**Fundamental of Fluid Mechanics for Chemical and Biomedical Engineers**
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**Lecture 5**
**Introductory Concepts 1**

So, in this lecture, we will discuss some basic introductory concepts which are required to understand a fluid mechanics course.

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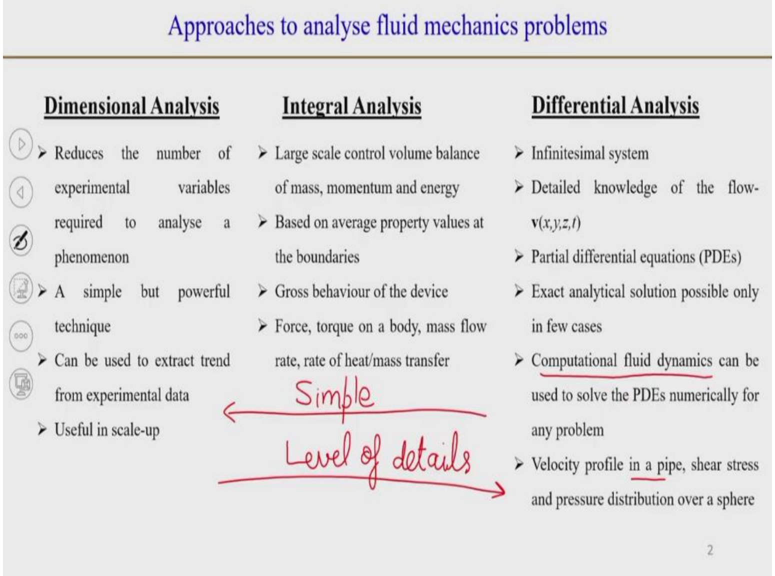


So, first there can be three different approaches to analyze fluid flow problems and these approaches can give us different level of information about fluid flow the different level of detail we can obtain using these approaches. So, the first one is what we call dimensional analysis. So, dimensional analysis is basically what you do is write down all the variables on which a particular dependent variable is dependent upon.

So, for example, when we are looking at force on a sphere that is placed in a stream of fluid, it will depend on the diameter of the sphere, it will depend on the fluid velocity, it will depend on the density and viscosity of the fluid. So, if you want to know or if you want to develop a formula that what is the force on this sphere, so you will need to do a number of experiments to find out the dependence of the force on diameter of the sphere, on velocity of the flow, on the properties of the fluid.

However, if we can combine these, in this approach what we do is combine these variables into dimensionless groups and then finding out the dependence on each variable we can find the dependence of the dimensionless variable consisting of force in this course, in this case it will be a say drag coefficient which is ratio of drag force divided by area 1/2 $\rho u^2$ or $\rho u^2$ that will depend on a Reynolds number which is a combination of ρ u d and μ which is where ρ is density and mu is the viscosity.

So, dimensionless analysis it can reduce our number of experiments significantly. So, it can reduce the number of experimental variables that we require to analyze a phenomena. It is a simple technique we do not know how does a variable depend, what, to what power for example, the drag force depend to what power of diameter but we can group the non-dimensional number and reduce the number of experiments required.

So, we can, once we group into dimensionless parameters using the experimental data we can find the dependence. So, this can be used to extract trends from the experimental data. We can also use it in scaling up; lot of scaling up in engineering is done at least in the first cut it is done using dimensional analysis. Moreover, the beauty of the technique is that it is very simple and you can do some back of the envelope calculations and find out the numbers.

The next approach is what we call Integral Analysis. So integral analysis, in the integral analysis one take a control volume through which the fluid is flowing or the volume, which is our region of interest in which we want to understand the flow behavior. And in this control volume we can apply mass, momentum and energy balance. And we will be able to find for example, the mass flow rate that is passing through this control volume, what is the force on a particular body etc.

So, it gives us the gross behavior, the average behavior or the integral behavior for example, force on the entire sphere if we talk about the problem that we talked about for dimensional analysis. It can give us the torque on the sphere, we can find the mass flow rate if it is a heat transfer or mass transfer problem using the balances, we can find out the rate of heat transfer etc.

Now, the third technique or third approach is what we call differential analysis. So, as the name suggests, we take a infinitesimal or small volume and apply again these principles of mass momentum and energy balance. So, what we end up with is partial differential equations and by solving these partial differential equations, we can get the detailed knowledge of flow fields.

So, we can get velocity field in terms of at every point in the domain, if we are able to solve these equations, but the problem is that these partial differential equations are nonlinear and it is possible to solve them only for some very simple cases. So, exact analytical solution is possible in very few cases. Analytical solution means that when you have formed a differential equation, and if you can integrate and find the functional dependence of velocity on x, y, z and t that is the analytical solution.

But with a lot of development in numerical techniques and powerful computers, to solve the algebraic equations developed from those numerical techniques, one can almost solve the these equations for any kind of complex geometry and this technique is known as Computational Fluid Dynamics or CFD. So, CFD is nothing but solving the partial differential equations governing fluid flow and heat transfer.

So, the technique is very powerful we can get the detailed information about the flow behavior, but it requires of course, the large amount of time to solve these equations etc. So, some examples that you can find the velocity profile in a pipe that at every location in the pipe, what is the velocity or if we talk about the problem, the flow around a sphere. So, what is the pressure distribution or shear stress distribution on the surface of the sphere.

From the dimensional analysis, we could know that on what non dimensional parameter the force depends upon. And the, the integral analysis will give us the force acting on the sphere whereas the differential analysis will give us the force acting on the sphere or the stresses acting on the sphere pressure and shear stress as a function of (r) and as a function of ($\theta$) on the surface of the sphere.

So, if we look at in terms of the detailed information available, we can go through along this direction that as we go from dimensional analysis to integral analysis or differential analysis, level of information or the level of detail, we can find out increases when we go to differential analysis. However, so, this is what we call level of detail, we know more and more about the problem at hand.

On the other hand, if we talk about simplicity and the time required, the dimensional analysis approach is the simplest than integral analysis, differential analysis we have partial differential equations and if we want to solve it numerically, we need more time and effort.

