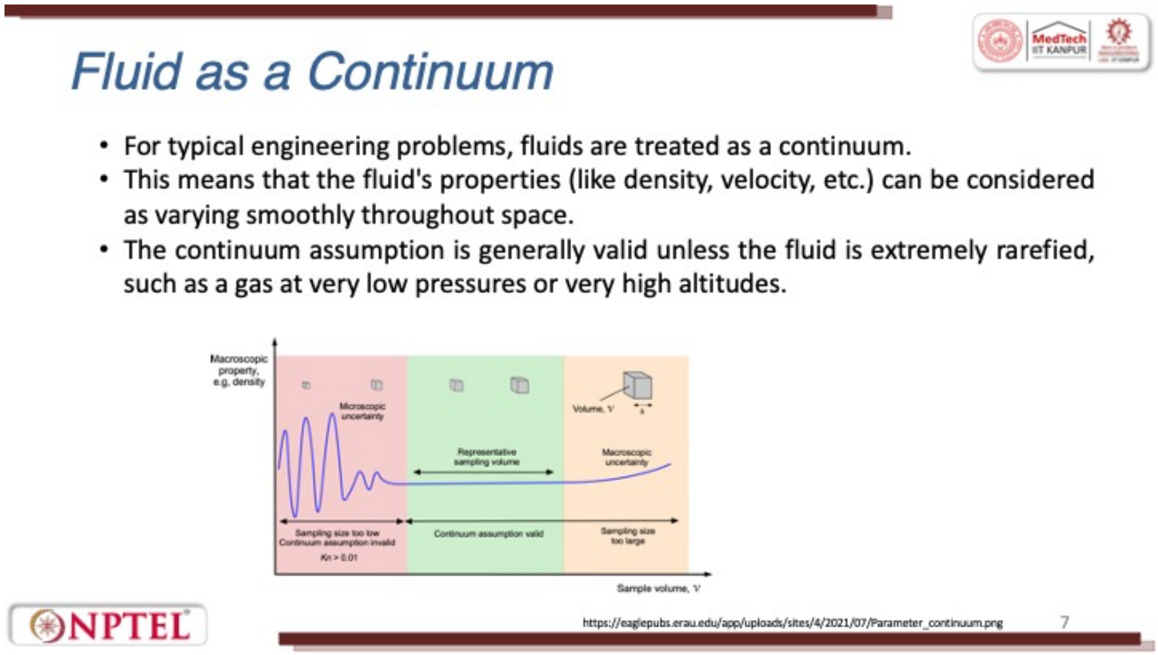
Within fluids, there are two classes: liquids and gases. This distinction relates to the effect of cohesive forces between their molecules. A liquid with strong cohesive forces tends to retain its volume and will form a free surface in a gravitational field if unconfined from above. Please note this point: A liquid with strong cohesive forces tends to retain its volume and will form a free surface in a gravitational field if unconfined from above. The free surface of liquid flows is dominated by gravitational effects. A gas with negligible cohesive forces expands to fill its container and has no definite volume.

The gas cannot form a free surface. This is a big difference. Free surface liquid flow is dominated by gravitational effects. The arrangement of molecules in solid, liquid, and gas. So this is solid, liquid, and gas.

So intermolecular spaces are very small. The intermolecular space in liquid is more than in solid, and the highest is in gas.

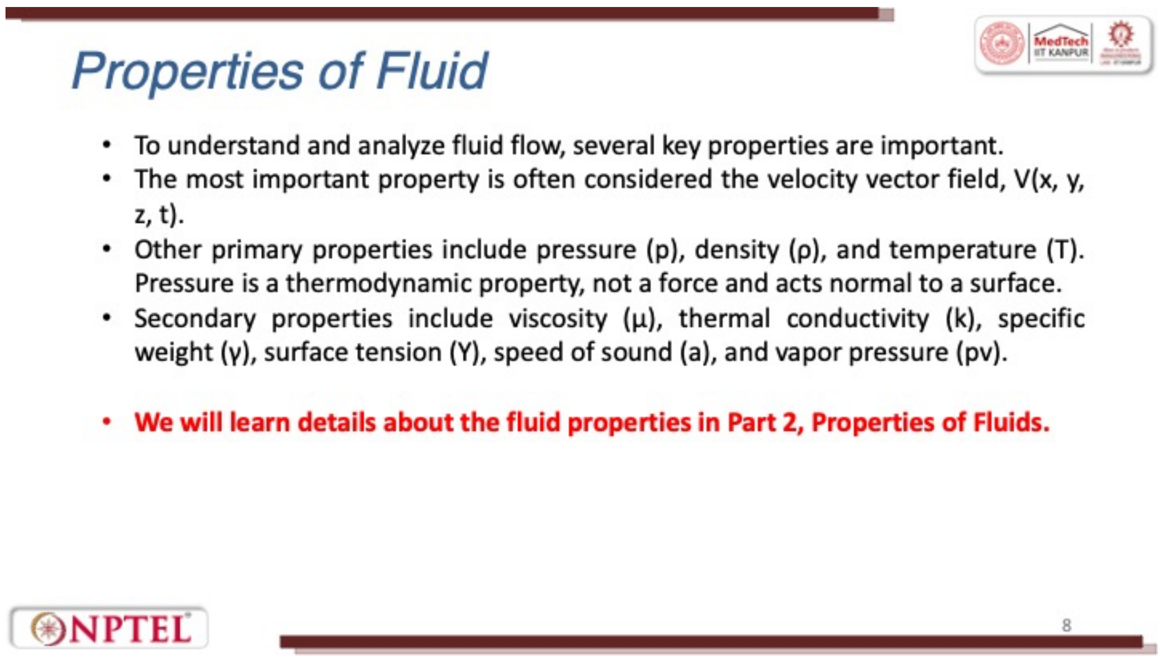


Fluid as a Continuum. For typical engineering problems, fluids are treated as a continuum. This means that fluid properties like density and velocity can be considered as varying smoothly throughout the space.

So this is fluid as a continuum. So they call it continuum mechanics also. The continuum assumption is generally valid unless the fluid is extremely rarefied, such as gas at very low pressures or very high altitudes. The continuum assumption is generally valid. Everywhere it is valid.

