Basics of Mechanical Engineering-3

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Lecture 36: Classification of Flow (Part 2 of 2)

Welcome to the new lecture on Newtonian and Non-Newtonian Fluids, Compressible vs. Incompressible Fluids. Blood is a non-Newtonian fluid. Ketchup is a non-Newtonian fluid. Toothpaste is a non-Newtonian fluid. Water is a Newtonian fluid.

Compressible, incompressible. Compressible. So, fluid I said. Gas is also a fluid which can be compressed. Gas can be compressed. Incompressible. Liquid cannot be compressed. So, this is what we will try to see in detail in this lecture.

Contents

- Introduction
- Newtonian fluid
- Application
- Non-Newtonian fluid
- Types of Non-Newtonian fluid
- Application
- Compressible fluid
- Incompressible fluid

So, the content will be introduction, then we will try to see Newtonian fluids, then its applications and why non-Newtonian fluids exist at all, what are its applications, what are

the different types of non-Newtonian fluid, its applications, compressible fluid and incompressible fluid.

Introduction

Fluid:
- Fluids are the material who deform continuously when subjected to a shearing stress, no matter how small.
- Classical fluid mechanics, as treated in the sources, primarily deals with fluids and excludes materials like clay or mud, which are studied in rheology.

Fluids are materials which deform continuously when subjected to a shearing stress, no matter how small. Classical fluid mechanics, as treated in the sources, primarily deals with fluids and excludes materials like clay or mud, which are studied in rheology. So, in classical fluid mechanics, we always look at what primarily deals with fluids.

Introduction

Viscosity:

- Viscosity is an important property of fluids.
- Experimental observation shows that when a fluid is sheared between two plates, the shearing stress is proportional to the rate of shearing strain for common fluids like water and oil.
- The constant of proportionality in this linear relationship is the dynamic viscosity .
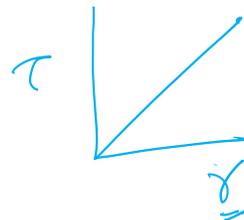
Viscosity is a very important property in fluids. Viscosity is an important property of fluids. Experimental observations show that when a fluid is sheared between two plates, there is one plate, and there is another plate.

Now, what you do is you put a droplet here, and this is sheared. Experimental observations show that when a fluid is sheared between two plates, the shear stress is proportional to the rate of shearing strain for common fluids like water and oil. The constant of proportionality in this linear relationship is the dynamic viscosity.

So, what we are trying to say is tau, and then I try to say strain. So, if it is linear. Experimental observations show that when a fluid is sheared between two plates, the shear stress is proportional to the rate of shearing strain for a common fluid.
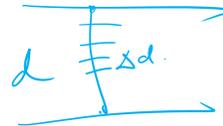
Newtonian Fluid

This relationship can be expressed by the equation:

$$\tau = \mu \times \left(\frac{du}{dy}\right)$$

where:

τ is the applied shear stress.

(du/dy) represents the velocity gradient, which is equivalent to the shear strain rate (dθ/dt) for common linear fluids.

μ is the viscosity coefficient, which is the constant of proportionality in this relationship
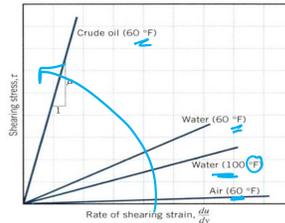
So, the relationship can be expressed as $\tau = \mu \times \dfrac{du}{dy}$ where τ is the applied shear stress. du/dy represents the velocity gradient. This is a gradient. From here, this is d, and from here to here, there are Δt and Δd. So, these are gradients. So, du/dy represents the velocity gradient. This is nothing but the velocity gradient, which is equivalent to the shear strain rate dθ/dt for a common linear fluid, where μ is the viscosity coefficient, the constant of proportionality in this relationship. So, μ is a constant of proportionality, the viscous coefficient.