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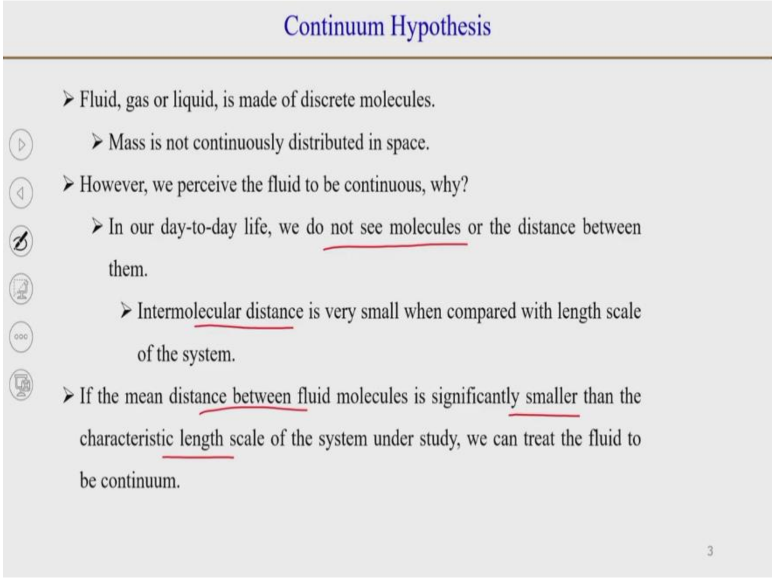


Then, the first assumption that we need to make in this course is what is called Continuum Hypothesis. So, when we look at a fluid, we treat it as a continuum. However, if we know that all the matter they are made up of atoms and molecules. So, a gas or a liquid they are made up of molecules. So, there will be discrete molecules and there will be some vacuum between them there will be nothing between two molecules and these molecules are moving randomly, the order of randomness depend on their state they are liquid, in the liquid state or in the gaseous state.

In the gaseous state, they are free to move more freely whereas, in the liquid state they are relatively in a packed state. So, that means, if we talk about mass because these molecules only have mass. So, the mass is not equally distributed in the space, it is not continuous it is discrete in space, we have number of molecules. If for example, if we talk about gas in this room, there are a number of molecules of gas in this room and they are moving around randomly.

So, the mass is concentrated in these molecules. But, when we perceive these molecules or when we perceive a material or we perceive a fluid, we think about it subconsciously as a continuous medium, because, we do not see these molecules or we when we see water, we do not see that this is, there are water molecules and there is some space between them we see it as a continuous fluid, because we cannot see the space between the molecules or we cannot see the molecules between them.

So, the intermolecular distance or the molecular length scale is very small, when we compare with what we see, if we have a large enough or we have a microscope with which we can look at the molecule then we will be able to see such things. So, the reason why we do not perceive it in our day to day life is because the length scale of the system of the fluid that we see is significantly larger than the distance between these molecules.

Now, that is what we say that if the mean distance between the fluid molecules, it is significantly smaller than the characteristic length scale of the system that we are studying or that we will be studying in this course, then we can treat the fluid to be continuum. So, we will we can treat the fluid to be a continuous fluid, because we will be using lot of calculus etc. in this and all those in which case, we will consider the functions to be continuous. So, if we want to huge the calculus, we need to assume the fluid to be in continuum which is a valid assumption.

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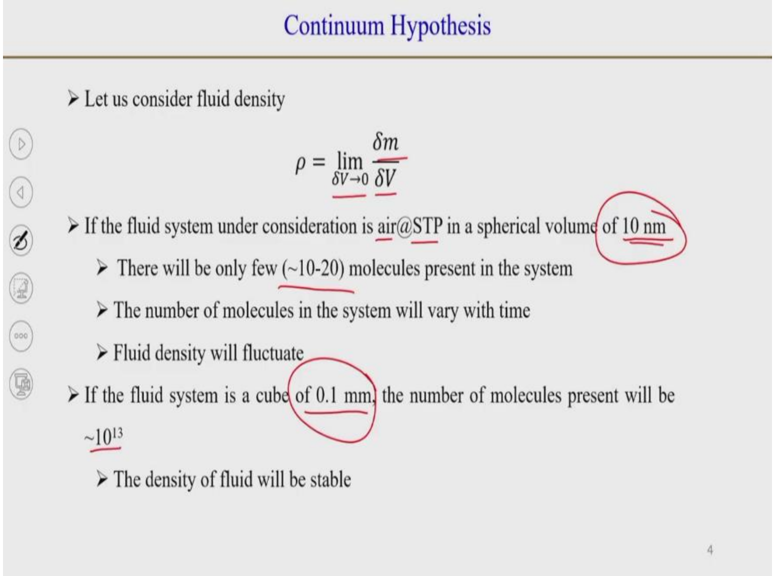


Now, if we go into more detail and think about density of fluid, how do we define the density of fluid because the fluid is made up of molecules. So, if we take as infinitesimal volume, let us say δV. So, in this δV volume, you will have a certain number of molecules and the mass of these molecules is what is δm. So, in the limit a δV approaching to 0 δm, where δm is the mass of molecules present in volume δV, we defined density in this manner that limit δV tends to 0 δm by δV.

Now, if we take this volume, let us say of 10 nanometer diameter sphere, then in this volume if we look at air at standard temperature and pressure, we can find out by simple calculation that the order of number of molecules. So, the number of molecules that will be present will be of the order of 10s, 10-20 molecules will be present in this system. Now, because these molecules in a gas are moving randomly.

So, these molecules sometimes may go out of the boundary of the system and then they can come in. So, let us say if you have 10 molecules in the system and 2 molecules go out at a time you have you are left with 8 molecules, and then suddenly 3 molecules come in and then you have 13 molecules. So, the density will be changing significantly 20 percent, 30 percent change in the density why, because the volume is small and you have only 10-20 molecules.

So, the number of molecules will vary and as a result the density will be varying, the density will fluctuate. Now, if you take a cube of 0.1 mm, so the dimension of your system, you have changed it from 10 raise to the power of minus 8 to 10 raise to the power minus 4, 4 order of magnitude change and the number of molecules present you can make a rough calculation which will be about of the order of 10 raise to the power 13.

So, again there will be some molecules that will be going out that will be coming in and they may be in the order of say 1000 but, because the number of molecules present are 10 raise to the power 13. So, going 1000 molecules here and there will not make much difference to the mass of the molecules. So, the density of the fluid will be stable.

So, that gives us again a picture that if our system under study, the system that will we will take the length scale of the system, if it is large enough, we will be able to treat it as a continuum because we can treat density as a density field it will not be fluctuating. Whereas, if our length scale up the system is small then, we will not be able to do so.

So, this also gives us an idea that what are the numbers that we are looking at that are of the order of few nanometers, we will not be able to assume our system to be in continuum or we cannot assume continuum hypothesis or continuum approximation to be valid. So, most of the problems that we deal with in chemical and biomedical engineering, they are of the scale of millimeters or larger. So, we will be able to use the concept of continuum hypothesis and solve the problems and analyze the problems.