Unless the fluid is extremely rarefied. That means the gas is at a very low pressure or at very high altitudes. You go to a mountain, and then you see that the continuum mechanics or continuum assumptions do not work. So here, if this is a plot between macroscopic properties such as density with respect to surface volume, you can see the sample size is too low where the continuum assumption is invalid.

So here, macroscopic uncertainty will be present. The representative sampling volume where the continuum assumption is valid is in this zone, right where the specific sample volume exists. Then, macroscopic uncertainty occurs when the sampling size is too large. We will try to have volume, and then delta, which is the thickness.



To understand and analyze fluid flow, several key properties are important. The most important property is the velocity vector field, denoted as V, expressed in the x, y, z coordinate system and time t. Other primary properties include pressure, density, and temperature. Pressure is a thermodynamic property, not a force.

Pressure is force per unit area, not a force itself, and acts normal to a surface. Secondary properties include viscosity. Oil has higher viscosity, ghee has much higher viscosity, and honey has much, much higher viscosity.

Viscosity

- Viscosity (μ) is a fluid property associated with its resistance to being set in motion or resistance to flow.
- For common linear fluids (called Newtonian fluids), the applied shear stress (τ) is directly proportional to the rate of shear strain or the velocity gradient (du/dy). The constant of proportionality is the viscosity coefficient, μ.
- This relationship is given by $\tau = \mu \, (du/dy)$.
- A key characteristic of viscous flow near a solid wall is the no-slip condition, where the fluid velocity at the wall is zero relative to the wall.

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Viscosity, the flowing property, is very important. Other secondary properties are thermal conductivity, specific weight, surface tension, speed of sound, and vapor pressure. All these are secondary properties that are part of a fluid. And viscosity is very important. On a cold winter day, if you try to apply oil to your hair, you can see the oil is frozen.

So now what happens? You will try to generate heat by pressing and rubbing it against your two hands. The friction creates heat, and the solid oil, which is frozen, gets converted into liquid. Now, this liquid can be applied to your hair because the flow ability of the liquid on your hair is much higher. So, viscosity is very important. Let's take a piece of bread on which you try to apply butter. So, what happens when you have solid bread and a solid cube of butter?

Solid bread means hard bread, I am saying. A cube of butter, you are trying to smear it on top of the bread—it is very difficult, very difficult. So, what you do is you try to slowly soften the butter and then smear it on top of the bread. So, there also, viscosity plays a very, very important role. Thermal conductivity, specific weight, surface tension—surface tension is very important. Surface tension will allow the bubble to form and then move in the air.

Speed of sound and vapor pressure. We will learn details about fluid properties in part 2. Properties of the Fluid. Second part of this lecture. Viscosity, a very, very important parameter.

So I have said viscosity is a measure of the fluid's resistance to flow. If a fluid has to flow, what is the resistance the fluid gives for flowing? Water has low viscosity, which is 1.0 centipoise. Honey has a very high viscosity, around about 12,200 centipoises. Viscosity is a fluid property associated with its resistance to motion or resistance to flow. For a common linear fluid called Newtonian, which I already mentioned, the applied shear stress is directly proportional. So this is τ, and this is strain.

So there is a linear relationship directly proportional to the rate of shear strain or the velocity gradient, which can be represented as $\partial u/\partial y$. It is a linear relationship. The constant of proportionality is the coefficient, which is the viscosity coefficient (μ). So $\tau = \mu \times du/dy$. The relationship is given.

The key characteristic of viscous flow near a solid wall is the no-slip condition. You have a solid wall, like glass. A key characteristic of viscous flow is when the oil is dropped. Flow near a solid wall is the no-slip condition, where the fluid velocity at the wall is zero relative to the wall. So there is a wall. There is a liquid. The key characteristic of viscous flow near a solid wall is the no-slip condition, where the fluid velocity at the wall is zero relative to the wall.

Basic Flow Analysis Techniques

Fluid motion problems can be approached in two main ways:

- **Control Volume Analysis (Integral Approach):** Working with a finite region, balancing flow in versus flow out to determine gross effects like forces or energy exchange. This uses integral forms of the conservation laws.
- **Differential Analysis:** Seeking point-by-point details of the flow pattern by analyzing an infinitesimally small region or fluid element. This results in the basic differential equations of fluid motion.

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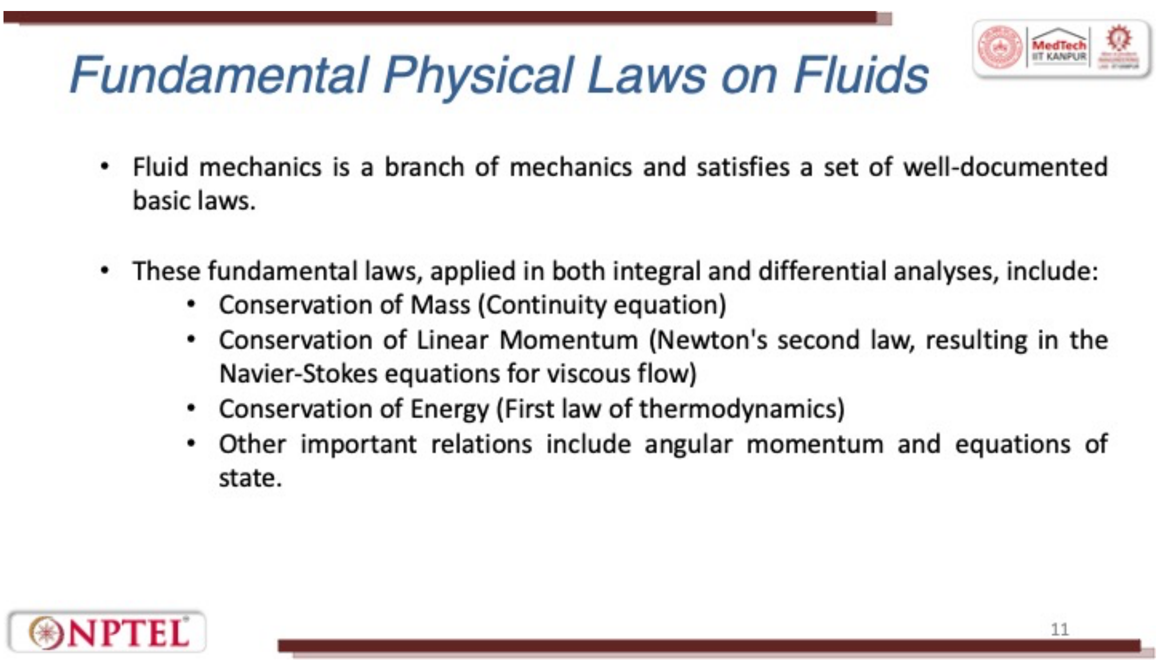
What are the basic flow analysis techniques? The fluid motion problem can be approached in two ways. One is called control volume analysis.

