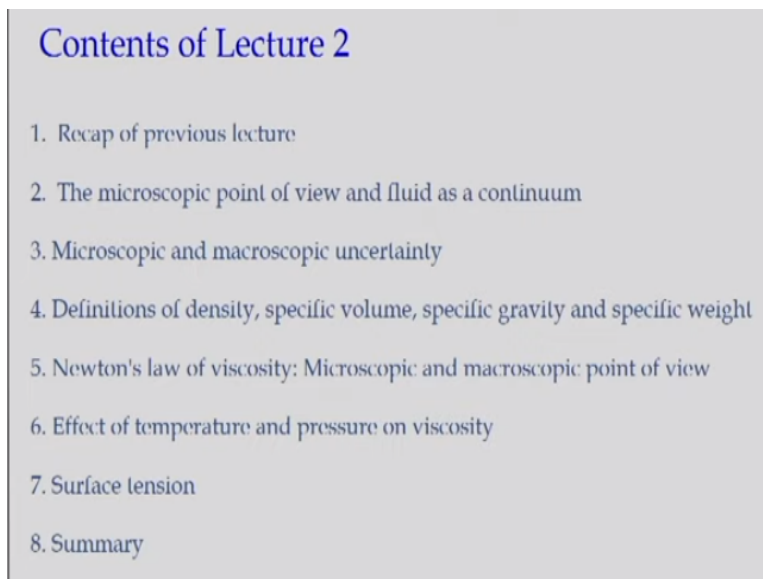**Fluid Mechanics**
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Lecture - 02
Properties of Fluid

Welcome to the second lectures on fluid mechanics. Last class we discuss about the basic concept of fluid mechanics and introductions level.

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So today I will just have a recap of the previous lectures. Then we will go for the two concept which prevails in fluid mechanics is microscopic and macroscopic. That the things we will discuss more details. Then we will go for the fluid properties like density, specific volume, specific gravity, and the specific weight. And very interesting well known Newton's laws of viscosity that what today we will derived at both the concept at microscopic level and the macroscopic point of view.

And then we will discuss about what is the effect of the temperature and pressures on the viscosities, then the surface tensions. So let us have a recap of the previous lecture, the first lectures what you studied, discussed.

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Recap of the Previous Lecture

1. FLUID MECHANICS is the science that deals with behavior of fluids at rest or in motion and the interaction of fluids with solids or other fluids at the boundaries

2. A fluid in direct contact with a solid surface sticks to the surface and there is no slip. This condition is called as NO-SLIP CONDITION

Classification of Fluid Flows:

1. Flow of unbounded fluid over surface 2. Flow of fluid in pipe or duct	External flow Internal flow
3. Density of fluid flow is constant 4. Density variability in fluid flow	Incompressible flow Compressible flow
5. No change in flow with time 6. Change in flow with time	Steady flow Unsteady flow
7. Depending on flow properties changing in directions	1D, 2D, 3D flows
8. Smooth layered flow 9. Rough flow with eddies and mixing between the layers	Laminar flow Turbulent flows

In fluid mechanics as you discussed is that we are talking about the behavior of the fluid either at the rest or in the motions and also the interaction of fluids with the solids or other fluids at the boundary. The more important concept what we have discussed is no-slip conditions. That means, when a fluid is moving fluid in a stick with a solid surface, the velocity of the moving fluid is equal to the velocity of the solid surface. That is what at that point the no-slip conditions exists.

So that is the very basic concept and that is what governs the fluid flow process what we will discuss many times about this no-slip conditions. As I in the last class I discussed so many problems of the fluid flows considering from engineering problems, flow through the pipes, the wind blow over the mountains, all what we can categorized or classified into different groups like external flow, internal flow, incompressible flow, comprehensible flow.

And when you talk about incompressible flow and compressible flow, the basic properties of the density that was a key factor decides as whether it is a fluid incompressible flow or the compressible flow. Similar way when the flow when you talk about the time component, if it is the time the flow properties do not vary with the time then we call the steady flow that means, we can consider some of the fluid flow problems where the flow properties do not vary with the time.

So that is the assumptions we can take it and solve the problems. So that is what the steady problem. Similar way we can have the unsteady flow where the flow properties

like the density, velocity, the pressures they vary with time within the flow. If that is the case then we have the unsteady flow. Then we have also discussed about one dimensional, two dimensional, and three dimensional flow.

That is what is talk about, when you talk about any flow conditions it is the three dimensional flow. But we can approximate it or into a one dimensional flow behaviors based on the flow characteristics two dimensional flow behavior as we discussed in the last class and more instantly again I have to talk about that what in the last class we just I have given you a just a definitions for the laminar flow and the turbulent flow.

The laminar flow in a pipes or in domain where it is well behaved field or the orderly behaved flow. The smooth layer type of the flow behavior happens it and when you come to the turbulent flow, where you have a lot of eddies formations will be there. There is a lot of flow accents between the two layer of the fluids and the mixings will be there. That is what is the turbulent flow. And the more detail we will discuss it as we will proceed in the lectures on laminar flow and the turbulent flow.

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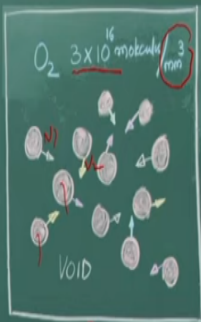
Now let us consider coming to the fluids, the definitions of the fluids and if you look it if fluid is composed of the molecules in constants, motions and collisions okay. Then you can just think it that the fluid flow what is happening it that is what the representations of million number of molecules are in motions, also they are colliding each others.

If it that is the conditions like for example, if you look at these figures, here I am very zoomed view of molecules what we are showing it where is having some sort of per oxygen 3 into 10 to the power 16 number of molecules are present in a just a millimeter cube area volume. So that what is indicates how many molecules are there if you take a one millimeter cubic volume of oxygen.

That means so many molecules are there and these then molecules are having the random motions okay there will be velocity here and here. So they have the random motions each others and they are colliding each others okay. The main effects to what we get it the density variations or pressure variations or the velocity variations these are the molecules, the gross characteristics what we get it at the density or the pressure variations or the temperature variations.

Also they are relative properties, what we will discuss about viscosity and all. So if we look at that, if these are the molecules are there in a one millimeter cubic millimeters, this many molecules are there. They are having the random motions, they are colliding each others, very basic things which call that what is the average distance traveled by a molecule before collisions.