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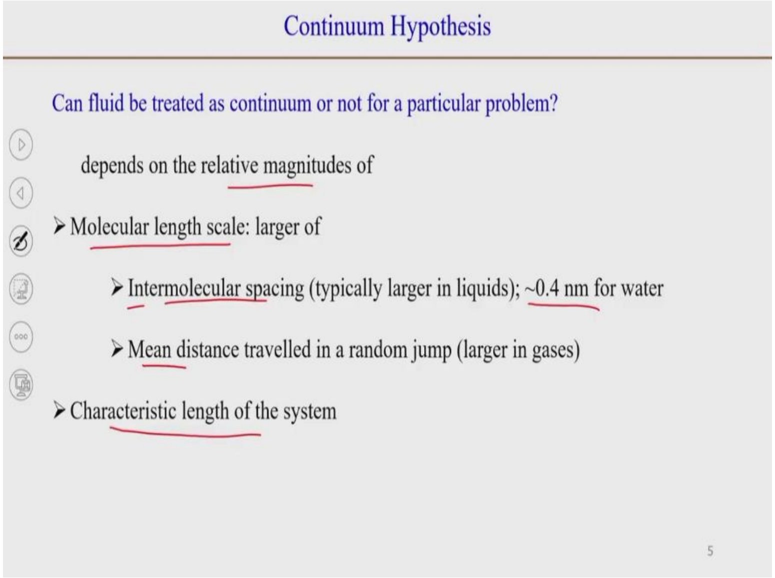


So, to find out some guidelines that can we treat the fluid for a particular problem as continuum or not, it will depend on the relative magnitudes of the two length scale, the one length scale is molecular length scale and another one is what is the characteristic length scale of the system that we are studying. So, molecular length scale, it can be the intermolecular spacing which is let us say center to center distance between two molecules or distance between two molecules or the mean distance travelled in a random jump by a molecule.

So, we will see that out of these two the intramolecular distance and the mean distance or what we call mean free path, out of these two which one is larger. So, when we compare the larger of this molecular length scale out of intermolecular spacing and mean free path and compare it with the correcteristic length scale of the system and see their relative magnitudes, then we can say that we can treat this problem as a continuum, we can assume the fluid to be as a continuum or not.

Now, so, the intermolecular spacing is distance between the molecules because in the liquids, the molecules are not free to move so much. So, in liquids generally the intermolecular spacing will be larger than the mean distance travelled by the molecules in a random jump it will be only a fraction of intermolecular spacing.

So, for liquids it will be the intermolecular spacing which will act as the molecular length scale. And this number will be of the order of say, 1 nanometer, 0.4 nanometer for water or organic liquids of the order of nanometer or less. Now, for gases they, the molecules are free to travel and when the molecules travel the distance, they can travel is more than the intermolecular spacing. So, in the case of gases the molecular length scale will be the mean distance travelled by the molecule, gas molecule in a random jump and this is larger in gases.

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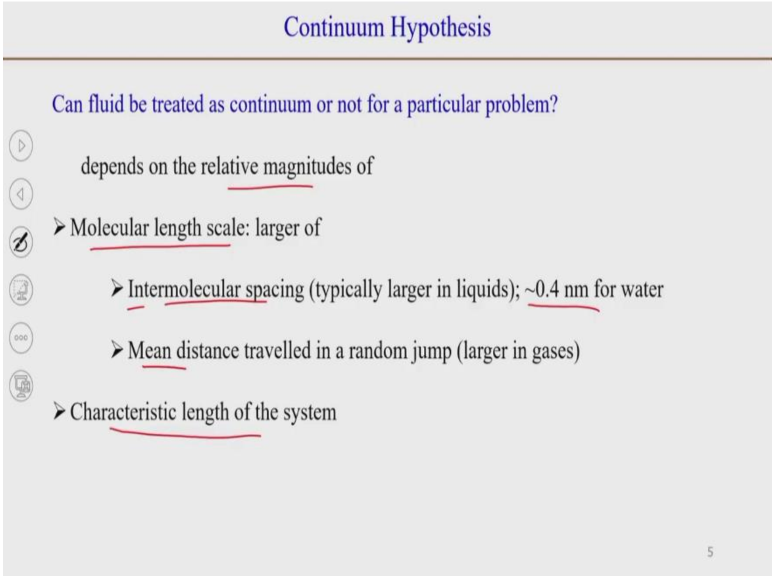


So, we define a non-dimensional number generally it will be gases, where you will see that the continuum hypothesis breaks down because the mean free path can be larger, especially when we talk about gases at low pressure or rarefied gases. So, a number is defined, a non-dimensional number is defined which is known as Knudsen number as the ratio of mean free path and the characteristic length scale of the fluid system.

The characteristic length scale of the fluid we will typically take the smallest characteristic dimension of the fluid system and $\lambda$ is of course, mean free path which is average distance travelled by a molecule between two successive collisions and we can find out the formula for it from kinetic theory of gases, where $k_B$ is the Boltzmann constant, T is temperature, P is pressure, d is the diameter of the molecule.

So, we can calculate the value of $\lambda$ at a particular temperature and pressure for gases and compare it with the system and find out the Knudsen number. Now typically, if the Knudsen number is less than 0.1 that means, if the mean free path is less than one tenth of the characteristic length of the fluid system, we can treat fluid as continuum. In liquid this number, the intermolecular spacing is about 4 nanometers, so 0.4 nanometer is the intermolecular spacing and it is 10 time.

So, 4 nanometer it is a good criteria. For gases, one can take L is greater than 1 micron at ambient conditions. So, greater than a micron or few microns is, we can treat gases as continuum and most of the cases except in microfluidics, we can treat the fluid to be in continuum. In rarefied gases, $\lambda$ can be significantly large.

So, we will need to be careful, but all the things that we deal in this course we do not have rarefied gases. To emerging areas in chemical engineering as well as having lots of applications in biomedical engineering is microfluidics and Nano fluidics and they deal with of course, with fluids. So, one need to understand the fluid flow behavior in those areas.

So, every time you look at a problem in micro and Nano fluidics one should ask himself or herself a question is the continuum hypothesis valid in this case, and then look at further and analyze the problem or apply the concept of fluid mechanics there.

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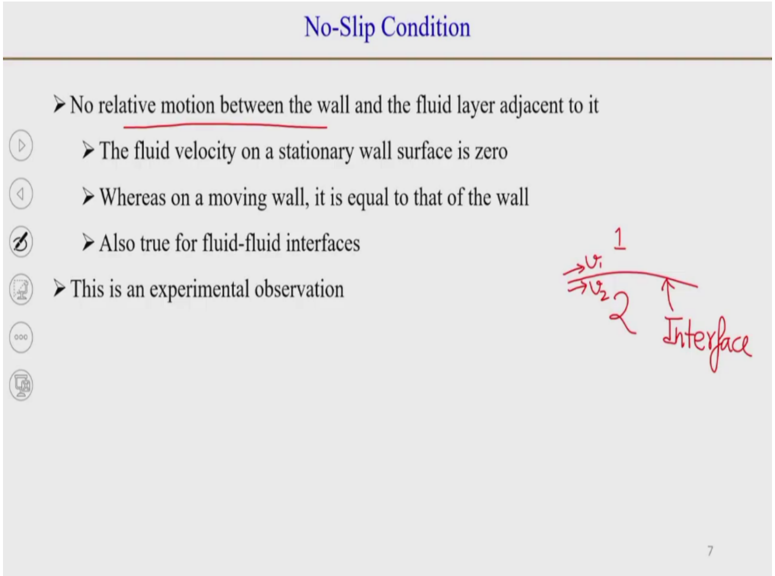


