Fundamentals of Compressible Flow
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Module – 01
Review Concepts of Fluid Mechanics and Thermodynamics
Lecture – 01
Review Concepts of Fluid Mechanics and Thermodynamics - I

I welcome you all to this course, Fundamentals of Compressible Flow. Now, we were in the 1st module 1 which is essentially contents the topics Review of Concepts of Fluid Mechanics and Thermodynamics.

So, essentially at UG level entire portion of this fluid mechanics and thermodynamic courses has been covered, but however, since it is a advanced course on compressible flow it is now a customary to revisit the contents of some of the important contents that we are going to use in this course.

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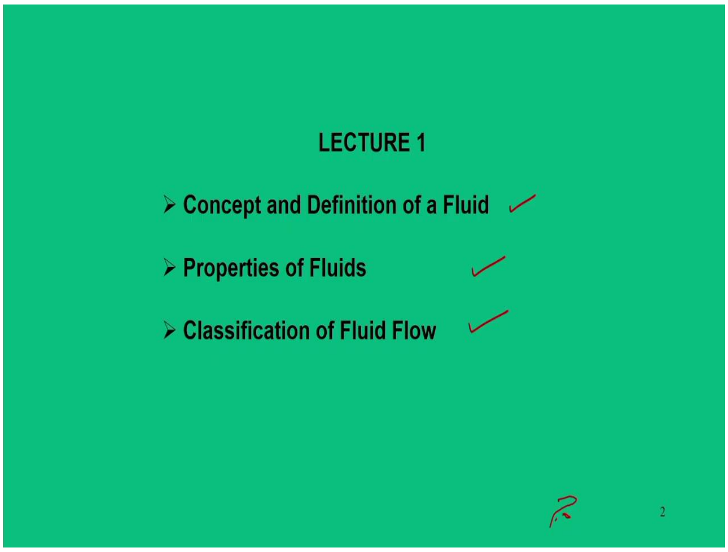

Now, in this lecture we will concentrate on three important aspects; first is concept and definition of fluids; second is properties of fluids and third is classifications of fluid flow. So, essentially this course is about fluids so, which contents mostly liquids and gases and our main focus would be mostly on gases. So, based on that, we are going to discuss about the properties that are mostly important for the gases.

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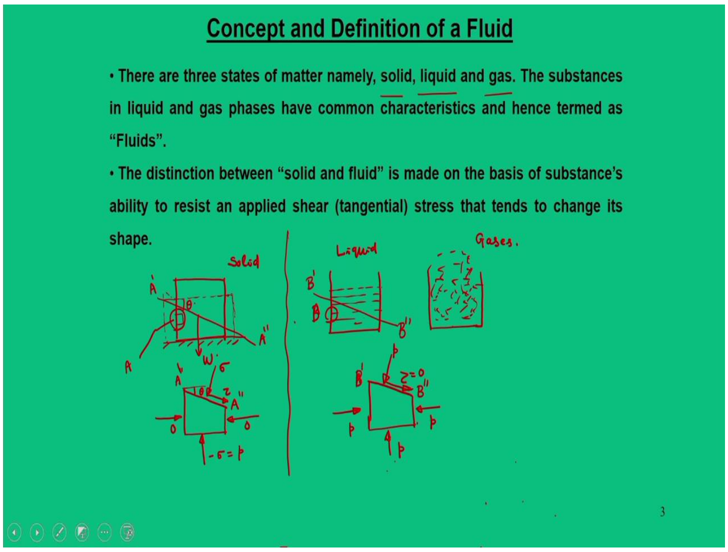

The next part is the first part or what we say is the concept and definition of fluids, but before you go for those definition of fluids, it is the most important concept of matter that exist in three different states, so that is namely solid, liquid and gas. So, the substances that are in liquid and gas phase they have a common characteristics and they are called as fluids.

But, however, there is essentially catch between the solids and liquids and we have a very fundamental scientific definition for it. So, which means, which is the essentially the ability of the any substance to resist the shear.

So, start this things, let me explain the way we define the scientifically the definition of a solid. So, we can imagine a solid block is being placed on a surface and in a similar way we can also see there is a container having a liquid and same container or similar container with gases in it. So, these gases are spread all around the container above or within it.