That is what is called the mean free path. Mean free path what is there, what is the distance traveled, on average distance traveled by these molecules before its collisions with another molecules. That is the mean free path. This is what gives us a very interesting phenomena to us. Like for example, if I look at the number of oxygen molecules in one millimeter cube is 3 into 10 to the power of 16.

But the mean free path of this oxygen's molecules at one atmospheric pressures at the 20 degree temperatures is equal to 6.3 into 10 to the power minus 8 meters. So if you look at that, this mean free path is about to 200 times of the diameter of oxygen molecule. That means there are lot of void space are there and the molecules are having random motions and colliding each others.

And the distance between average distance traveled by the molecules here, the oxygen molecules is a 200 times of the diameter of the oxygen molecules. So lot of void

space are there. So you can imagine it that there are fluid molecules are there and they are having random motions. And there are the average distance they travel it.

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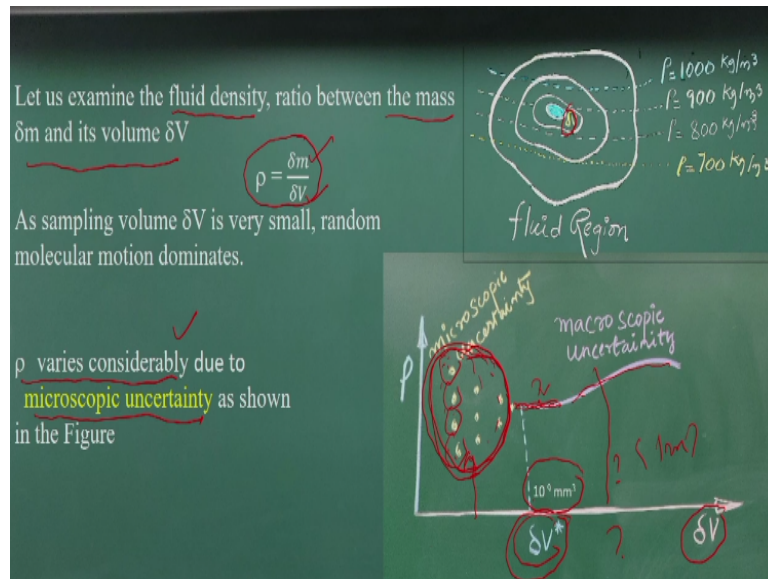
So these properties what is happening it at the molecules levels that is what is reflect us very interesting concept what let us consider very basic fluid properties is the fluid density, okay? That means that is what is the mass per unit volumes. That means, if I consider a very tiny delta V and that delta V is the sample volume for me. And if I consider that sample volumes, I will have the density the delta m by delta V okay mass per unit volume.

That is the density what will be there. Now if I look it as I am going to increase the delta v which is assembling the volumes, which is very less to go for the higher order as this figures is showing it that this side I have the density. There is here is I have the sampling volume. Okay let us consider it that the sampling volume delta V I have considered it to represent the density.

If I have a delta V is very small okay and which is less than 10 to the power minus 9 cubic millimeters you can see these values are will be changed like this. That means, when you have a very small the sample volumes so the mean path, mean free path deviation, the molecular motion of the random motions that is what is changing the density value.

That means indirectly it indicates that the number of the molecules within that small sampling volume that what it changes drastically as instant to instant. As the number of molecules are coming in and number of molecules are going out that what is a give a random motions what is exhibited within the fluids, that what is give a lot of variations of the density value as the number of molecules coming in and going out, they are not balancing each other.

That is the reasons you have a the uncertainty, the density will vary drastically. These are not a time dependent component but that is it will be vary as we will have the sampling measurement, it is lesser than a threshold value. Similar way, that is what is called the microscopic uncertainty as the density vary considerably as were sampling volume is lesser than this.

But there is a limiting conditions like the delta v star, it is a limiting conditions. At that limiting conditions if you look at these reasons the density fairly constant. That means what I am telling it that the sampling volumes as we increase it at a particular limiting value, we can see that the density is remains constant that what indicates is that the, with that the sampling volumes, the number of the molecules coming it as a random motion into that and going out more or less balanced each others.

So we will have a, the density the constants. So, we have to do a measurements or we have to do the analysis beyond this point, then the density remains fairly constant for regions, with respect to the sampling volumes. I am talking about with respect to sampling volume. But if I increase the sampling volumes, it is much larger, okay. It could be one meters or the two meters like this.

So I can consider big sampling volumes. So in that case also we will not have the density constants. The density will vary it.
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Macroscopic uncertainty :

If sampling volume δV is too large, there is density variation within the volume.
Then, the average density (ρ) must differ from the actual density at the centre of the sampling volume.
It is caused by spatial variation of the density. This is called Macroscopic Uncertainty.

That's why, the sampling volume (δV*) → not too large nor too tiny and must contain around million molecules.
The density at a point in space is defined as

$$\rho = \lim_{\delta V \to V'} \frac{\delta m}{\delta v}$$

→ ρ can be defined as continuous and continuously differentiate function

$$\rho = \rho(x, y, z, t)$$

Then,

Pressure $p = p(x, y, z, t)$, $u = u(x, y, z, t)$, $v = v(x, y, z, t)$, $w = w(x, y, z, t)$
Velocity Vector $\vec{V} = u\hat{i} + v\hat{j} + w\hat{k}$

Non Validation : Rarefied gases (where pressure close to zero), microfluidic applications, the flow devices at the micro and nanoscales, the continuum hypothesis does not valid.

That means, we call the macroscopic uncertainty. That sampling volume is too large that like if you consider this is the room is a sampling volume for me see in that case what will happen it that the density variations within this room that what will play the rules that will not be a constant value. So the density will vary within this the sampling volume.

Because of that, if I consider the average density for this sampling volume will be different than the actual density at the center of the sampling volume. So that is the reasons we will have a the variability this partial variability the locations variability is 2y these sampling volume will not represent the density value what should be the required for the analysis.

So if you look at the two type of uncertainty happens it with respect to the sampling volumes. One if it is very lesser than the limiting conditions where is 10 to the power minus 9 millimeter cube you will have a microscopic uncertainty. And if you go for a very large sampling volume, you will have a macroscopic uncertainty; microscopic and macroscopic uncertainty. So that is the reasons what we do it.