The next one is differential analysis. Otherwise, it is called the integral approach. There are two approaches. One is the fluid motion problem: integral approach or differential approach. Integral approach: Working with a finite region, balancing flow in versus flow out to determine gross effects like force or energy exchange.

This uses the integral form of the conservation laws. So, working with a finite region, balancing flow in versus flow out to determine gross effects like forces or energy exchange which happens. The differential analysis: Seeking point-by-point detail of the flow pattern by analyzing an infinite assembly of small regions or small elements. So, there is a large one; I take a small element and I start looking at it—that is differential analysis. This results in the basic differential equation of fluid motion. So, there are two approaches. This is very important: one is the integral approach, the other is the differential approach. So, flow in versus flow out to determine gross effects like force or energy exchange. Fluid mechanics is a branch of mechanics and satisfies a set of well-documented basic laws.



These fundamental laws, applied in both integral and differential analyses, include conservation of mass and conservation of linear momentum. Conservation of energy and other important relationships include angular momentum and equations of state. The conservation of mass is nothing but the continuity equation.

Conservation of linear momentum is Newton's second law, resulting in the Navier-Stokes equation for viscous fluids, derived from the conservation of linear momentum. Conservation of energy is the first law of thermodynamics, and the other laws include angular momentum and equations of state.

Dimensionless Numbers

- Fluid mechanics is a highly visual subject, and flow patterns can be visualized in many ways.
- Understanding flow patterns qualitatively and quantitatively is important.
- Basic line patterns used include Streamlines (lines everywhere parallel to the local velocity vector), Streaklines, and Pathlines.
- Visualization techniques like Particle Image Velocimetry (PIV) can provide insights into flow fields.

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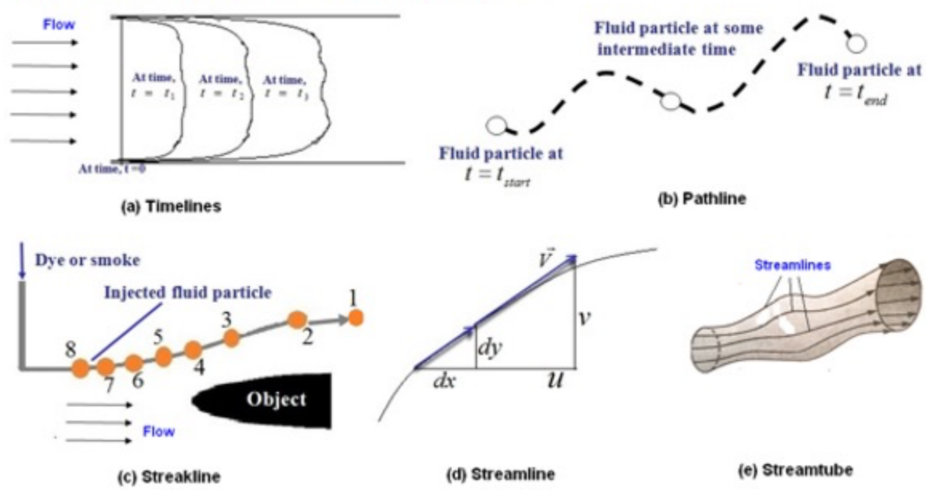
Dimensionless Numbers



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What are dimensionless numbers? Fluid mechanics is a highly visual subject. Flow patterns can be visualized in many ways. For example, if you have a gas leaking out of a cylinder, one way to detect it is by smell.

Another way is to pressurize and spread a powder on the floor to observe the flow patterns. When conducting experiments, we aim for laminar flow—constant and smooth—and observe when it transitions to turbulent flow. Flow patterns can be visualized in many ways. Understanding flow patterns qualitatively and quantitatively is very important. Qualitatively means good, bad, fast, or slow. Quantitatively means describing it with respect to velocity or other parameters. The basic flow patterns include streamlines, streaklines, and pathlines.

You will see that in detail: streak lines, path lines, and stream lines—basic lines. The visualization techniques can be done by particle image velocimetry, which can provide insight into the flow field—how the flow is progressing. So, the dimensionless number arises because the flow patterns can be qualitatively and quantitatively understood. So, in this slide, you can see the dimensionless number. So, where a fluid is flowing inside a glass tube, you can see at time t = 1, t = 2, t = 3—where the line is moving, or where the fluid is moving.

So, we see here there are different types of line patterns: streamline, streak line, and path line. So, here is an example of a path line. A fluid particle is here when t is equal to start, and it is here at t equal to end. From start to end, what is the path it travels? It is shown here. The fluid particles at some intermediate times are here.

So, this explains the path line. Then, we would like to see the streamline. So, where the fluid is flowing on top of a boundary. So, it is a smooth line that moves at a velocity. This is a streamline. What is a stream tube? There is a tube inside a tube—how does it form? Those are the streamlines. What is a streak line? A streak line is made of smoke or dye that flows past an object. You can see the profile of the dye that is present.

Dimensionless Numbers

- Dimensionless numbers are crucial in fluid mechanics as they reveal the basic parameters governing fluid motion.
- A key dimensionless parameter is the Reynolds number (Re).
- The Reynolds number relates inertia effects to viscous effects.
- $Re = \rho VL / \mu$ or $Re = VL / \nu$, where V and L are characteristic velocity and length scales, ρ is density, μ is dynamic viscosity, and ν is kinematic viscosity.
- The value of Re indicates different flow regimes: very low Re (viscous creeping motion), moderate Re (laminar flow), and high Re (turbulent flow).