Newtonian Fluid

Why water is Newtonian fluid :

Water demonstrates a consistent, linear relationship between the applied shearing stress and the resulting rate of strain, characterized by a constant dynamic viscosity at a given temperature, it fits the definition of a Newtonian fluid, unlike substances whose viscosity changes with the shearing conditions.

Linear variation of shearing stress with the rate of shearing strain for common fluids

Philip M. Gerhart, Andrew L. Gerhart, John I. Hochstein - Munson, Young and Okiishi_s Fundamentals of Fluid Mechanics-Wiley (2020).-pg 18   6

Why is water called a Newtonian fluid? Water demonstrates a consistent linear relationship between the applied shear stress and the resulting strain rate, characterized by a dynamic viscosity at a given time.

It fits the definition of a Newtonian fluid, unlike substances whose viscosity changes with the shear condition. For example, you have a drop of fluid like tomato ketchup or honey. It tries to stay in its position, like a dot itself. So when you try to push it, it moves a little bit and then freezes again. Unlike substances whose viscosity changes with the shearing condition. So here you can see the shear stress versus shear strain.

For air at 60 degrees, it follows a linear trend. Then for water at 100 degrees Fahrenheit. Friends, note down: it is Fahrenheit. Water at 60 degrees Fahrenheit, and crude oil at 60 degrees Fahrenheit. So you see how the viscosity changes.

Newtonian Fluid

Why air is Newtonian fluid:
- The actual value of the viscosity depends on the particular fluid, and for a particular fluid, the viscosity is also highly dependent on temperature, as illustrated in Figure with the two curves for water, Fluids for which the shearing stress is linearly related to the rate of shearing strain (also referred to as the rate of angular deformation) are designated as Newtonian fluids.
- **Fortunately, most common fluids, both liquids and gases, are Newtonian.**
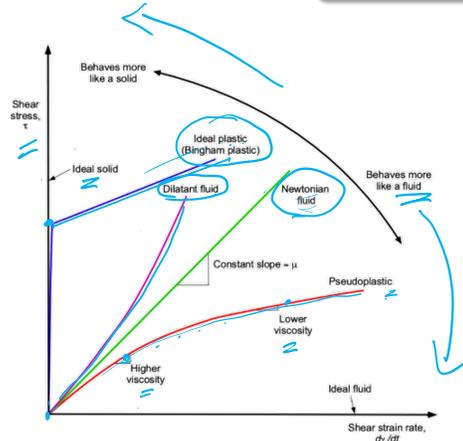
The stress/strain rate for various fluids. Air behaves as a Newtonian fluid in that its viscosity remains independent of its shear rate.

The actual value of viscosity depends on the particular fluid. For a particular fluid, the viscosity is also highly dependent on temperature. As illustrated in the figure, you can see the temperature. As illustrated in the figure, with two curves of water, a fluid for which the shear stress is linearly related to the shear strain. And this is designated as a Newtonian fluid. Fortunately, most common fluids, both liquids and gases, follow Newtonian behavior.

So if you see in this diagram, the shear stress through the shear strain rate is given here. So you can see here the viscosity for a pseudoplastic material. This is for Newtonian, which we saw is directly proportional. And there are fluids in which it tries to stiffen as you apply shear stress to it. So those are called dilatant fluids, where you apply shear and then the viscosity changes.

So here, these materials are highly viscous, and these are low viscous. You have ideal plastic, Bingham plastic, in which it tries to remain constant until you apply a particular shear rate and shear stress, and then it increases. The shear strain rate is almost constant, and it then goes. So this is called ideal plastic, which is otherwise called Bingham plastic. So it behaves more like a solid when you go down.

Sorry, when you go down, it behaves more like a liquid, and when you move to the other end, it behaves like a solid. So, we are always more focused on Newtonian fluids. The other one, all the other things, are called non-Newtonian fluids. Dial and fluid, pseudoplastic and ideal plastic, are all non-Newtonian fluids. They don't follow the

proportionality. If you have a medium mixed with abrasive and viscous material, and you try to push it inside a bottle, that one is called an ideal solid.