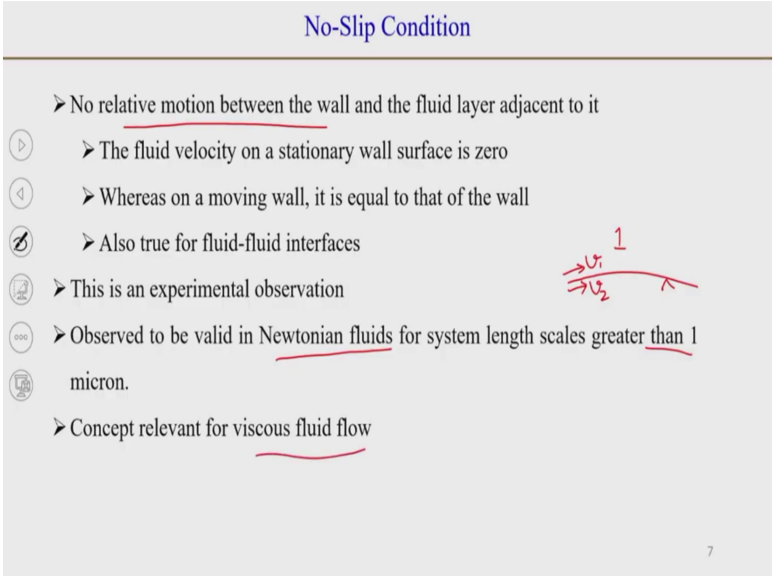

So, a related concept is what is called No-Slip Condition. So, we would have studied about viscosity and we will later study in this course about viscosity. So, viscosity is the property of fluid because of which the fluid opposes the relative motion between to its adjacent layers. Now, we are talking about the adjacent layers in the fluid itself. What if, what happens when the fluid is in contact with a solid wall or a solid.

Now, it has been observed from experiments that near the wall there is no relative motion between the wall and the fluid layer. So, this is called no slip conditions that means, there is no slip between the wall, solid wall and the fluid layer that is adjacent to it. So, if the wall is stationary, the fluid that is in contact with the wall will be having zero velocity, if the wall is moving with a velocity say, 1 m/s then the fluid next to it will move with the velocity 1m/s.

So, the same concept is also true at fluid-fluid interfaces. So, for example, if you are looking at a gas liquid interface or a liquid-liquid interface, so liquid 1 and liquid 2 or fluid 1 and fluid 2 to talk about in general and this is the interface. So, you will see that the fluid velocity at the interface is continuous that means, the velocity of the fluid 1 at the interface will be equal to velocity of the fluid 2 at the interface.

So, $V_1$ is equal to $V_2$ the normal velocity will of course, depend if there is a phase change or not so there is a mass transfer or not, but when we looking at when we are looking at the tangential velocity, the tangential velocity at the interface will be equal to the interface velocity, fluid velocity 1 and fluid velocity 2 both will be equal at the interface.

So, this observation is there for more than 100 years and so, and later on it has been verified experimentally and it has been observed to be valid in Newtonian fluids. So, it has been observed to be valid for Newtonian fluids for system length scales larger than 1 micron. So, generally what happens if you have a surface, on the surface there will always be because of the, the way it is being made there will be some roughness and this roughness even if you try to be make it smooth of the order of microns or few nanometers.

So, when you talk about large fluids, the roughness is very small, but in micro systems for example, where the channel size is 1 micron or so, there might be some air trapped and the no slip boundary condition may not be valid when you are looking at the system velocity. So, in any case, we can use no-slip boundary condition for all the cases when we talk about problems viscous fluid flow problems in this course.

But one need to be careful or one need to again ask a question, is no slip boundary condition valid in the micro system that I am studying. Also note that the concept is relevant only for viscous fluid flow, when we talk about inviscid flow then the problem of no-slip or the question of no slip boundary condition does not come into picture.

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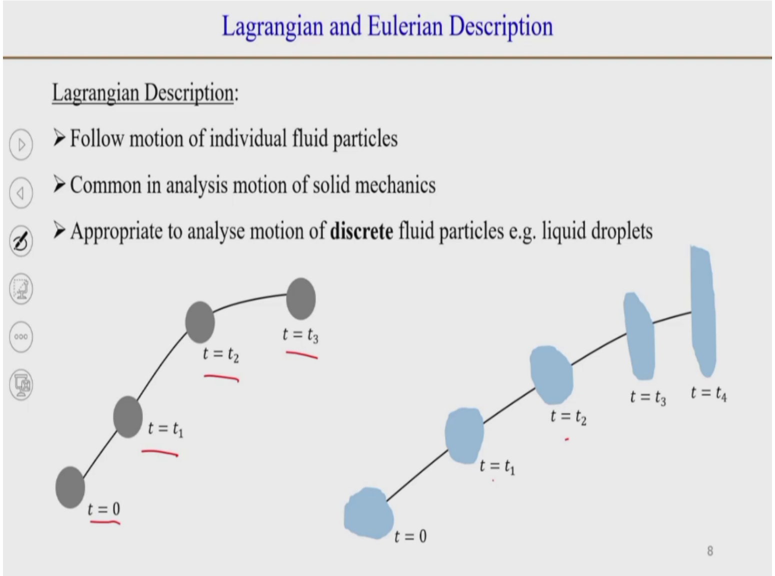


Now, there is another concept which we call Lagrangian and Eulerian description and that these two words we will be using frequently in the course. So, it is important to understand what do these words mean. Now, let us look at Lagrangian description first, because that might be more familiar to us. So, when we talk about analyzing fluid flow, analyzing problems in say, solid mechanics.

So, we take a body and find out the force on it and find the acceleration, from the acceleration we find the velocity or the displacement. So, we are following the motion of this particular rigid body. So, we are interested about the motion of a particular body and we follow its motion and this is what is called Lagrangian description. Now, replace this rigid body with the, with the fluid particle.

So, if we take a fluid particle or a group of fluid particles and follow its motion, then this is called Lagrangian description and this is common in solid mechanics. So, this is a conceptualized picture here you see a particle at time t is equal to 0 then where it has gone to time $t_1$, $t_2$ and $t_3$. Now, we can do the same for fluid particles that let us say a some droplet or some bubble it is at time t is equal to 0 at one place and then where it is going at time t to time $t_1$, $t_2$, $t_3$, $t_4$, so on.