So, dimensionless numbers are crucial in fluid mechanics as they reveal the basic parameters governing fluid motion. The dimensionless number parameter is the Reynolds number (Re).

The Reynolds number relates inertial effects to viscous effects. The Reynolds number (Re) relates inertial effects to viscous forces or viscous effects. So, $Re = \rho VL / \mu$ or $Re = VL / \nu$, where VL represents the characteristic velocity and length scales, ρ is the density, mu is the dynamic viscosity, and V is the kinematic viscosity. The value of the Reynolds number plays an important role in distinguishing whether the fluid flow is smooth or turbulent. So, the value of Re indicates different flow regimes.

One is a very low regime, which is viscous creeping motion. The next one is moderate, called laminar flow, and high Reynolds numbers indicate turbulent flow. When you want significant convection, we use turbulent flow.

The Vast Scope of Fluid Mechanics

- Fluid mechanics touches nearly every human endeavor.
- It is fundamental to natural phenomena like meteorology, oceanography and biological flows (breathing, blood circulation).
- Transportation (airplanes, ships, automobiles) heavily relies on fluid mechanics principles like drag and lift.
- Energy generation (hydro, wind, steam turbines) involves fluid motion.
- Many classic engineering problems like irrigation, flood control, pipelines, and pumps involve fluid mechanics.

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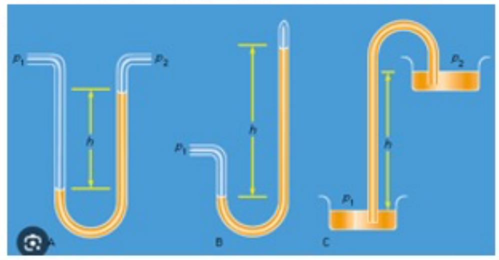
The vast scope of fluid mechanics means it touches nearly every human endeavor. It is fundamental to natural phenomena like meteorology, oceanography, and biological flows. Transportation, such as airplanes, ships, and automobiles, heavily relies on fluid mechanics principles like drag and lift. Airplanes—drag and lift. Automobiles—drag and lift.

Energy generation, hydro, wind, steam turbine also includes fluid motion. Many classic engineering problems like irrigation, flood control, pipelines, and pumps involve fluid mechanics. In all these areas, fluid mechanics plays a very important role. So, if you look at the center of viscous fluid mechanics, you can see here Newtonian and dynamic viscosity, Reynolds number loss under the NS equation, Navier-Stokes equation, impact sputtering, then laminar flow.

Impact sputtering will happen on coating, right? Then laminar flow happens in laminar flow and turbines, while turbulent flow occurs in ships. Boundary layer problems in the layer theorem in heat exchangers and previousness. Then you will have simulations and algorithms in automotive engineering and airplane engineering.

Manometry and its Principle

- A manometer is a device specifically used to measure pressure differences between two points.
- It is a type of gravity-based pressure measurement instrument.
- Based on the hydrostatic formula.
- A change in elevation of a liquid is equivalent to a change in pressure.
- Specifically, the pressure change (p_2 - p_1) is equivalent to $\gamma(z_1 - z_2)$, where γ is the specific weight and (z_2 - z_1) is the elevation change.
- Thus, a static column of one or more liquids or gases can be used to measure pressure differences.



Frank M. White - Fluid mechanics-McGraw-Hill Education (2017).pdf

Manometry and its principle. The manometer is a device specifically used to measure the pressure difference between two points. It is a type of gravity-based pressure measurement instrument. It is based on the principle of hydrostatic force and constant pressure.

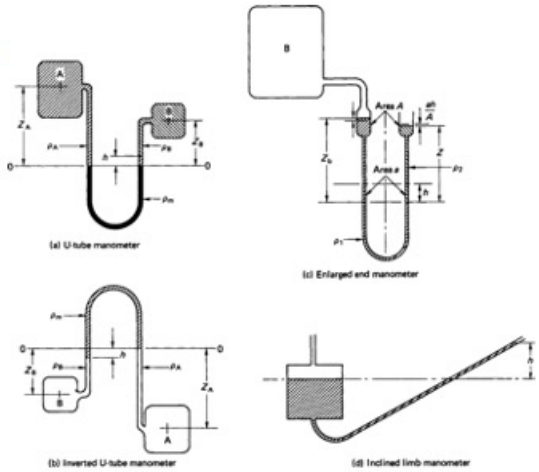
The change in the elevation of the liquid is equal to the change in pressure. Specifically, the pressure change (p_2 - p_1) is equivalent to $\gamma(z_1 - z_2)$, where γ is the specific weight and (z_2 - z_1) is the elevation change. So, the pressure change can be equated to gamma times z1 minus z2. z1 minus z2 is the elevation change specific weight. Thus, a static column of one or more liquids or gases can be used to measure the pressure differences.

So, you can try to have both ends open, one end open, one end closed, and then you can have both of these things. For example, if you wanted to pump from a tank of kerosene to a small container, you could use this mechanism. When we are trying to do elevation, this is what you do in your class 8 or 9 experiments, where you try to figure out the change in pressure with change in height.

Working of Manometry

A pressure difference is balanced by the height difference of the fluid column(s)

- For multiple fluids, the pressure change through each fluid is calculated separately as we move from one fluid to another.
- The total pressure difference is found by adding the successive pressure changes across each fluid column. Intermediate pressure values cancel out in the sum.



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So, the working of a manometer: the pressure difference is balanced by the height difference of the fluid column only. So, you have a fluid column ZA, then this is ZB. So, you have PA, PB, and there is a difference called h. This is the density of the liquid, whatever it is.

For multiple fluids, the pressure change through each fluid is calculated separately as they move from one liquid to another. So, this is a U-type manometer, this is an enlarged-end manometer, this is an inverted U manometer, and this is an inclined-limb manometer.