We work on the regions where the density does not varies with the sampling volumes. So that means our sampling volume such a way that the fluid characteristics does not vary as the random motions of the molecules are not playing the major roles to varying that properties. So that is the indicator here in the sampling volume, which is 10 to the power minus 9 millimeter cube.

More often in engineering applications like any measurements, we do it much larger than that. So any correct analysis what we do it for engineering applications that the sample volumes represent much larger than this part. So we can consider that the sampling volumes what you have neither to be a too large nor too tiny.

It must contain the million number of the molecules so that the random behavior of the molecular motions that the collisions that what will not reflect in our characteristics or properties of the fluids. So that is in a mathematical I can define it that we are looking the density, where the limit is tending the sampling volume tending towards the limiting velocities, volumes of these things.

So that is the density, the properties. So that means this what we consider there is a density variations, but that density variations our sampling volume is so large near to the limiting conditions, which does not have a effect of microscopic or macroscopic uncertainty. In that regions we can consider the density. Any fluid domain part I consider it okay.

Any fluid domains I consider it so if density is varying let be this is 1000 kg/m cube this may be 1200 kg/m cube, this will be 1400 kg/m cube. This lines are representing 1400 kg/m cube, 1200 kg/m cube and this. So on these fluid volume or fluid domain the we can consider the density is a functions of space dimensions that is x, y, z and also the time.

When you consider as a continuous and continuously differentiate functions that means it is now very easy we can use the integral concept differential concept as it is a functional behavior with a space and the time. We remember that if you have a microscopic of macroscopic uncertainty you cannot define it is a continuous function.

So now we call it as the fluid as a continuum, because we can use a continuous functions of the density of fluid properties, differentiated functions to define that flow process. So we define as a fluid as continuity. So similar way as the densities having a continuous functions we can define these the pressure is also a continuous functions of the space and the time.

The velocity, this scalar velocity component like vectors u, v, w can have a space and the time the space and the time and space and the time component. So all these component the fluid flow characteristics we can define in a space functions, also the time functions x, y, z and the t provided consider as the fluid as continuum.

That means we do the analysis of the sampling volume such a way that the randomness behavior of the fluid molecules and they are collisions are not give any uncertainty at microscopic scale and the macroscopic scale. But the some of the case we cannot apply this fluid as a continuum hypothesis. For example, if you go to have very high altitudes in the space, you will see that places will come to very close to the zero.

So that is what the rarefied gas conditions where the pressure is very close to zero. There we cannot apply these because, the mean free path motions of that type of gas is much higher order as compared to the normal gas and the liquid what we consider in common engineering problems. So that is the reasons we cannot use this continuum concept of rarefied gases where the pressure is close to the zero.

Exactly same way there are micro fluid applications that the fluid devices at micro and nanoscales we cannot apply the continuum hypothesis. There are a lot of advanced research advances going on how to handle the fluid flow, which does not follow the continuum hypothesis okay. Let us go for the fluid properties, one of the basic properties as you know it mass, okay or the weight of the fluids.

As you can know it in different fluids have a different mass. Like the mass of the air, mass of the waters, mass of mercury that part will be different. So different fluids what we use it they have the different mass and any fluid flow problems analysis the mass is a the primary component which we use it to analyze the fluid flow problems.
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Density, Specific Volume, Specific Gravity and Specific weight

Density is defined as mass per unit volume

$$\rho = \frac{m}{v} \ (kg/m^3)$$

Specific Volume is defined as volume per unit mass

$$v = \frac{V}{m} = \frac{1}{\rho} \ (m^3/kg)$$

Specific Gravity is the ratio of density of substance to density of well known substance (water considered here)

$$SG = \frac{\rho}{\rho_{water}}$$

Specific Weight is the weight of unit volume of a substance

$$\omega = \rho g \ (N/m^3)$$

Weight of a fluid (weight of air in a room) = ρg (volume of the room)

Weight of the total fluid column $= \sum_{i=1}^{n} \rho_i \, g \, V_i$

$\rho_1 > \rho_2 > \rho_3 > \rho_4$

That is the reason as I told earlier that if I consider a small volume of the fluid the mass of the fluid if a measure it okay as the volume of the sample in volume is larger than the limiting volumes or the continuum hypothesis. So if I consider that part and get a mass of that fluid and do a mass per unit volume. That means we are that is what is the density.

So mass per unit volume, if the volume is one unit, any cube of millimeter or cube of meters, that whatever the mass that is what will give us the density. So that is what we can get it in terms of kg. That means, if I take a one meter cube of water, whatever the mass of the 1000 kg that what will be the density for me that means 1000 kg per meter cube.

So the very basic thing is mass per unit volume, that is the density. I am just reemphasize that any fluid flow problems you do it the first foremost requirement is to calculate what is the mass of the fluid. So if I know the volume of the fluid and the density, I can compute the mass the very simple way. Like if I know the volume we can convert it that and there are the tabulated values available to that.

But there are the problems what like any gas flow and all where we do not talk about with respect to the mass per unit volume. Here we talk about mass is the fixed quantity. That means, we are looking it the volume per unit mass. That means one kg of hydrogen, what is that volumes it is coming it as volume is a variables in a much higher variable as compared to mass in a gas. So we use the specific volume.

That means, the volume per unit mass okay. This is what the density, mass per unit volume. Definitely it is a reciprocal to, the specific volume is reciprocal to the density. So you will have the unit is the cube meter by the kg. But many of the times either you know the mass or the density or you know the specific volume, you can solve the problems.

But to make it a very simple way to represent it which is one is heavier and the lighter okay. So in that case we have to consider a reference liquid or reference gas. As we will I will focus more on liquid, we consider the reference liquid is here is the water okay? That means we are looking it the ratio of density of a liquid to the density of a reference of liquid which here is water that what is give us the specific gravity or relative density.

So this specific gravity gives us, it is heavier or lighter than the with respect to the water. So like a specific gravity of the mercury is 13.6 what does means that it is a 13.6 times heavier than the water. That is what indicate for us. So any of the textbook you can have you can see the table of specific gravity values or the densities or the specific volumes value.