But, most of the time what we are interested in the flow in a particular region. For example, flow inside a reactor, we are not concerned with what happened to a fluid particle that came in the reactor now, what happened to it before or what will happen to it when it goes out, we are looking at or we want to know and understand the fluid flow behavior inside a reactor and we are interested in the velocity of the fluid molecules that are present inside the reactor at a particular instant of time.

So, we are interested in a particular region and the fluid that is present there we are not generally interested in fluid flow problems, the motion of individual fluid particles. Moreover, it is difficult to analyze the motion of individual fluid particles there because it is not like a rigid body.

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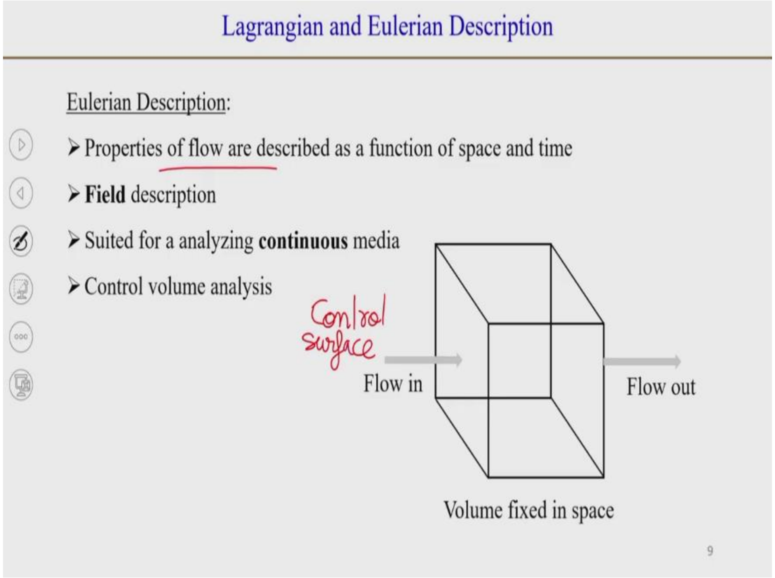


So, the approach that has been developed to analyze or study fluid flow problem is what we call it Eulerian Description. So, in place of Lagrangian description, where we follow the motion of individual fluid particles in Eulerian description what is done is, we take a control volume and in this control volume we describe the properties of flow the properties, by properties we mean the velocity, the stress, the pressure etc. as a function of time and space.

So, t, x, y, z, in the Cartesian coordinate system. So, velocity or stress or pressure or density everything we can give a field description, field description means it is a function of time and space. So, this is suited for analyzing a continuous media what we do a, we take a control volume. So, we can take a control volume which is fixed in space and analyze the flow coming in and flow going out.

This control volume may or may not be there physically it is, it might be just an imaginary control volume for our analysis purpose. And we look at the flow coming in, flow going out the control volume may be, it may be fixed or its boundaries may be rigid. The boundaries of the control volume or the outer surface of the control volume is what is called control surface.

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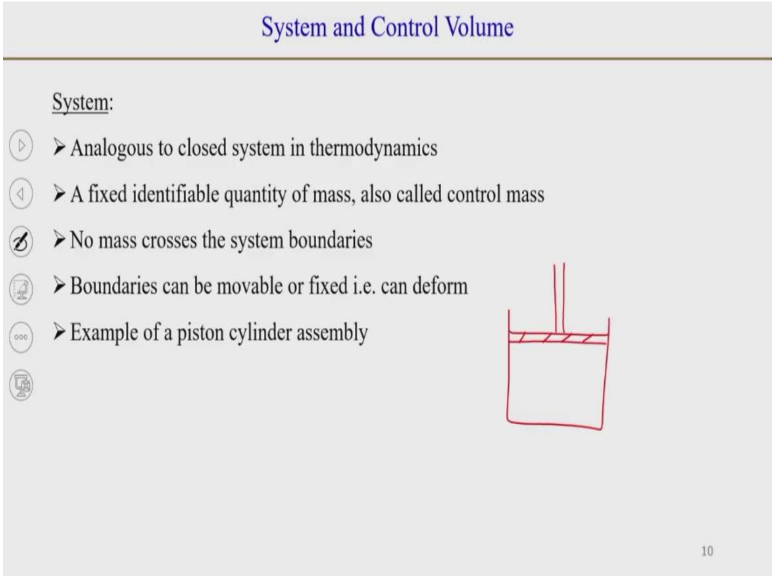


So, let us look at the system and control volume concept and as we can just guess that control volume is related to Eulerian description where system is generally related to Lagrangian description.

So, system is analogous to closed system in thermodynamics. So, you might have studied thermodynamics and in thermodynamics we talk about isolated system, closed system and open system. Isolated systems are one in which neither heat can come in and, nor any mass can come in. So, isolated system is the system which does not exchange heat as well as mass from its surroundings.

Whereas, closed system is one which can exchange heat from its surroundings, but it cannot exchange mass from its surroundings. And open system is which can exchange heat as well as mass, as well as mass from its surroundings. So, we can say that the system is analogous to a closed system in thermodynamics that mean the mass cannot come it from the system boundaries, it is also known as control mass.

So, it is basically when the mass cannot come in or go out. So, during that entire analysis the mass is fixed, you have a certain number of molecules fixed and no mass can cross the boundaries of the system. So, these boundaries again can be fixed or it can be movable. So, you can think of a balloon which is filled with air and it is airtight. So, no air can come in and go out from this balloon, but this balloon can deform.

So, again that can be an example of a system. Or you can think of a piston cylinder assembly, that you have a cylinder on top of which there is a piston. Now, because of the heat are given to the system or the heat exchange, the piston can move up or down the gas may expand, but the mass of gas that is present in the system that remains constant, it does not exchange any gas from its surroundings.

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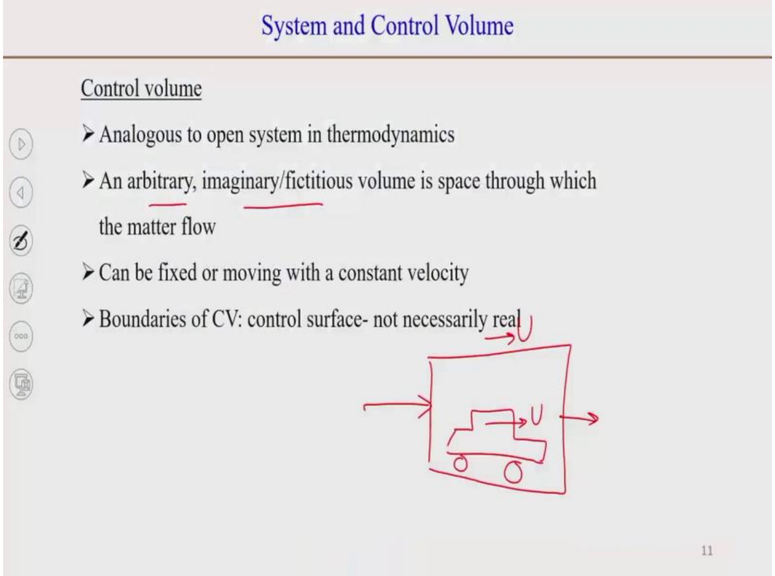


Now, coming to control volume. So, control volume is analogous to open system that the mass of fluid can come in and can go out. So, the fluid or the material that is present in the system that can change with time. You can or we imagine in a arbitrary imaginary fictitious volume in a space through which the matter floats. So, you can consider a control volume and through which the fluid comes in and goes out you can have the semi open system.