Hydrostatic Relationship

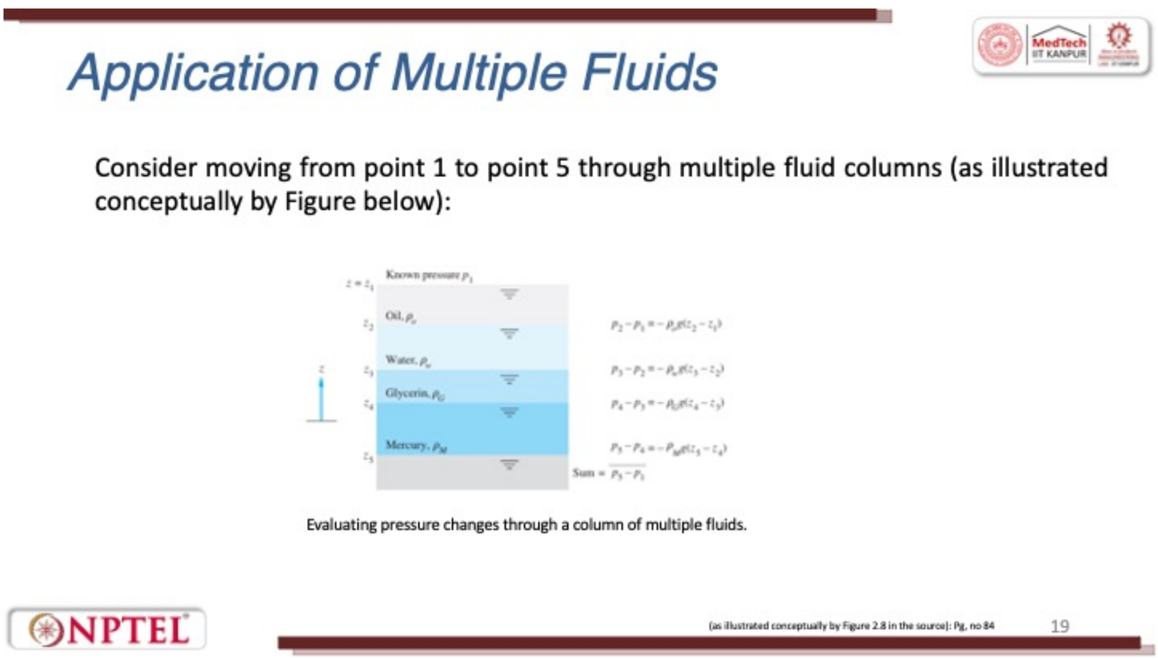
For a single fluid column of height *h* (difference in elevation, Δz) and specific weight γ:

Change in pressure (Δp) = specific weight (γ) X Height of fluid (h)

This directly follows from the principle stated in:

$$(p_2 - p_1)/\gamma = z_1 - z_2,$$
so if $h = z_1 - z_2$,
$$\Delta p = p_2 - p_1 = \gamma h$$

For a single fluid column of height h, the difference is Δz, and the specific weight is gamma. So, the change in pressure, rho, the Δp = the specific weight x h. So, $\frac{p2 - p1}{\gamma} = z1 - z2$. So, if h = z1 - z2. So, p2 - p1 will be $\Delta p = p_2 - p_1 = \gamma h$. This is the formula relationship.



Considering moving from point number 1 to point number 5 through multiple fluids; for example, first you have oil, then you have water, then you have glycerin, then you have mercury. And then you have mercury, and finally you have something else.

So now the pressure will be

$$p_2 - p_1 = -\rho_o g(z_2 - z_1)$$

$$p_3 - p_2 = -\rho_w g(z_3 - z_2)$$

$$p_4 - p_3 = -\rho_G g(z_4 - z_3)$$

$$p_5 - p_4 = -\rho_M g(z_5 - z_4)$$

$$\text{Sum} = \overline{p_5 - p_1}$$

Application of Multiple Fluids:

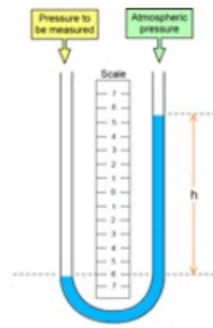
- Start at p_1.
- Add or subtract pressure change for the first fluid column ($\gamma_1 \Delta z_1$).
- Add or subtract pressure change for the second fluid column ($\gamma_2 \Delta z_2$).
- The sum equals the pressure at point 5: $p_5 = p_1 \pm \gamma_1 \Delta z_1 \pm \gamma_2 \Delta z_2 \pm \ldots$
- The signs depend on whether you are moving down (pressure increases) or up (pressure decreases) through the fluid column.

So, where is the application for multiple fluids? Start at a point P, add or subtract process change from the first fluid column is ($\gamma_1 \Delta z_1$), add or subtract the change in the second fluid is this add.

So, $p_5 = p_1 \pm \gamma_1 \Delta z_1 \pm \gamma_2 \Delta z_2 \pm \ldots$. So, the sign depends on whether you are moving down through a fluid column or not moving down or moving up. That is the sign, that is why I said plus minus.

Configurations & Uses of Manometry

- The classic configuration is the U-tube manometer.
- Manometers are used to measure pressure drop, such as across sections in a pipe or flow measurement devices like orifice plates.
- They can be used with instruments like the Pitot-static tube to measure flow velocity by measuring the pressure difference .



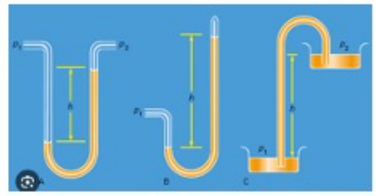
https://instrumentationtools.com/u-tube-manometer-principle/

So, the configuration and the use of a manometer. So, here if you see a U-type manometer, there is a scale which is there. So, from here there will be atmospheric pressure, then the pressure to be measured will be moving here. So, the difference will be delta h or h. So, the classic configuration is the U-tube manometer. The manometers are used to measure the pressure drops, not the pressure. Pressure drop such as the cross-section in a pipe or flow measurement device like orifice plates. Orifice plates are you have a small hole and then you in a plate. They can be used with instruments like pitot-static tube to measure the flow velocity by measuring the pressure difference. So, this is important.

So, here in the first one, you found out the pressure drop. So, they can be used with this manometer. They can be used with another instrument, like a pitot-static tube, to measure the flow velocity. So, what is the definition and the principle for this manometer?