So, what the basic philosophy of solid and this we say solid and this we say liquid and this we say gases. So, when you actually see the scientific definition for this what has been done is that all these substances they have their own weights and because of their own weights the typical solid blocks is inherently a kind of a compressive compression at some point some location which we say this and its weight is always acting downwards because of this, any point on this solid block is inherently experiences a kind of stress or a kind of load onto it.

And, in fact, this when you actually put at this cross-section for this when you put this, then typically it looks in the manner that same point if you take any cross-section like this A-A or A`-A`` and this is at an angle θ to the horizontal. Then what we see is for solids that this solid block is a kind of a compressive load and a shearing load at that surface. And, all other side surfaces it experiences there is no force and from the bottom this there is a compressive load and that is nothing, but the pressure acting from the bottom surface.

So, this is what we see at any locations or any location at the cross-section location at point A and making a cross-section A` and A``; in a similar philosophy or similar equations if you can draw the similar story here, then what we see for these liquids and gases it is something like a structure in which all the surfaces except the inclined surfaces, they experience a pressure which acts on this fluid element at that locations.

But, in this inclined location what you see I will say B`-B``. So, this turns out to be a. So, here instead of stress we experience a pressure and, but we have a shear stress which is zero in this case since the liquid and the gases they are at rest. So, this is the basically scientific definition that tells a basic distinction between solid and fluid on the basic of substances ability to resist the applied shear.

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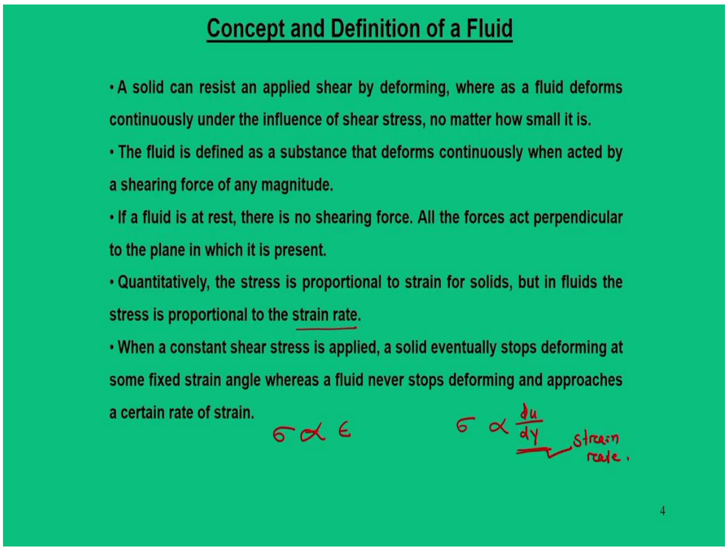

Next is the solid can resist the applied shear by deforming whereas, the fluid deforms continuously under the influence of shear stress, no matter how it is small. The fluid is also defined as a substance that deforms continuously when acted upon a shear stress or shear force of any magnitude.

Now, when as I told earlier when the fluid is at rest there is no shearing force and all the forces are perpendicular to the plane due to which in which it is present. Now, for solids the stress is directly proportional to strain and for fluids the stress is proportional to the strain rate.

So, typically we say σ which is directly proportional to strain that is for solids and for fluids this stress is proportional to a another factor which is called as strain rate and then down the line we will say this strain rate as $\frac{du}{dy}$. We will define this; this is termed as strain rate. The when a constant stress is applied the solid eventually deforms and deforms at a fixed strain angle whereas, fluid never stops deforming and approaches a certain strain.

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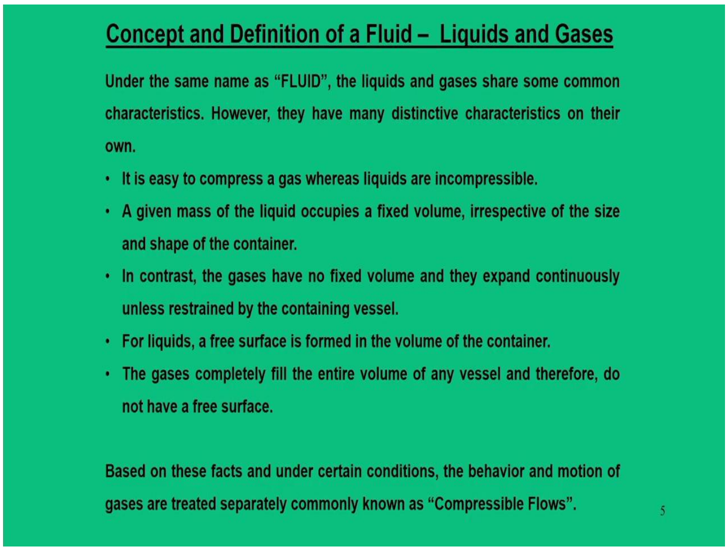