So, for example, the fluid can through just coming in or the fluid is just going out but eventually it will be filled up or it will be emptied out of the from the fluid and this control volume it may be fixed or it may be moving with a constant velocity. So, for example, when we talk about a moving control volume, if you want to analyze the motion of a car and the force on a car, then you are interested in the fluid flow behavior surrounding this car.

So, it will be convenient to consider a control volume which is. So, if this car is moving with the velocity U you can consider a control volume which also move with the velocity U with the car or if you want to analyze the drag and lift on an airplane you will consider a control volume which is moving with the velocity of the airplane surrounding it. So, this control volume can be moving or it can be fixed.

Of course, the boundaries may not be real for example, around the car when we want to analyze the fluid flow problem, we will consider a region around the car which where the fluid flow is significantly affected because of the presence of this car.

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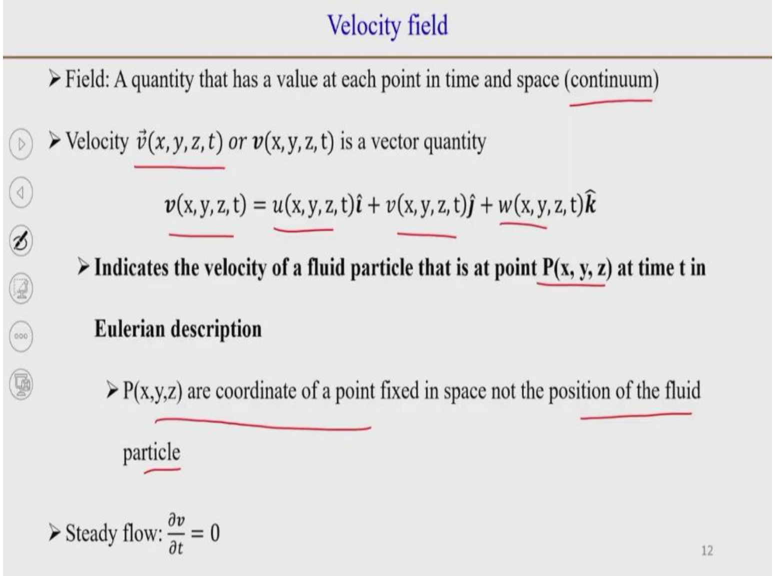


So, as we said that in the Eulerian system, we have a field description of the variables. So, for example, when we talk about density of the fluid, so density of the fluid will be a function of time and space. So, ρ is a function of x, y, z and t and the ρ when we talk about ρ it will represent the density at point having coordinates x, y, z at time t. The density may change at this point with time or the density at two points may be different at same time.

So, we will use very frequently the velocity field because, in this course, what we are going to use or all the analysis that we will be doing will be based on Eulerian description. So, where we will use the field description of the variables and one of the very common because we are interested in fluid flow. So, fluid velocity is one of the common variables that we will be talking about.

So, velocity field when we talk about, but before that the field is just a quantity which has a value at each point in time and space. So that means, we prepared the field for it when we talk about, when we talked about continuum description. So, the field description is valid only when we are talking about continuum because we can treat our fluid as continuum. So, we can give a field description there and at each and every point the variable or has a value.

So, in this case velocity has value. Now velocity, so we can define velocity as vector v at as a function of x, y, z, t it is a vector quantity. Now, in Cartesian coordinate system we can have its component in terms of u, v and w which are components of velocity along x, y and z directions. Note that they are velocity, the velocity is along x, y and z direction, but that does not mean that u cannot be a function of y and z.

So, the x component of velocity is u, but it can vary along y and z directions. Of course, it can all the components that can vary with time. So, it is important to remember and understand what does this represent or what does this indicate, the velocity this gives the velocity of a fluid particle that is present at point x, y, z at time t.

So, it is not the velocity of a fluid particle, but it is the velocity at of a particle that is present at point x, y, z at time t. If that particle goes away at time t is equal to a $t_2$ at a different location then its velocity, the velocity of the particle will be represented by the velocity field at that point, let us say the coordinates of the point are $x_2$, $y_2$, $z_2$. So, $x_2$, $y_2$, $z_2$ at time $t_2$ will be the velocity v at $x_2$, $y_2$, $z_2$ at time $t_2$ will be the velocity of the fluid particle at time $t_2$.

So, it represents not the velocity of any particular fluid particle, but it represents the velocity of a fluid particle that it, that is present at that point of time at that location. So, this we need to remember when we are solving problems or looking at derivations.

So, of course, when we talk about x, y, z, they are coordinates of a point and not the position of a fluid particle. And when the velocity is when the flow is steady, then $\frac{\partial v}{\partial t} = 0$. So, we need to remember when the flow is steady that means, the velocity does not change with time a fluid particle will have a velocity and its position will be changing with time.

But, what does this mean that the when the fluid is steady that means, at a particular point, the velocity does not change with time. So, if you take a point having coordinates say 1, 1, 1 and the velocity if there at is, if there is 1 m/s in a steady flow, then the velocity for all times will remain 1 m/s if the flow is steady. But at the same time at a coordinate say, x, y, z 2, 2, 2.

So, having coordinates 2, 2, 2 the velocity may be point 5 m/s. So, at for a steady flow you can have different velocities at two different locations. And when the fluid particle goes from point 1 to point 2 its velocity will change the velocity of the fluid particle will change from 1 m/s to 0.5 m/s when it goes from point 1 to point 2.

But the velocity, so when we say steady flow, it is not the velocity of the fluid particle that we are talking about, it is the velocity of the fluid particle that is present at a particular location that we are talking about. So, that is velocity field.