Definition and Principle: Manometer

- A manometer is a device used to measure pressure differences between two points.
- It is classified as a gravity-based pressure measurement instrument.
- It works by utilizing a static column of one or more liquids or gases.
- The fundamental principle is based on the hydrostatic formula.
- A change in elevation (Δz) of a liquid is equivalent to a change in pressure.



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Key Hydrostatic Formula of Manometry

- For a single fluid column with a height difference *h* (which is equivalent to the elevation difference, Δz) and specific weight γ (where specific weight $\gamma = \rho g$, density times gravity):

$$\Delta p = \gamma h$$

- (This relationship stems directly from $(p_2 - p_1)/\gamma = z_1 - z_2$, meaning the pressure difference $(p_2 - p_1)$ equals γ times the elevation difference $(z_1 - z_2)$ between two points in a static fluid.

So, we saw a manometer is used to measure the delta p, right? So, the manometer is a device used to measure the pressure difference between two points. It can work on gravity-based measurement. It is classified under gravity-based measurement devices. It works by utilizing a static column of one or more fluids or gases.

The fundamental principle is based on the hydrostatic formula. The change in elevation of a liquid is equal to the change in pressure. So, what are the key hydrostatic formulae of a manometer? This we already saw. So, for a single fluid column with a height difference h (which is equivalent to the elevation difference, Δz) and specific weight γ (where specific weight $\gamma = \rho g$, density times gravity):

$$\Delta p = \gamma h$$

Applying the Principle For Multiple Fluids:

- When moving from one point to another through a series of connected fluid columns
- Start at the pressure of the initial point (e.g., p_1).
- Move through each fluid column, adding the pressure change ($\gamma \Delta z$) if moving downwards, or subtracting it if moving upwards. Use the specific weight (γ) of the fluid in that particular column
- Adding these pressure changes allows you to determine the pressure at the final point (e.g., p_5) relative to the starting point:

$$p_5 = p_1 \pm \gamma_1 \Delta z_1 \pm \gamma_2 \Delta z_2 \pm \ldots$$

The signs depend on the direction of movement - up or down - through each column

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When the same manometer is using multiple fluids, then what do we do? When move from one point to the another through a series of connected fluid columns, so that is what in a series of connected fluid columns, the start at the pressure of the initial point P1. Move through each fluid column adding the $\gamma \Delta z$. If moving downward or subtracting it moving upward, use the specific weight (γ) for the fluid column. So, this can be represented in this way. So, the $p_5 = p_1 \pm \gamma_1 \Delta z_1 \pm \gamma_2 \Delta z_2 \pm \ldots$ The sign depends on the direction of movement up or down through the column.

Hydrostatic Forces
- on Submerged Surfaces

Origin of Hydrostatic Force:

- A fluid at rest cannot support shear stress. This means the stress on any plane within a static fluid is purely normal and is called the fluid pressure.
- Pressure is a thermodynamic property of the fluid. It is not a force itself, but it *creates* a force on a surface due to fluid molecules. This force is always normal to the surface.
- In a static fluid under gravity, pressure varies with depth. This pressure distribution results in a net force on any submerged surface – the hydrostatic force.

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Hydrostatic Forces
- on Submerged Surfaces

Motivation / Motive of Study:

- Many fluid problems involve static fluids and their effect on solid surfaces, such as submerged bodies.
- The design of containment structures, like tanks or dams, requires computing hydrostatic forces.

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So, what is Hydrostatic Force? Hydrostatic force on submerged surfaces. When we are trying to take a cup and when we are trying to move the cup, keep it at the atmosphere, try to take the same cup, go 10 meters below the sea level, go 100 meters below the sea level, you can see the cup deforms. So, that is what we said on submerged surfaces. Motivation or motivation of this motive of study is many fluid problems associated with static fluid and their effect on solid surface such as submerged bodies.

The design of containment structure like tank, dams require computing of hydrostatic forces. So, where does this hydrostatic force come from? The fluid at rest cannot support shear stress. This means that the stress on any plane within the fluid, the static fluid is purely normal and is called as fluid pressure. The pressure is a thermodynamic property of a fluid.

It is not a force itself, but it creates a force on a surface due to fluid molecules. This force is always normal to the surface. Hydrostatic, it is always normal to the surface. This is a surface, normal to the surface. The static fluid under gravity pressure varies with depth. This pressure distribution results in a net zero on any submerged surface the hydrostatic force come into existence.

Hydrostatic Pressure Distribution:

- on Liquids

For incompressible liquids (density can be considered constant):

$$p_2 - p_1 = -\gamma(z_2 - z_1)$$

Where:

- p is pressure.
- γ is the specific weight of the fluid (γ = ρg, density times gravity).
- z is the vertical elevation (upward is positive).
- **This formula shows that pressure increases linearly with depth**

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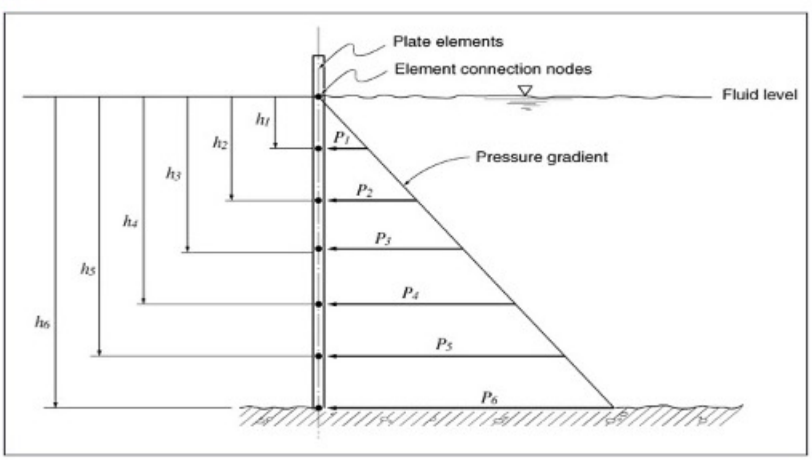
Hydrostatic Pressure Distribution:

- on Liquids



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So the hydrostatic pressure distribution follows the same principle delta P is equal to specific weight into the height difference. The formula shows the pressure increases linearly with respect to depth. So, as and when you go down the pressure linearly goes that is what they say. The plate element, the element connected to the node. And when you go to heights less than h1, h2, h3, h4, h5 then you can see the pressure which is plotted P1, P2, P3, P4, P5, P6 and here is a gradient this is a fluid flow.