Initially, it follows a high shear stress, and there is no improvement, meaning it is almost like a solid. The moment you push it harder, it starts deforming and getting inside. This is Bingham plastic, and you have pseudo-plastic.

Newtonian Fluid

Application:

- Newtonian fluids like water, air, and mineral oils are primary choices in heat exchangers and coo ling systems (e.g., for electronics, HVAC, and industrial reactors) because of their stable viscosity and high heat transfer efficiency.

- In mixing tanks and industrial reactors, Newtonian fluids are preferred since their viscosity doesn't change with shear, allowing uniform mixing, temperature distribution, and accurate process control (e.g., in food, pharmaceuticals, and chemicals).

- Newtonian drilling fluids and muds are employed for drilling operations, providing lubrication, cooling, and pressure balancing in oil and gas wells.

Newtonian Fluid

Newtonian fluids, like water, air, and mineral oil, are the primary choice in heat exchangers and cooling systems. In electronics, HVAC, and industrial reactors, they are used because of their stable viscosity and high heat transfer efficiency. That's why we always use Newtonian fluids. In mixing tanks and industrial reactors, Newtonian fluids are preferred since the viscosity does not change with shear, allowing uniform mixing, temperature distribution, and accurate process control in a Newtonian fluid. When you try to mix juice or something, you put syrup and then water, then you mix it. Mixing happens in a Newtonian fluid.

It can lead to accurate process control. Newtonian drilling fluids and mud are employed for drilling operations, providing lubrication, cooling, and pressure balancing in oil and gas wells. So, they use Newtonian drilling fluids. So, all these things are Newtonian fluids. Water, mercury, olive oil, honey, mineral oil, gasoline, and milk—all these things are Newtonian fluids.

Non-Newtonian Fluid

- Non-Newtonian fluid is defined by the fact that it does not follow the linear relationship between applied shear stress (τ) and the resulting shear strain rate that characterizes newtonian fluids.

- Nonnewtonian fluids, however, have a nonlinear relationship between shear stress and shear strain rate. This means their resistance to flow isn't constant.

- The slope of the nonlinear curve at any point on a shear stress vs. shear strain rate plot is referred to as the apparent viscosity.

What are non-Newtonian fluids? A non-Newtonian fluid is defined by the fact that it does not follow the linear relationship between the applied shear stress and the resulting strain rate that characterizes a Newtonian fluid. Non-Newtonian fluids, however, have a non-linear relationship between shear stress and the shear strain rate. This means that the resistance to flow is not constant. So it changes with respect to time and temperature.

The slope of the non-linear curve at any point on the shear stress versus shear strain rate plot is referred to as the apparent viscosity. So whatever you measure here is called the apparent viscosity.

Non-Newtonian Fluid

Types of Non-Newtonian Fluid :

- Dilatant: These are shear-thickening fluids. Their resistance to flow increases as the shear strain rate increases.

- Pseudoplastic: These are shear-thinning fluids. They become less resistant at higher strain rates. Very strong thinning is sometimes called plastic.

- Bingham plastic: This is a substance that requires a finite yield stress before it begins to flow. The sources describe yielding followed by linear behavior in some cases, though nonlinear flow after yielding can also occur .

There are types of non-Newtonian fluids. They are dilatant, pseudoplastic, and Bingham plastic. These are shear-thickening fluids. Their resistance to flow increases as the strain increases. The moment you strain it, it becomes more solid. Pseudoplastic fluids are shear-thinning, while dilatant fluids are shear-thickening. They become less resistant at higher strain rates. A very strong thinning effect is called plastic.

It is pseudo-plastic. Shear, when you are trying to apply shear, if the fluid becomes solid, it is called shear-thickening behavior. Thus, it is dilatant. Bingham plastic is a substance that requires a finite yield stress before it starts to flow. You keep on pushing; it resists, resists. After some point in time, it starts flowing.