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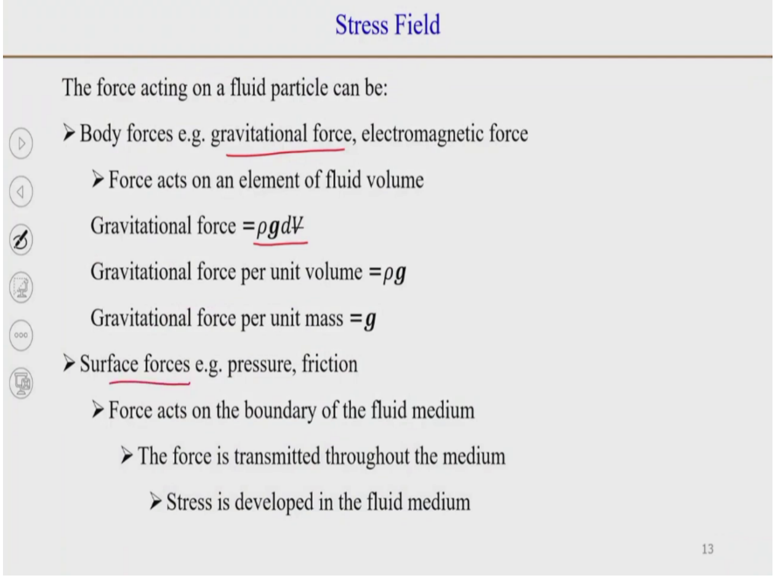


Now, another important field is because we are talking about generally the mechanics here or the dynamics. So, when we talk about dynamics, we are interested in what is the force on a fluid because of the flow or what is the flow because of a force. So, the two important quantities are velocity which we just looked at and another important field is force field.

So generally, force field we will be talking about, there are two kinds of forces we can have or we generally deal with in fluids; one is body forces and another one is surface forces. So, the forces, body force that we talk about can be the example, very common example is the gravitational force or electromagnetic force.

So, since in this course, we will not be taking examples or we will not be talking about electromagnetic forces, the very common force that we will encounter in this course, which is a body forces, gravitational force. Now, this gravitational force it acts on the entire fluid. So, it will act on the surface of the fluid, it will act at a point at a depth 1 meter, at a depth 1.5 meter.

Everywhere in the fluid the force will be acting. And this gravitational force we can give by an expression ρ gdv if you have a fluid volume of dv then the magnitude of this force will be ρ gdv where, ρ is density g is the acceleration due to gravity, it is a vector and dv is the volume of the fluid element. So, we can give gravitational force per unit volume if you take a infinitesimal volume in which you can consider or you can assume the force to be constant.

So, you can define this for infinitesimal analysis, the gravitational force per unit volume ρ ρg and because it is infinitesimal volume, so you can also say that gravitational force per unit mass is equal to g. Now, when we come to surface forces, for example, the very common surface force is pressure force which acts on the surface of the fluid or viscous forces or frictional forces when we talk about solids.

So, pressure and frictional forces or viscous forces are two very common surface forces. So, when we have surface forces on a body, then this force acts on the surface or boundary of the fluid medium or boundary of the material that we are talking about. In solids for example, if you put a force on it, on the surface of it, if you put a pressure on it that pressure will be distributed in the, in the internal medium of the fluid or into the internal medium of the solid.

And to represent this that how this pressure is distributed inside the fluid medium or inside the solid medium we, we talk about stresses. So, we say that the stress have been developed in the fluid medium or in the solid medium inside the solid. So, the concept of stress comes into picture when we are talking about that how the surface forces are distributed internally in a fluid medium.

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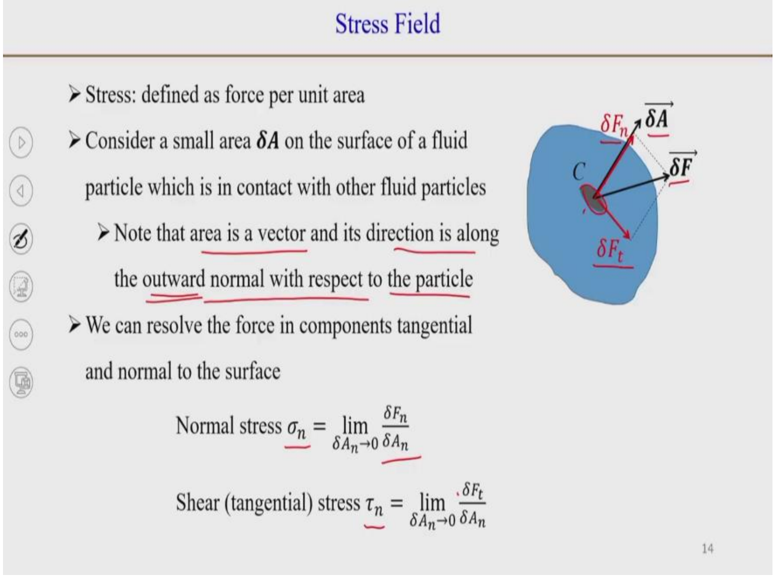


So, very simply when we talk about stress it is defined as force per unit area. So, then the question comes area of what. So, if we consider a small area on a surface of a fluid and in this fluid of particle or small fluid which is in contact with other fluid, we take a surface there and a small area, let us say the magnitude of this area is δA and the direction which is in, is normal to it.

So, remember that area, probably you already know that area is a vector and its direction will be the direction of area because area can be oriented, any surface can be oriented in different directions or in a surface itself you can have a different orientations. For example, if you look at this pointer, you have the area is not a plane. So, at this point the it will be oriented, the normal will be oriented normal to it whereas, at this point it will be somewhere in this direction, at this point it will be along this direction.

So, the area is a vector and its direction is normal with respect to the particle or normal with respect to the surface and it is outward normal. So, when you talk about surface the area is normal to it now, normal can have two directions; in this direction or pointing the other direction. So, to guide this we are saying that it is outward with respect to the particle. So, if you take a fluid particle normal to it is what is the direction of the area vector.

Now, on a surface which you take internally on a fluid, you can of course have a force, if you are talking about this surface, then the normal will be along this direction, if you are talking about this plane, then the area will be along this direction towards pointing towards me. So, you have a small area at point C, the area is δA and let us say the force acting at this point is δF and this is the direction of the force.

So, we can resolve this force in two components δF can be resolved as a force which is in the direction of normal, which we call $\delta F_n$ or the normal component of force and $\delta F_t$ or the tangential component of force, the tangential component of force we also call it shear force. So, the normal stress is defined as δF by $\delta/A_n$ in the limit $\delta A_n$ approaching 0.

So, the normal force divided by the area is what is normal stress and it is represented often with the symbol σ. The tangential stress or shear stress is defined as $\tau_n$. So, it is being represented with the symbol $\tau\ \delta F_t$ or the tangential force divided by the area of the surface is the tangential stress. So, you have two directions coming into picture here that the force itself will be acting in a particular direction it may be a normal stress or it can be a tangential stress.

So, when we talk about in general for stress, we have two directions involved; the direction of the force and the direction of the area normal. So, that is why when we talked about tensors, we said that we will need two directions to represent second order tensor. So, stress as a second order tensor because we need two directions to define a stress what is the direction in which the force is acting and what is the direction of the area normal at that point?