Hydrostatic Forces
- on Submerged Surfaces

Concept:

For a plane surface submerged in a liquid, the pressure varies linearly with depth. The hydrostatic force is the resultant of this distributed pressure force over the surface area.

Calculating the Total Force:

- The total hydrostatic force (F) on one side of a submerged plane panel is given by the integral of pressure over the area dA:

$$F = \int p \, dA = \int (p_a + \gamma h) \, dA$$

- Where p_a is the atmospheric pressure at the free surface and h is the depth to the area element dA.

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On submerged surface, the concept is for a plane surface submerged in liquid. A plane surface submerged in liquid, the pressure varies linearly with depth. The hydrostatic force is a resultant of the distributed pressure force over the surface area. When you want to calculate the total force, the hydrostatic force F on one side of the submerged plate panel is given by integration of pressure over a dA. So $F = \int p \, dA = \int (p_a + \gamma h) \, dA$, where pa is the atmospheric pressure at the free surface and A is the depth area element.

Center of Pressure (CP)
- for Plane Surfaces

Concept:
- The hydrostatic force is a distributed load, but for engineering calculations, it can be represented by a single resultant force (F) acting at a specific point on the surface.
- This point is called the center of pressure (CP).

Location of the CP:
- Because pressure increases with depth, the pressure is higher on the lower parts of a submerged surface.
- Therefore, the CP is always below the centroid (CG) for a submerged plane surface in a uniform gravity field

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So, the Center of Pressure for a Plane Surface (CP). This is calculate the total force. So, here we are trying to do a center of pressure (CP). The hydrostatic force is a distributed load, but for engineering calculations, it can be represented by a single resultant force F acting at a specific point on the surface.

So, the point is called the center of pressure. The hydrostatic force is a distributed load. So, as I told you, deep into the water, the pressure is distributed all around the object, but for engineering calculations, it is represented as a single resultant force F acting at a single point, the CP. The location of CP is very important because the pressure increases with depth.

The pressure is higher on the lower part of the submerged surface. Therefore, CP is always below the centroid of a submerged plane surface in a uniform gravity field. This is important.

Fundamentals of Pressure

Fundamentals of Fluid Pressure are:

- Fluid pressure is the force exerted by a fluid per unit area.
- Pressure can be measured relative to different reference points.
- Absolute Pressure: Measured relative to a perfect vacuum (absolute zero pressure).
- Gage Pressure: Measured relative to local atmospheric pressure.
- Gage pressure = Absolute pressure - Atmospheric pressure.
- Vacuum Pressure: This term is often used for pressures *below* atmospheric pressure. It can be thought of as negative gauge pressure.
- Vacuum pressure (positive value) = Atmospheric pressure - Absolute pressure.

So the Fundamentals of Fluid Pressure. The fluid pressure is a force exerted by a fluid on a unit area. The pressure can be measured relative to different reference planes. Absolute pressure: measures relative to a perfect vacuum (absolute zero). Absolute pressure is measured relative to a perfect vacuum. Gauge pressure is measured relative to the local atmospheric pressure. So, gauge pressure is absolute pressure minus the atmospheric pressure. So gauge pressure is measured relative to the local atmospheric pressure.

The term 'vacuum pressure' is often used for pressures below atmospheric. Vacuum is below atmospheric pressure. It can be rated as negative gauge pressure. Vacuum pressure is a positive value when atmospheric pressure minus the absolute value. So you have to understand the terminologies.

What is absolute pressure measured relative to a perfect vacuum? What is gauge pressure measured relative to the local atmospheric pressure? Absolute pressure minus atmospheric pressure gives you gauge pressure. Then vacuum pressure below atmospheric pressure gives. It is always negative gauge pressure.

Then vacuum pressure is positive when atmospheric minus absolute gives positive. A vacuum is a theoretical state where pressure is absolutely zero. This is very important. Absolutely zero. This means no fluid molecules are present to exert force.

The Concept of Vacuum

- A vacuum is a theoretical state where pressure is absolute zero. This means there are no fluid molecules present to exert force.
- In reality, achieving a perfect vacuum is practically impossible. Even in deep space, there are some particles.
- In fluid mechanics, when we talk about "vacuum," we usually mean a region where the absolute pressure is significantly lower than atmospheric pressure.
- For example, atmospheric pressure is often around 101 kPa. A pressure of 50 kPa absolute would be a "vacuum" condition relative to atmosphere, equivalent to a gauge pressure of -51 kPa or a vacuum pressure of 51 kPa.

When it is a vacuum, a vacuum is a theoretical state where pressure is absolutely zero. In reality, achieving a perfect vacuum is practically impossible. Even deep inside the sea, there are some particles. So, it is not possible. That is why they call it a theoretical state.

In fluid mechanics, when we talk about a vacuum, we visualize a region where the absolute pressure is significantly lower than the atmospheric pressure. What is absolute pressure? Measured relative to a perfect vacuum, right? For example, atmospheric pressure is often 101 kilopascal. A pressure of 50 kilopascal absolute would be a vacuum condition relative to the atmosphere, equivalent to a gauge pressure of minus 51 kPa or a vacuum pressure of 51 kPa. So now we are able to understand that 101 minus 50 is 51.

So here we are saying gauge pressure means it is equivalent to minus kPa and vacuum pressure. The term 'vacuum pressure' is often used for pressure below the atmospheric pressure. It can be thought of as a negative gauge pressure. That is what minus 51 kPa means.

Occurrence of Low Pressure in Flows

- Low-pressure regions (approaching vacuum conditions relative to the surroundings) occur in various fluid flows
- Vacuum Cleaners: These devices work by creating a low-pressure region (a vacuum relative to the room) to draw air and particles in.
- Pumps & Turbines: Low pressures can occur on the suction side of pumps or in specific areas within flow machinery.
- Biological Systems: Human lungs can create a "vacuum pressure" (negative gage pressure) to draw in air or liquids, estimated at around 3000 Pa below atmospheric pressure for drinking a milkshake.