Those things are called Bingham plastics. The source described yielding followed by a linear behavior in some cases, though nonlinear flow after yielding has occurred. So these are dilatant, pseudoplastic, and Bingham plastic. They are all non-Newtonian fluids.

Why corn starch and water mixture is non-Newtonian fluid :

- A corn starch and water mixture is specifically identified as a shear thickening fluid.

Why corn starch and water mixture is non-Newtonian fluid :

- For shear thickening fluids, the apparent viscosity increases with increasing shearing rate. As these mixtures can behave like "quicksand" they become harder or more resistant to flow when you try to move quickly through them (high shear rate).

- The figure visually illustrates this behavior, showing that the plot of shearing stress versus rate of shearing strain for a shear thickening fluid is not a straight line; the slope (representing apparent viscosity) gets steeper as the shear rate increases.

Philip M. Gerhart, Andrew L. Gerhart, John I. Hochstein - Munson, Young and Okiishi_s Fundamentals of Fluid Mechanics-Wiley-pg no 19.

Why is the cornstarch and water mixture a non-Newtonian fluid? The cornstarch and water mixture is specifically identified as a shear-thickening fluid. You mix it; it gets thickened. For a shear-thickening fluid, the apparent viscosity increases with the shearing rate.

As the mixture can behave like quicksand, it becomes harder or more resistant to flow when you try to move quickly through it. So it is a non-Newtonian fluid where shear thickening happens.

The figure illustrates this behavior, showing the plot of the shearing stress versus the rate of shear strain for a shear-thickening fluid is not a straight line. So you can see here, it is not a straight line. It is not a straight line. The slope gets steeper as the shear rate increases.

Non-Newtonian Fluid

Applications :
- Blood, a shear-thinning fluid, is critical in medical diagnostics and analysis, as its variable viscosity affects circulation and is considered in designing biomedical devices like artificial heart valves and blood pumps.
- Drug delivery systems and tissue engineering utilize smart non-Newtonian fluids that adapt to physiological conditions to better target specific tissues or release medication.
- Many foods (e.g., ketchup, yogurt, mayonnaise, jam, soup) are non-Newtonian, with tailored flow properties for desirable texture, pourability, and mouth feel .
- Chocolate and caramel toppings leverage shear-thinning or thickening effects for easier manufacturing, packaging, and consumer use.

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14

Non-Newtonian Fluid

NON-NEWTONIAN LIQUIDS

Asphalt — Lava — Molten Metal — Blood — Sperm — Toothpaste — Paint — Glue — Corn flour and water — Whipped Cream — Gypsum paste

https://americanbobcat.blog/2023/08/02/what-are-the-non-newtonian-liquids/
15

So application of non-Newtonian blood here is a shear thinning fluid, is critical in medical diagnosis and analysis, as its variable viscosity affects the circulation and considered it in designing a biomedical device like artificial heart valve and blood pumps. Then drug delivery systems and tissue engineering utilize smart non-Newtonian fluids that adapt to psychological conditions.

Many food are non-Newtonian fluids with tailor flow properties for desirable texture, pourability and mouth-filling chocolates. And the caramel topping leverages sear thinning or thickening effect for easier manufacturing, packaging and consumable products. So food items, blood and drug delivery, all these things are non-Newtonian fluids. So here in the non-Newtonian shear thickening, shear thickening is this behavior, shear thickening you see here, the slope increases with respect to rate. So all these things are non-Newtonian fluids.

Asphalt, blood, glue, cornflour with water, sperm, then lava, molten metal, toothpaste, wimped cream, gypsum paste, paint and ketchup. All these things are non-Newtonian fluids. They can have shear-thinning or shear-thickening behavior.

Compressible Fluid

A fluid is considered compressible if its density (ρ) changes significantly. These changes in density are typically due to variations in pressure and temperature.

- Gases are inherently compressible.
- Their density is highly variable and changes significantly with modest changes in pressure and temperature.
- Compressible flow is quite common for gases, especially at high speeds (Mach numbers greater than about 0.3) .
- The analysis of compressible flow often focuses on gas dynamics .