Most often as I say that either you talk about the mass or you talk about the weight, that means force due to the mass. What is the gravity force is acting for that? We do the analysis for that. That is what is we consider the weight per unit volume of a substance is the unit weight. That means, this is very easily any fluid flow problems what is the weight of the fluid is there that what we can compute it just multiplying the volume of the fluids.

So specific weight and in relationship wise it will be the mass into the accelerations due to gravity. So the specific weight is rho into g. That is what the specific weight of this thing. Now if you look at these examples, which are very simple examples what we have given here that there are the layer of the fluids are there and which is having a density rho 1, rho 2, rho 3 and rho 4; V 1, V 2, V 3, V 4 are the volumes.

As you know it you will have a heavier liquid and lighter liquids you will have here okay. So you have a heavier liquid and lighter liquid as basic concept is that. So that means the density of rho 1 will be larger than the rho 4 as this is indicating that. So how much of mass of the fluids are there? If I take a like for example I take it what is the mass of this room?

I can get what is the density of the air here and the volume of this room, multiply that I will get the mass. And if I looking the weight of the fluid that what will be the mass into the accelerations due to gravity, that what will give us the weight. Very simple concept, the density multiplications of the volume that what will give you a mass.

Similar way as I said it if I have a layer of the fluids are there okay in generally it happens it is a layer of the fluids are there. They are having the density variations. We can just compute it what will be the weight. It is sum of the weight for each zone. We can compute for zone 1, zone 2, zone 3 and zone 4 and sum of that what we did to turn weight of the total fluid columns.

So this is what a very simple example what I have given it. I am not highlighting what is the density of different fluids which you can refer to any fluid mechanics book.

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Now let us go to the very interesting concept, the Newton's laws of viscosities okay. It is very simplified, simple common laws of viscosity which we use for solving many of the problems in laminar and also approximate for other flow conditions. Let us talk

about this Newton's laws of viscosity. I am presenting you in two ways. One is microscopic analysis and the macroscopic analysis.

If you look it that you have the plate, okay. If you can look it which is at the rest conditions and you have in the top another plate is there, where you are applying a force F and the velocity V is it is moving this plate. As we know it that whenever we have the fluid flow conditions, we will have the no-slip conditions. That means, at these locations I will have the velocity zero.

At these locations the contact of the fluid particles on the solid surface will give a velocity equal to the velocity of the plate. So I have the velocity V, I have velocity zero at these points. So no-slip conditions prevails for these two points as we are dragging this ones. Now if you look it if I consider A and B two locations okay. And in these two locations I consider a small representing volume of the fluids which is moving with let be a V 2 velocity and the V 1 velocity.

Try to understand it that I have the two fluids pockets. One is moving with V 1. Within that there are million number of molecules are there. The similar way the V 1 the next layer of the packet what the fluid is moving with a million number molecules is moving with V 1. So if you look it the nature wise we need two packets are moving it. One is higher velocity another is lower velocity.

At this interface, what we can say that it is a virtual interface. There is no real interface is there. We make it the flow representations as a two packets okay. Packets A and the packet B, they are containing million number of the molecules which are in a random motions and colliding each others. So if that is the conditions the definitely the basic concept what it comes it this fluid molecules what is there they are crossing each others going off okay from layer B to the A.

As they are the molecules are coming from the B going to A they are transporting the mass. Also they are transporting as a momentum clocks to the next level. Because of that the packet B will try to reduce the velocity of V 1, packet A. Okay, just like that in nature what will happen if somebody running fast and other is slow. So slower one will try to make it other to reduce the speed okay.
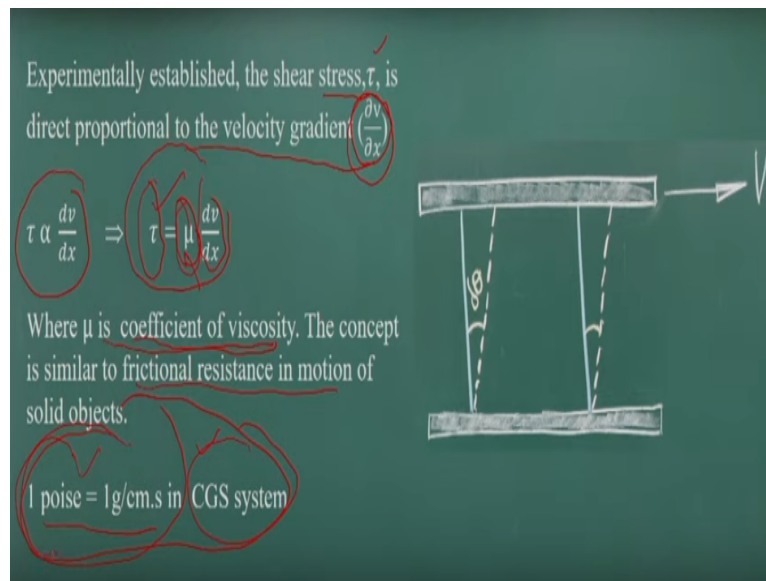
Exactly same way happens here that molecules at the B pockets which are moving slower they are will try to reduce the velocity of the flow of the A. Where as the A what will do it that the same way the molecules in the A packet that what will be again exchange to the B. They will try to increase the velocity of these packets on average the velocity of this packet to this.

So in these the artificial boundary layers they are as we have not we cannot see it, we can visualize these problems okay. We cannot see these things how the molecules are, motions are happening it, as the random motions are happening it or colliding each others. That what we cannot see it, but in conceptually there are the mass flux are going up and the momentum flux is exchanging between that and the momentum flux mass exchange what it happens between these two layer of the fluid packets that what will cause a force on these layers, this interface layer.

And that force will act like a shear force, a resisting force between this two layers. That what will be act like a resisting force between these two packets of that. And that what it happens it the layer A tending to reduce the velocity okay, due to the molecular mass and the momentum flux exchange, where as layer B due to these exchange tending to increase the velocity so that the larger times are these process it goes on.

After certain time maybe these two velocity is coming to equilibrium. That means they will be the same order same value. So looking these the mass exchange and the momentum exchange of the molecules at these the artificial interfaces between two packets of the fluid of packets, we can see that definitely there will be the force will be act on that interfaces as the momentum flux i crossing each other.