So there are a lot of occurrences of low pressure in flow. The low-pressure regions where approaching vacuum conditions relative to the surroundings occur in various fluid flows. Vacuum cleaner: the device works to create a low-pressure region to draw in air. It sucks. And when you try to drink cool drinks through your pipe, through your straw, the device works by creating a lower-pressure region to draw air and particles in.

Then, pumps and turbines: low pressure can occur on the suction side of the pump or in specific areas within the flow machinery. In biological systems, the human lungs can create negative pressure to draw in air or liquid. It is estimated to be around 3000 Pascal below atmospheric pressure for drinking a milkshake. So, look at the vacuum pressure it creates.

The Limit: Vapor Pressure and Cavitation

- Every liquid has a vapor pressure that depends on its temperature. This is the pressure at which the liquid starts to boil or vaporize.
- If the absolute pressure in a liquid flow drops to the liquid's vapor pressure, the liquid can flash into vapor, forming bubbles.
- Cavitation is the phenomenon where these vapor bubbles form in low-pressure regions and then collapse violently when they move into higher-pressure regions.
- Cavitation can cause noise, vibration, and severe damage to machinery like pumps, propellers, and turbines due to the force of the collapsing bubbles eroding surfaces. This happens when local pressure drops below the liquid's vapor pressure.

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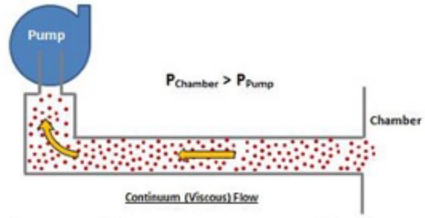
The Limitation: Vapor Pressure and Cavitation. Every liquid has a vapor pressure that depends on temperature. We have seen it in the thermodynamics lesson. Every liquid has a vapor pressure that depends on its temperature.

The pressure at which the liquid starts to boil or vaporize is called vaporization. This is the vapor pressure. If the absolute pressure in a liquid flow drops to the liquid's vapor pressure, the liquid can flash into vapor, forming bubbles. If the absolute pressure in a liquid flow drops—absolute pressure in a liquid flow drops to the liquid's vapor pressure—then the liquid can flash into vapor, forming bubbles. Cavitation is the phenomenon where vapor bubbles form in low-pressure regions and then collapse violently when they move into high-pressure regions.

Cavitation is the phenomenon where these vapor bubbles form in low pressure. So, the bubbles which are formed are in low pressure, and when they collapse, they create very high pressure. It is like a balloon, right? When the balloon collapses, it will create high pressure. So, when this vapor pressure forms a low-pressure region, this is a low-pressure region, and when the cavitation occurs, it can cause noise, vibration, and severe damage to machinery.

That's why we try to avoid two-phase flow, liquid and steam, right? We try to have dry steam. So it's because of this cavitation effect which is there.

Vacuum and the Continuum Assumption



- In many engineering problems, we treat fluids as a continuum, assuming properties like density and velocity vary smoothly. This ignores the fluid's molecular structure.
- The continuum assumption is valid when the scale of the flow is much larger than the average distance molecules travel between collisions (the mean free path).
- At very low pressures, approaching a hard vacuum, gases become very rarefied. The distance between molecules increases, and the mean free path becomes comparable to the flow dimensions.

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https://vacaero.com/wp-content/uploads/2018/08/Fig-2-lg.gif

So the Vacuum and Continuation Assumptions. So you can see there is a pump and then there is a chamber. So the continuum viscous flow is there. So the water flows from here, and the pump is pressurizing it to go up. So the chamber pressure is less than the pump pressure. In many engineering problems, we treat fluid as a continuum, assuming the properties like density and velocity vary smoothly.

The continuum assumption is valid when the scale of the flow is much larger than the average distance molecules travel between collisions, that is, the mean free path. When the scale of the flow is much larger than the average distance molecules travel between collisions.

At very low pressures approaching hard vacuum, gases become rarefied. The distance between the molecules increases, and the mean free path becomes comparable to the flow dimensions. That's why the continuity equations, when applied at a microscale, are challenging.

To Recapitulate

- What is a Fluid?
- What do you understand by Fluid Mechanics?
- Name the Key Properties of a fluid. What is Viscosity?
- State the Fundamental Laws on fluids.
- Which is the Dimensionless Number of relevance in Fluid Mechanics?
- How is Fluid pressure measured? Explain.
- What are the Hydrostatic Forces?
- Discuss about Pressure Concepts & Cavitation.

Reference

1. Patrick Chassaing, 2023. Fundamentals of Fluid Mechanics_ For Scientists and Engineers-Springe.
2. Frank M. White, 2017. Fluid mechanics-McGraw-Hill Education.
3. Kundu, P.K., Cohen, I.M., Dowling, D.R. and Capecelatro, J., 2024. Fluid mechanics. Elsevier.
4. Munson, B.R., Okiishi, T.H., Huebsch, W.W. and Rothmayer, A.P., 2013. Fluid mechanics (pp. 271-274). Singapore: Wiley.
5. Nakayama, Y., 2018. Introduction to fluid mechanics. Butterworth-Heinemann.
6. Shaughnessy, E.J., Katz, I.M. and Schaffer, J.P., 2005. Introduction to fluid mechanics (Vol. 8). New York: Oxford University Press.

So, friends, what did we study in this full chapter? We studied what a fluid is, then what you understand from fluid mechanics, what the key properties are—like fluid viscosity—then loss of fluid, then dimensionless numbers, then fluid pressure measurement, where we talked about manometers, then hydrostatic forces, and finally, we discussed pressure concepts and cavitation. Cavitation is created because of low pressure or vacuum.

Cavitation is a phenomenon where vapor bubbles form at very low pressure, and when they burst, they create high-pressure collapses. So, these are the references, friends, we used for making this chapter, and I am sure you enjoyed this lecture. We have tried to cover the basic fundamentals of fluid mechanics and some properties of fluids.

Thank you.