The next fundamental definition that goes is that after having the definition between solid and fluid, then we will talk about only on fluids that essentially constitutes liquids and gases. So, as we say the as you know that liquids and gases they resemble a common behaviour however, there are some distinctions so, which we can; which we can characterise under certain conditions.

So, first fundamental difference is that it is easy to compress a gas whereas; liquids are inherently treated as incompressible. A given mass of liquid occupies a fixed volume and irrespective of size and shape of the container whereas, gases have no fixed volume and they expand continuously unless restrained by the vessel.

So, as we say as it is known that liquids contains a free surface whereas, the gases are occupies the entire volume of the vessel. And, but our main focus in this course will be mostly on gases because these gases are compressible in nature.

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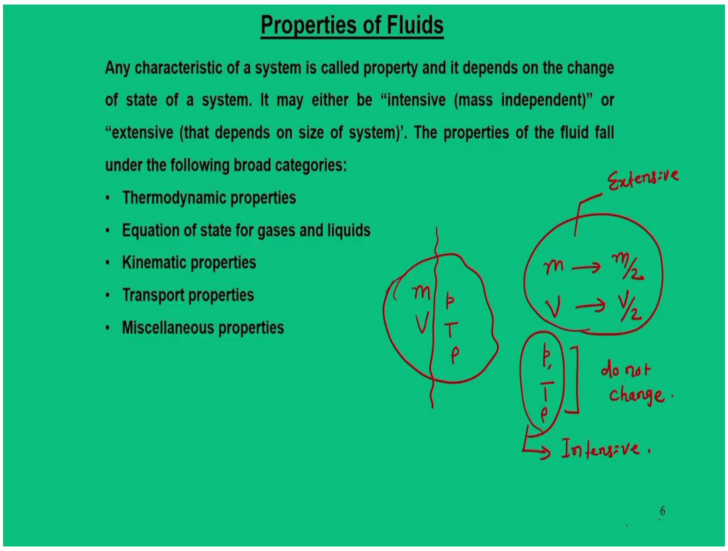

Now, moving back to the this the next part of this lecture, which is properties of the fluids. So, the thermodynamic definition of the property of a fluid means it is a characteristics of the systems that depends on the state of a system. So, these properties may be intensive which is mass independent or extensive with that depends on the size of the system.

So, a classical example for this type of intensive and extensive properties is given. For example, if you have a kind of a container and we there are it has certain mass it contains certain mass of any gas and it has a volume V and it inside this the properties are defined by pressure, temperature and density. So, the for example, if you make this things equally half. So, then the what is going to change in this process?

So, your m becomes half, volume becomes half, but pressure, temperature, density do not change. So, which says that these mass and volume they are extensive properties, pressure, temperature and density they are treated as intensive properties. So, likewise this will apply for any kind of properties for which we can make this kind of distinctions.

Now, in this category of properties of fluids we will talk about the following properties that is thermodynamic properties and equation of state typically for gases, kinematic properties, transport properties and some other miscellaneous properties which we already know. About these properties while exaggerating more on to this we will talk about the thermodynamic properties sometimes we will talk about the fluid properties as and when they appear.

And, most of these things already although it is known, but it is advised that these properties we are going to use routinely at any subsequent lectures down the line. So, that is the reason this properties needs attention at this stage.