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Experimentally established, the shear stress, τ, is direct proportional to the velocity gradient $\left(\frac{dv}{dx}\right)$

$$\tau \propto \frac{dv}{dx} \Rightarrow \tau = \mu \frac{dv}{dx}$$

Where μ is coefficient of viscosity. The concept is similar to frictional resistance in motion of solid objects.

1 poise = 1g/cm.s in CGS system

And shear stress will develop at this interfaces level and many of the studies the experimentally establish that this shear stress will have a directly proportional to the velocity gradient okay. If the more the they have the directly proportionality okay. That means more the velocity gradients is there so we will have the more shear stress. But it has a directly proportionality quantity.

And the proportionality is known as the coefficient of viscosity or dynamic of viscosity. That constant of proportionality constant is known as a coefficient of viscosity. So that means, it varies from the fluid to fluid because their molecular motions, the exchange of molecules, the momentum flux, the random motions all depends upon molecular structures of the fluid.

So when you apply a shear stress or resulting a velocity gradient which will be will have the shear stress formations that what as a resistance of two layers, that what will be a constant proportionality which is a coefficient of viscosity which varies from fluid to fluid. As if you look it at the motion of the molecular point of view, considering as a mass exchange of the molecules and the momentum exchange that what will be there.

So the fluid to fluid will have a variability of the new value that is a coefficient viscosity, which as equivalent to that if a two solid objects are there as one is moving, and others you as you know that there will be a frictional resistance. So the hypothetical the same conditions are happening here that if I consider two fluid

packets, and if they are moving with having a motions, the molecular motions between these two artificial layers will have the shear stress formations and that shear stress formations will have the proportionality to the velocity gradient.

And that proportionality constant is a coefficient of viscosity or some of the book is referred as the dynamic of viscosity. And what you can know it what will be the unit of these ones you can put the unit of shear stress, the velocity gradient, you can see that it will have the mass per length and time. So that means, for a CGS systems the gram centimeter second systems we for a one gram per centimeter per second that what we call the poise.

That means one poise is one gram centimeter second. That is what we consider it the poise is in a CGS systems unit of the coefficient of viscosity or dynamic of viscosity. Yes let us considers microscopic point of view.

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If I consider the same fluid flow through a parallel plates okay. One of the plate the velocity is zero which is at the rest conditions and other the top plate is moving with a velocity V. So as a microscopic point of view I am not talking about the molecular motions or exchange of the molecular motions or the momentum flux that what is resulting a shear stress. Here what we consider that fluid element.

That means, I consider some space of A, B, C, D, this is what the fluid element. That means, whatever the fluids are there that reasons, I am defined as a fluid element. As

you know it that at the A point we will have the velocity V as the no-slip conditions. At the B point we will have velocity G. So velocity assuming it, it will have a linear velocity variations from B to A.

That linear velocity from zero to V as the y increases, the velocity will increase it and maximum velocity will be the V. If it that the conditions now if you look it that if a point which is the y distance from the plate which is at the rest conditions you will have velocity U okay. So as a linear proportionally we can find out what is the velocity of that one.

So next one is the velocity lesser than that or above one will go moving with the fluid is more than that. So if as a linear velocity distributions as you assume it as we got it some of the parallel flow conditions after delta t time these fluid element will be deformed as a angular deformations will happen it that there will be angle theta will come it at the B and E, F and D.

That is a new positions of the fluid element after delta t time. And the angular deformations at this point is delta theta. Similar way the delta theta at this point. So at the delta theta time we have a angular deformations of delta theta. So consider a very simple geometry of these problems. I can consider these distance of AE is V into delta t divide by the l will be the 10 delta theta by l okay.

So that is what will consider. Just rearranging that we can see that the rate of change of angular deformations of this fluid element is equal to v by l, v is a constant, l is the thickness of these two plates. That is a constant quantity what is coming it.

Now if I consider the at the y distributions and the angular velocity distributions if I consider it I will get it the small u the velocity at these points and ratio of the distance as a linear velocity distributions concept, we can get it u by y, v by l, simple geometry of this what gives us relationship. That is what if I differentiate it I will get it this part. We remember this is what is indicating us is that the velocity gradient.

If I consider this is the y directions how the velocity varies along the y directions that is the constant which is equal to the shear strain rate. The shear deformations per unit

time. So we can now consider it that the shear rate strain rate and the velocity gradient is equal for these conditions. These parallel flow conditions when you have velocity is linear distributions the shear strain rate and the velocity gradient they are equal.

So now we are coming to the exactly the solid mechanics concept the stress having the proportionality with the strain. But here we are talking about the stress is proportionality to the strain rate. That means the change of the shear strain rate with respect to time, not the absolute value of the shear strain. That is the basic difference between the fluid mechanics and the solid mechanics.

So same shear strain relationship we are doing it but in this case, we are telling it that the shear stress is a proportionality to the shear strain rate and that is the Newton's laws of viscosity that shear strain is having a, this experimentally proved it. That is what it happen this shear strain is a proportionality to the shear strain rate. Again I can emphasis to that shear strain rate not the shear strain.

That is the difference between the fluid mechanics and the solid mechanics as they have the proportionality and we can define as the shear stress is proportional to the velocity gradient. And the same way we can define it that proportionality constant is a dynamic viscosity or coefficient of viscosity the tau into mu into du by dy.

So the same concept, we can use a fluid element at the macroscopic levels define this relationship between the shear stress and the velocity gradient or at the microscopic levels, the fluid molecules movements in terms of mass and momentum exchange. Also, the experimental finding also give the same concept that the relationship between the shear stress and the velocity gradient.

We remember it here we are talking about velocity gradient along the y directions and the shear stress is a normal to that. That the point what you can look it. So that is the shear stress is equal to mu in d by dv. This is very basic equations used to solve many of the problems if you just have a basic concept is the stress is having a proportionality constant with constant proportional constant. That is what is the dynamic viscosity of the coefficient of viscosity.

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Effect of temperature and pressure variation on viscosity

For liquids,
Change of pressure -> very nominal change in μ.
Increase of temperature $\approx$ Reducing inter molecular forces $\Rightarrow$ Decrease trend of μ.

For gases,
Change of pressure $\approx$ very nominal change in μ.
Increase of temperature $\Rightarrow$ Increase of random motion of molecule $\Rightarrow$ Increase trend of μ.