Compressible fluid: A fluid is considered compressible if its density changes significantly. This change in density is typically due to variations in pressure or temperature.

The gas is inherently compressible. Their density is highly variable and changes significantly with modest changes in pressure and temperature for compressible fluids. Compressible flow is quite common for gases, especially at high speeds. Compressible flow is quite common for gases, especially when the speeds are at Mach 0.3. The analysis of compressible flow often focuses on gas dynamics.

Compressible Fluid

- When Liquids Behave as Compressible Fluids: Under certain extreme conditions, liquids can exhibit compressible behavior .
- This typically requires either very high pressures (on the order of 1000 atmospheres for water) or achieving velocities comparable to the liquid's speed of sound.
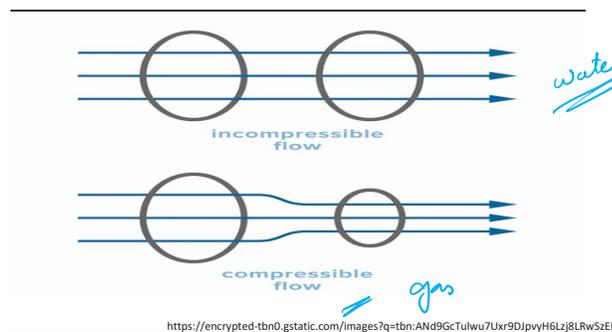
incompressible flow

water

compressible flow

gas

When a liquid behaves as a compressible fluid under certain extreme conditions, it can exhibit compressible behavior. So, this is for an incompressible fluid flow. This is for a compressible fluid flow. This is predominantly gas, and this is predominantly water.

This typically requires either high pressure on the order of 1000 atmospheres for water or achieving velocities comparable to the speed of sound in liquids. So, then at very high velocities or very high pressures, it starts behaving like a compressible fluid.

Compressible Fluid

- Another important consequence of the compressibility of fluids is that disturbances introduced at some point in the fluid propagate at a finite velocity.

- For example, if a fluid is flowing in a pipe and a valve at the outlet is suddenly closed (thereby creating a localized disturbance), the effect of the valve closure is not felt instantaneously upstream. It takes a finite time for the increased pressure created by the valve closure to propagate to an upstream location.

- That the speed of sound is related to changes in pressure and density of the fluid medium through the equation

$$c = \sqrt{dp/d\rho}$$

Another important consequence of fluid compressibility is that disturbances introduced at some point in the fluid propagate at a finite velocity. So, you drop a stone in water, and ripples form. For example, if a fluid is flowing in a pipe and a valve, which is the exit valve, is suddenly closed, The effect of the valve closure is not felt instantaneously upstream.
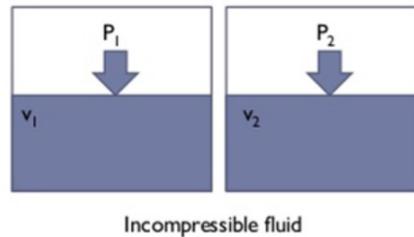
So it takes a finite time for the increase in pressure created by the valve closure to propagate to the upstream location. For example, you have a pipe, and the water is flowing through it when you close the pipe. After a period of time, there is a pressure increase, and then you can see the fixture gives way between the pipe and the tube.

If the fluid is flowing in a pipe and a valve at the outlet is suddenly closed, the effect of the valve closure is not felt instantaneously upstream in the pipe. It takes a finite time for the increased pressure created by the valve closure to propagate to an upstream location. The speed of sound is related to the change in pressure and the density of the fluid medium through this equation.