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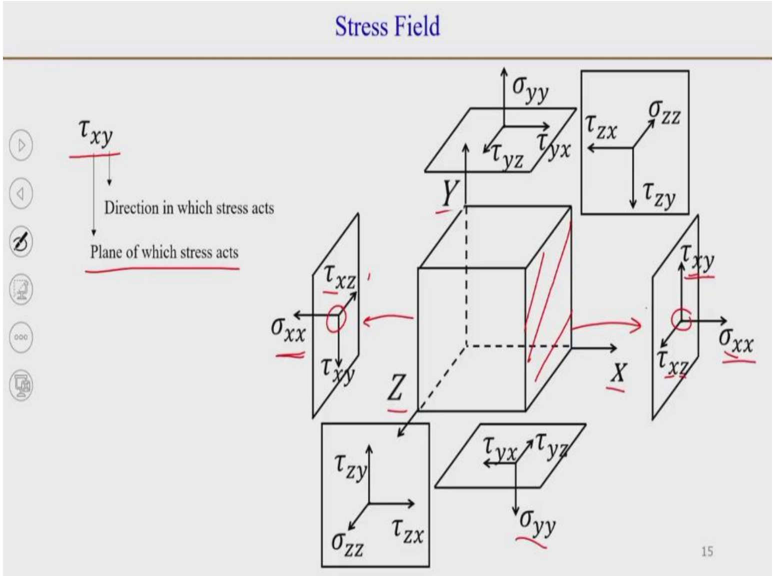


So, when we represent a stress, we have generally two subscript to it. So, in this case $\tau_{xy}$ , the first subscript conventionally represents the plane on which this stress acts. So, in this case x represents the x direction. So, the force is acting that means the force is acting on the x plane and y direction is the direction in which the stress or in which the force acts.

Now, if we take a point and in the rectangular coordinate system, we can have six planes on which we can define stresses in the Cartesian or rectangular coordinate system. So, these six planes, the directions are shown here X direction, Z direction and Y direction. So, if we look at this X plane first which is shown here.

So, on this plane the normal to the plane is along X direction, so you see that all the stresses, there can be three components of the stresses the first subscript is x. And in this you can have three directions of force on this plane X direction, Y direction and Z direction. Because the area normal is pointing in the X direction. So, the force in X direction will be normal stress so it is named as $\sigma_{xx}$.

Other two directions the force is or the stresses and y and z directions they are they will be shear stresses. So, $\tau_{xy}$ is the force on this X plane acting along y direction whereas the third component $\tau_{xz}$is forced on this X plane acting on Z direction. So, this is you can say the positive X plane if you look at the negative X plane on the other side of it.

So, in this case the area vector will be pointing outward or in the negative X direction and the force will be or the normal stress $\sigma_{xx}$ $\tau_{xz}$is the stress on this X surface acting in the negative Z direction, $\tau_{xy}$ in the negative Y direction. If you look at the directions at this plane and this plane which are in the opposite, so the stresses are acting $\sigma_{xx}$ and $\sigma_{xx}$ they are acting in the positive and negative X direction. Similarly, the $\tau_{xy}$ are acting in the opposite direction on the two surfaces and same for $\tau_{xz}$.

So, on these two opposite surfaces, the direction of the stresses they are opposite and the same will be true for other surfaces. So, for example, if we take a Y surface where the area normal is in the negative Y direction you have $\sigma_{yy}$ normal stress, $\tau_{yx}$ the stress acting on the negative Y direction, sorry on the negative X direction and $\tau_{yz}$ as stress acting on the negative yz direction or negative Z direction. So, this way you can represent the stresses at a point.

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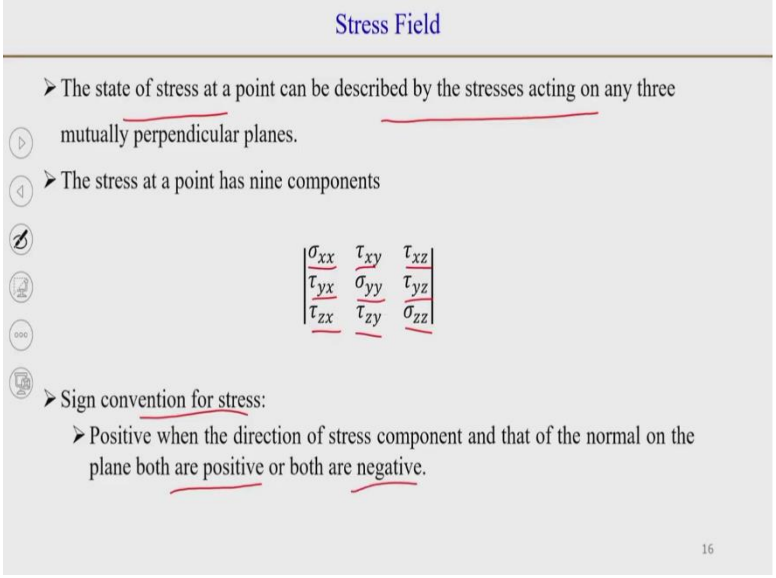


Now, because stresses when we talk about and it is inside the fluid, so we can have any, because we need to just imagine a surface and we can assume any surface. So, the orientation of the surface can be different and of course, the stresses that one can get will be different. But the good thing is that we can define the condition of a stress at a point it can be shown but we will not show here I think it is generally done in solid mechanics courses.

If you have taken a solid mechanics course or you are going to take a solid mechanics course, you will study it in detail and you will see the proof of this, that the state of stress at a point, it can be described by stresses acting on any three mutually perpendicular planes and because, we will be generally working with Cartesian coordinate systems, so we will be talking about the stresses on X, Y and Z planes.

And when we will be working with cylindrical coordinate system, so we will be talking about r θ and z plane. So, stress if we combine all the components that we saw in the previous slide, we will have three normal stresses $\tau_x$, sorry $\sigma_{xx}$, $\sigma_{yy}$ and $\sigma_{zz}$ and six shear stresses. So, $\tau_{xy}$, $\tau_{xz}$, $\tau_{yx}$, $\tau_{yz}$, $\tau_{zx}$and $\tau_{zy}$.

So, in all we will have nine components and these nine components comes because you have three directions for the normals to the plane or three directions of the area, and three directions of the force, so three multiplied by three, you will have nine combinations and that is why you have nine components of a stress. Now, sign convention of stress.

So, it is positive when the direction of his stress component and that of the normal on the plane if both are positive, then we will take this stress to be positive, if both are negative then also, we will consider the stress to be positive. If one of them is positive one of them is negative, then we will consider or we will say that the stress is negative.

So, in this class, we have looked at quite a few basic concepts which built up the foundation for this course. We have looked at the continuum hypothesis, which is the first approximation that we need to make. We have looked at what is Lagrangian and Eulerian description and a related concept, what is system and control volume. And then we have looked at what is velocity field and what is a stress field. And we have looked at that how we define a stress. So, we will stop here. Thank you.