The Sutherland correlation (from the US Standard Atmosphere)

$\mu = \dfrac{aT^{1/2}}{1+bT}$ for gases

$\mu = a10^{b/(T-c)}$ for liquids

where,
T is absolute temperature.
a, b and c are experimentally estimated constants.

Now let us commit that how does the temperature effect on the coefficient of the viscosity. Now we have to look at the molecular levels okay. So if you look at this molecular levels, when you talk about the liquids, they will have a molecular bonding forces between two molecules okay. But that is much weaker when talk about the gases.

So gas are at more random motions as compared to the molecules are more random motion as compared to the liquids. So when you increase the temperatures okay or increase the pressures, like if I increasing the pressures that means I am compressing the fluid things. A fluid volumes I am just compressing it. As I compress it whether these molecular motions exchange of the molecular motions in terms of mass and momentum does it change drastically?

What is experimental find that if you let it is this now having a one atmospheric pressure. This is the if I increase to the 50 atmospheric pressure the coefficient of the viscosity on this room will not change that high. That may change it less than 0.5% of the at the one atmospheric value. So change of the pressures if you try to understand it that what does not change that significantly the molecular motions or exchange of the molecular motions mass are the momentum flux as mu will not change drastically.

So you look at in terms of molecular motion as a mass exchange and the momentum exchange. But if you look at the temperatures, the temperatures related is that how much of collisions are happening it. If you look it the fluid mass or the liquid mass

whatever the temperature of the fluid I am getting it that is indicating me the how the molecular motions are sustaining that temperatures.

So because of that, it is when you increase this the temperatures the definitely you increase the random motions of these things okay. For liquids, let us look it that change of the pressures will not change that significantly through coefficients of viscosity which represent as a proportionality constant of mass exchange of the molecules or momentum exchange of molecules from one layer to other layers.

If you increase the temperature which manifests to the molecular motions to sustain that temperatures. In that conditions what it will happen it, it will reduce the binding force, the intermolecular binding force between two molecules. Because of that, there will be a decreasing trend of coefficient of viscosity. If you look it at respect of the molecular mass motions and that what is causes us the mass transport and the momentum flux type force.

If it that the conditions if you are looking it then increase of temperatures will reduce the intermolecular forces and the definitely to reduce the decrease trend of the mu values like this case what is shown it here, decreasing trend will be there. That will vary from the liquid to liquid. We will discuss that. Let us talk about the gases where the intermolecular binding force are not that significant.

The molecular motions are much of the higher order as compared to the molecular motions in the liquid. The same way the change of the pressures will not much give a significant change of the dynamic viscosity but the change of the temperatures if I increase the temperature like 20 degree to the 40 degree or the 40 degree to 100 degree centigrade temperatures then there will be a increases the random motions of the molecules.

As it is increasing the lot of motions of the molecules the definitely it does the mass transport, also the moment transport. Because of that, you will see that in a gas as is given here, the viscosity and temperatures, the viscosity increases as the temperatures increases. Whereas is in the liquid, because the temperature increase reduces the internal nuclear forces, you will have a decreasing trend.

So the liquid and gas that what they are the coefficient of the viscosity that is what varied with respect to temperature, one is increasing trend and other is decreasing trend. Any of the gas or the liquids we can find out what is this effect as a the functions. Now if you look at this for the gases already established by with standard of atmospheres that for the Sutherland correlation technique, which gives a relationship between the dynamic viscosity and the temperatures.
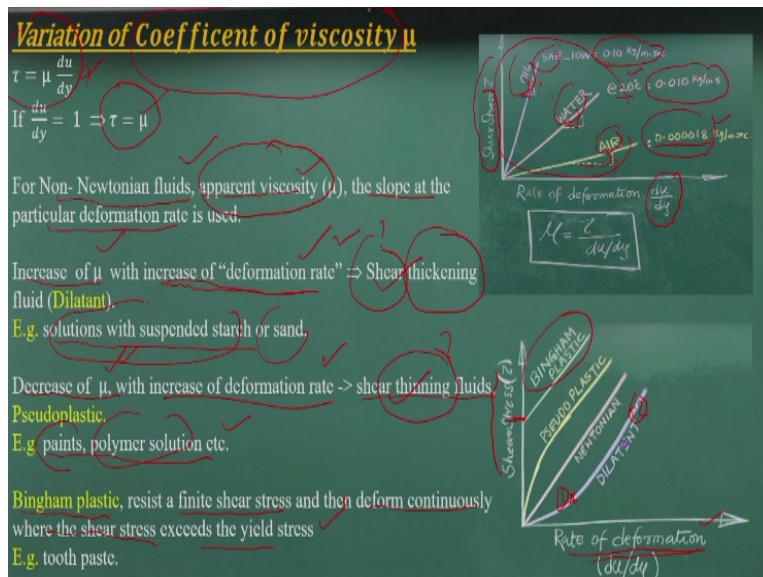
That is what for and a, b are the constant coefficients. These coefficients will be differ from the fluid to gas to gas. And that is what conducting any experiment we can get it what is the value the what is the value of the a and b as we are increasing or decreasing trend with respect to the mu value.

So simple experiment of the gases with different temperatures and using a viscometers we can quantify it, how the dynamic viscosity varies with the temperature. As I said it, it will have a increasing temperature, increasing with the temperatures, but this a, b coefficients will vary from gas to gas.

Similar way for the liquids if you look at that, it will have the 10 to the power the functions and band the c will be the constants and these things what we can compute get it from experimental or any reference book and text book you can see for the different fluids you will have a different value of a, b, c for the gases and these for the liquid and gas we have a different functions as the temperature dependent functions of with a dynamic viscosity and the temperatures and these coefficients will be differ from fluid to fluid.

So based on the gas and the liquid we will decide that which equations you have to follow it what are the coefficient. Mostly it is available in a textbook and the reference book. Let us come to the next one. How does the coefficient of viscosity vary for different fluids.
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Variation of Coefficient of viscosity μ

$\tau = \mu \dfrac{du}{dy}$

If $\dfrac{du}{dy} = 1 \Rightarrow \tau = \mu$

For Non- Newtonian fluids, apparent viscosity (μ), the slope at the particular deformation rate is used.

Increase of μ with increase of "deformation rate" ⇒ Shear thickening fluid (Dilatant).
E.g. solutions with suspended starch or sand.