Incompressible Fluid

An incompressible fluid is an idealized fluid where its density (ρ) is treated as constant .This means the density does not change, or changes negligibly, with variations in pressure and temperature.
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Incompressible fluid

Philip M. Gerhart, Andrew L. Gerhart, John I. Hochstein - Munson, Young and Okiishi_s Fundamentals of Fluid Mechanics-Wiley (2020).-pg 39

Incompressible fluid: An incompressible fluid is an idealized fluid where the density ρ is treated as a constant. This means that the density does not change, or the change is very negligible with respect to pressure and time, which is quite common for fluids.
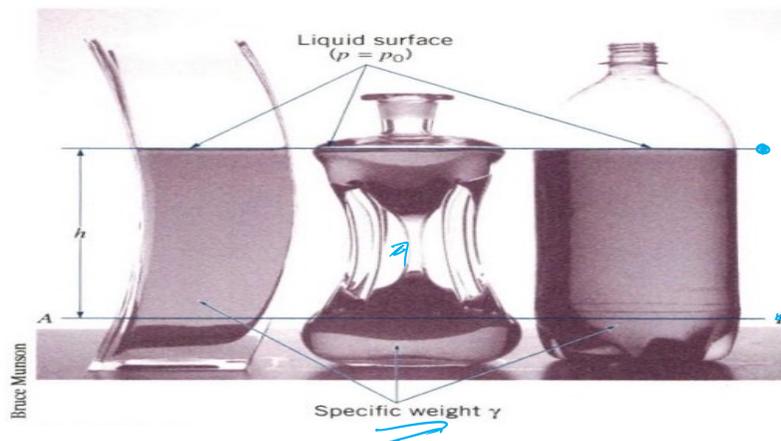
Incompressible Fluid

- Liquids are generally treated as incompressible in basic fluid mechanics problems because their density changes very little, even under large changes in pressure .
- Liquids have very high bulk moduli , which means they are very resistant to changes in volume (and thus density) when pressure is applied.
- For instance, the density of water increases by only about 1 percent when the pressure is increased by a factor of 220 .
- For many practical engineering applications involving liquids, the variation in density is considered negligible.

Philip M. Gerhart, Andrew L. Gerhart, John I. Hochstein - Munson, Young and Okiishi_s Fundamentals of Fluid Mechanics-Wiley (2020).-pg 39

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Incompressible Fluid

All liquids are treated as incompressible fluids because the density changes very little. Liquids have very high bulk moduli, which means they resist changes in volume. For instance, the density of water increases by 1% when you increase the pressure by a factor of 220.

For many practical engineering applications involving liquids, the variation in density is negligible. So this is the liquid surface, and these are the specific weights γ.

Incompressible Fluid

- The pressure in a homogeneous, incompressible fluid at rest depends only on the depth of the fluid relative to some reference plane.
- It is not influenced by the size or shape of container in which the fluid is held.
- Thus, in image , the pressure is the same at all points along the line AB, even though the containers have very irregular shapes.
- The actual value of the pressure along AB depends only on the depth, h, the surface pressure, p. and the specific weight, y, of the liquid in the container

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The pressure in a homogeneous incompressible fluid at rest depends only on the depth of the fluid relative to some reference plane. It is not influenced by the size or shape of the container in which the fluid is held. Thus, in the image, the pressure is the same whether you take it at the top or at the line AB.

Thus, in the image, the pressure is the same at a point along line AB, even though the container is irregular in shape. So it is like this: a glass or something like this, or a scent—this is a scent bottle, and this is a bottle filled with oil. The actual value of p along AB depends only on the depth, h, the surface pressure p, and the specific gamma of the liquid in the container.

To Recapitulate

- What is Fluid? Name its important property?
- What do you understand by a Newtonian fluid?
- How do we say that water is a Newtonian fluid?
- What makes us say that air is a Newtonian fluid?
- State applications of Newtonian fluids.
- State and explain Non-Newtonian fluids.
- What are different types of Non-Newtonian fluid?
- State applications of Non-Newtonian fluids.
- Describe about Compressible and Incompressible fluids.

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So, in this chapter, friends, we saw what a fluid is. What are the important properties? What do you understand by Newtonian fluid, applications of Newtonian fluid, non-Newtonian fluid, types of non-Newtonian fluid, and finally, compressible and incompressible fluids? These are the references we have used, and thank you very much.