Decrease of μ, with increase of deformation rate -> shear thinning fluids. Pseudoplastic.
E.g paints, polymer solution etc.

Bingham plastic, resist a finite shear stress and then deform continuously where the shear stress exceeds the yield stress
E.g. tooth paste.

Let us take it same very simple equations what we have defined it tau equal to mu into du by dy the velocity gradient. If it is du by dy and equal to 1 which means the velocity gradient is unit. That means the shear stress what will be equal to the mu. This very interestingly what is giving it that if I have a systems where we can create a velocity gradient equal to 1 the whatever amount of the shear stress that what will be the coefficient of viscosity.

That means, we can easily compute what will be the coefficient of viscosity if you have a just make a du by dy. So this coefficient of viscosity can consider as a force as a shear force when you have the velocity gradient is equal to 1. So if you look at that concept, that means if I plot the rate of deformations, the velocity gradient and the shear stress at these points and if I have a two common fluids like air, water, and the oil.

As you experience is that whenever you drag okay any solid surface on water or air or the oil definitely you need a more force to drag when you are dragging on a oil mass as compared to the water. When you drag that object in a water definitely that what will be a more force required that means it has a more frictional resistance what we get it when you go for the water as compared to the air.

Okay, so that is the very common way every time we experience that when you different fluids give a different drag force that means different amount of frictional resistance what we define in terms of shear resistance here. The shear stress and the

rate of the deformations if I look it and if I look in the slope of the curve it gives me the mu value.

That is for air, if you look at the value is 0.00018. When you talk about the waters at atmospherics and the 20 degree temperatures will be 0.01010 case, but when you come to the engine oils okay which will be 0.10 kg. So if you look it from these figures, they are order you can understand it as how these, the coefficient varies from the fluid to fluid. And these slopes are indicating for us and these are constants.

So they have a straight lines, what we will get it and the slope will give us the coefficient viscosity. The fluids those follow this relationship, this constant the proportionality relationship between the shear stress and the velocity gradient, we call them Newtonian fluids, okay. That group of the fluid flow problems we call Newtonian fluid, where you have the shear stress causing by any shear forces is directly proportional to the velocity gradient or the shear strain rate.

Those fluid flow problems we call the Newtonian fluids. That means what the coefficient of viscosity which is a directly proportionality constant, that does not vary as the rate of deformations are, or the time is changing. So that is a constant. So that is the reason so we have a directly proportional and we can get it a very simplify the shear stress is mu is equal to mu times of the velocity gradient.

Most of the common fluid flow problems also follows Newtonian fluids but some of the case it does not follow the Newtonian fluids. So we call them non-Newtonian fluids or fluid flow problems. In that case what you do it like for examples as given here the rate of deformations and the shear stress if you look at the straight line, what is representing that straight line whatever the if the straight line between these two relationship and in this graph which are Newtonian fluids.

But there are two types the different type of fluids will be there. Like if you look at this pseudoplastic and dilatant okay. In case of the dilatant if you look it the slope of these curves are increasing it okay at rate of deformations. That means if it is a dilatant objects, okay the fluids in that case, as the deformation rate is increasing

where slope of the curve is increasing and that slope of curves we do not call it the viscosity here.

We call apparent viscosity. It is not, this viscosity has a depending upon the deformation rate. So that is the reason we call them as apparent viscosity, which is the slope at the particular differentiation rate what we consider it that what is if it is increasing with the deformation rate then what is happening it the shear thinning process is happening it. You can understand it that more shear force is necessary as you go for more the slope.

That means you need a more shear force to do the same amount of deformations as compared to the point A and the point 2. So shear thinning process are happening it. That means as the rate of deformation increases your the more shear forces is required to do the same deformation one unit of deformations rate as compared to the deformation rate when in the low level.

So this is a thinning process, thickening process happening okay. The more the shear forces we did it. But if you look at this curve which is a pseudoplastics, what it indicates that the slope is decreases as the rate of deformations is increasing trend. That means you need a less shear force as at the higher deformation state as compared to the you look it the deformations rate when you have the low deformation rate you need the less as compared.

So though your slope is the shear force what is necessary is going to decreases it for doing the same amount of deformations at two different rate levels. That means is a decreasing of this dynamic of viscosity with increase of deformation. So thinning process happening okay. And shear thinning fluids happen it and that the process happening the shear thickening and the thinning process happening the more forces.

There are the fluids like the toothpaste and all as you know it the when you apply a force to a toothpaste initially it does not come out. That means it need a limiting of force okay. That limiting force would be there, that what is the a finite shear stress there. After that the flow starts it. That is what it happens if you just squeeze a toothpaste.

You can feel that initially when you apply the low force there is no toothpaste is coming out. But when you apply more and more force after a certain force you look it the toothpaste is coming out. The fluid is starting the flowing it. So responding to the shear force as deformation starts it. So that is the reasons you will have the a limiting finite stress, shear stress after that you will have the shear stress and the rate of the deformations will be there.

This is what Bingham plastic what we talk about, which resist a finite shear stress and deform continuously when shear stress exceeds this yield stress okay. That is the way what you do it we the toothpaste flow mechanisms what is there but in case of pseudo plastics we have a paints, polymer solutions whereas dilatant is basically the solutions with a suspended starch and the sand.

So in these representations what I am talking about that the coefficient of viscosity which is indicates us that in a fluid element, how the deformations takes place between the deformation rate and the shear stress relationship can be linear can be nonlinear.

If it is a nonlinear we talk about non-Newtonian fluids and depending of the slope increasing with respect to the deformation rate we call shear thickening process or thinning process or we have a particular threshold value after that the fluid start deformations, shear deformation thing then we call Bingham plastic.

So the basically you try to understand it that we define a Newtonian fluid, non-Newtonian fluids the coefficient of viscosity, which is directly proportionality constant or we consider as a apparent viscosity when defining the fluid flow problems, if it is a non-Newtonian fluid flow problem. Let us discuss about another properties of the fluid is the surface tension.

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Surface Tension

At the interface of liquid and gas, net force due to imbalance of cohesive (like molecules) and adhesive forces (unlike molecules) as shown in the Figure

The interface surface of the liquid acts like a stretched elastic membrane under tension

The pulling force that causes this tension acts parallel to the surface and is due to the attractive forces between the molecules of the liquid.

The magnitude of this force per unit length is called surface tension

Unit: N/m

Dimension: MT^{-2}

Typical values: Water 0.074 N/m at 20°C with air

Surface tension decreases with the liquid temperature because intermolecular cohesive forces decreases

As the name implies that at the interface of the two fluids or fluid with two liquids or fluid and the gas what it actually happens it if you look at it that way that I have the liquid molecules if you look at this figures okay. I have the liquid molecules and this is the free surface I have the gas. So if I look at what is the intermolecular forces is there, okay like for example if fluid is at rest conditions, the molecules at these points is having the attracting force between the surrounding molecules.

There is a same molecules are there so the cohesive force are acting on this. So this cohesive force are making these fluid molecules in moment, moment considerations. But when you have the at the surface levels, if you look it that these molecules will have the cohesive force the molecular bonding force between the two like molecules and the adhesive force between the gas molecules and the water molecules.

So those will have the adhesive force. See, if you imagine it that if these force, the cohesive force is much larger than the adhesive force what is there. That means the molecules which is at the surface, they are going to have a net imbalance force is going to work it. Like you have a surface when which the top of the molecules they are having a pulling effect of the cohesive forces what is working it or bonding forces is acting on that. So this the surface will act like a elastic membranes.

That means you just stretch it. Give a force, the more, net force is more so that is what is a will be like a stretched elastic membranes with having the tension. So for

example, if we look it that you have a roof is connected with a two pillars and if you apply the force uniformly you will see that there will be tension force will act on that.

So the similar way as you can visualize that when you have the molecules at the surface, they have a net imbalance force between these the cohesive and adhesive. Because of that, that surface will be act like a stretched elastic membrane and under the tensions. That is what will be cause it. So that because of these effects, the force what will be resultant per unit length will define as a surface tension forces okay.

So this is what it happens it. Because of that if you look at the small insects they can walk on the waters, because of the surface tension forces that what is give a the force component because of that small insect can they can walk on the on a water and even if they are having the density is more than that, that is because of the surface tension forces that what resulting surface tension force can result in that ones.

It has a lot of applications of surface tension forces but here I will not give a more emphasis on that and if you look at that as the surface tensions is defined is a force acting per unit length and that is what will be Newton per meters and the at the surface tension the water with air interference 0.07 per Newton per meters. And if you look at the molecular perspective view that as the temperature is going to increase it so you will have a decrease of the cohesive forces.

As the cohesive forces decreases, you can know if the net force is going to decrease. So resulting effect the surface tensions will have a decreasing trend. So we can when you have a interface between the liquid to liquid or the gas to liquid, you will have a the surface will be act like a elastic membranes with a tension forces.

That is what we call the surface tension and it has a dependency with the temperature as increasing of the temperatures that is what reduces the cohesive forces and as a result the surface tension force also decreasing trend.
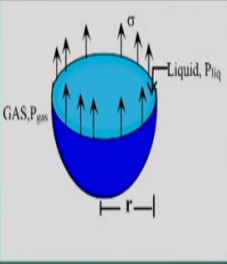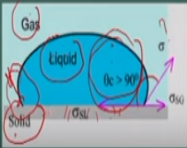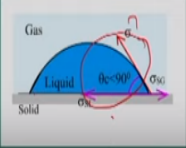**(Refer Slide Time: 1:07:09)**

Surface Tension

Pressure difference at the interface

consider a small spherical droplet of a fluid at rest.

$$(P_{liq} - Pgas)\pi r^2 = \sigma(2\pi r)$$

Angle of Contact

The angle between the solid surface and the tangent to the surface of the liquid at the contact point

If you have the surface tension if you can now there will be a net balancing effect of the force component which results us the pressure difference. Let us consider it is the surface tension is given very simple examples of raindrops okay. Any raindrop if you look at that, if you take that drop and make it two splits. At the interface surface there will be surface tension is working it.

The surface tension force is acting between the water and the air. I have considered a water droplet. So if I consider the just half the this things. If I consider this pressure inside is P liquid and the P gas, the outside is P gas. There will be difference of the pressures because of these tensional forces. And if I just equate the net force acting on this the pressure into the area, that is what is the net force will be acted, there will be a pressure difference will be there.

That what will be the force per unit length and the length is a circumference on which the surface tension is working it is a 2 pi r into the surface tension these force will be created. So similar way we can have a water droplet we can have a soap bubbles we can look it the surface and find out what will be the surface tension force.

This net force the balancing you can result as a pressure difference what it happens it and you can compute the pressure difference if you know the surface tension if I know the radius. Next interesting point is coming is that if a liquids interfacing with the solids whether it will be wet or not wet, the wetting condition or not wetting condition. That what is a interface between the three of things.

Like if you look it there is a interface between liquid to the gas, the liquid the solids. And that what is a at equilibrium at the point of the contact. And that equilibrium force is make a angle of resulting force the contact angles. So the surface tension which will be the gas and the liquid, the liquid and the solid. This net force what is acting it here that makes a angle to that. This is what angle of contact.

So you can look it if you take a liquid and you have the angle of contact more than 80 degrees more than 90 degrees, then this liquid will going to wet this solid surface. Whereas if this angle is less than that, this liquid can come into the solids. So that can come into the solids and can have the wetting front. So very simple way we can find out which are the liquids going to wet the solid surface or not based on the angle of contact.

The mostly this the surface tension the force because of the gas and liquid and the liquid and solid interference. We are not going more details because as you have a more understandings if you are looking for surface tension for mostly these chemical engineering and all but here we will not go more detail here. So with this, let me conclude this lectures two.

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And with the summary is that the very basic equations is that we derive today which is called Newton's laws of viscosities. That what we have look it microscopic and macroscopic point of view, the molecular motion point of view or a deformations of

the fluid element that what we have considered to define the shear stress and proportional to the velocity gradient or shear strain rate.

Then we also discuss is that, how does the viscosity increases or decreases with respect to the temperatures or the pressures. That what we have discussed it. And some of the fluid properties, but we discuss it with respect to the mass we discuss and the weight we discuss the density specific volume, specific gravity, specific rate and the force acting on this interfaces.

That what is a surface tension force as a interactions. I conclude that. With this I conclude this lecture. Thank you.