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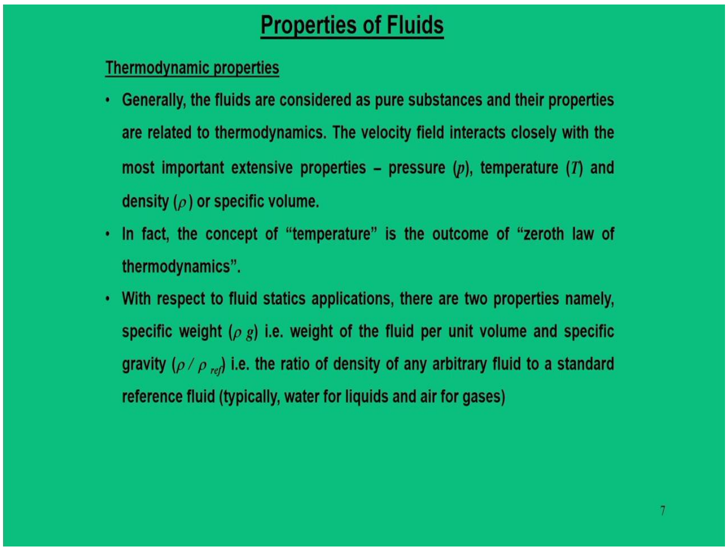

So, the thermodynamic properties that is the mostly when you talk about the fluids they are air or gases they are essentially treated as a pure substances and all most of the properties are related to the thermodynamic properties. And, at the same time the when you look at fluid mechanics angles to the flow, the velocity is one of the parameter which is treated as a fluid properties.

But, when a flow interacts during a situation when the flow in moves or flow interacts or flow passes to a medium there are change in the properties and it interacts with other fluids. As and when it does, it changes its properties and it mainly pressure which we mainly consider as a pressure, temperature and density.

With the first important or fundamental property that temperature it comes from the zeroth law of thermodynamics. So, apart from this the pressure and densities that are independent properties of any given substances.

So, this is all about we when you do about this the two important three important properties pressure, temperature, density or specific volume, but in fluid mechanics aspects when you deal with fluid statics since when you multiply the density with the acceleration due to gravity we call this another term we come across another term which is known as specific weight and that is the weight of the fluid per unit volume.

There is another property is specific gravity which is defined as the ratio of density of any arbitrary fluid to the standard reference fluids. And, in our situations we say that the standard reference fluids if it is a liquid, it is water and if it is a gas, it is air.

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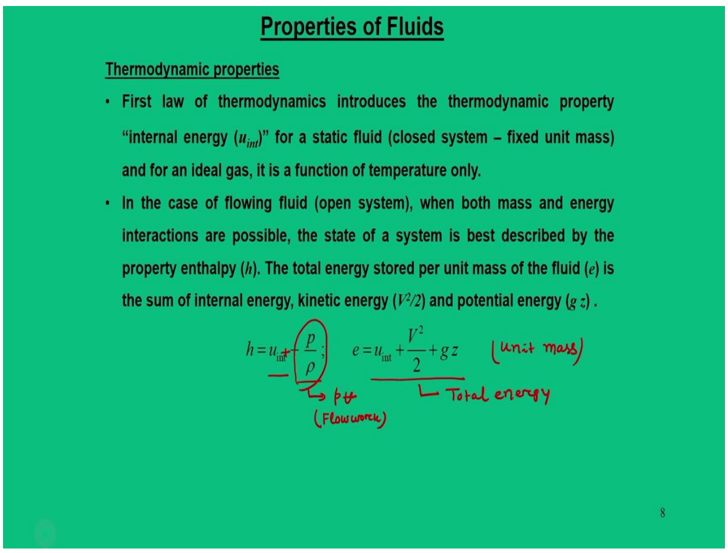

Now, move we move to the basic thermodynamic properties. So, when we say talk about the thermodynamic properties, we essentially talk about the first law or laws of thermodynamics. So, in the first law which is essentially the concept of conservation of energy the it introduces a properties which is known as internal energy for a static fluid and or in this case we call it as closed system or fixed mass system. And, this internal property is essentially a function of temperatures.

Now, in case of open systems and the thermodynamic definition of an open system is that where both are mass and energy interactions are possible. So, this particular in this particular open system, the properties that is of importance is enthalpy and its basic definition is internal energy u + $\frac{p}{\rho}$. And, some many a times this $\frac{p}{\rho}$ is termed as pressure times specific volume or we call this as a flow work.

So, the open systems keeps a characteristics which is called as enthalpy and in the having defining these two terms, we again call the total energy of the systems e and it is essentially composed of three parameters internal energy, kinetic energy that is $\frac{V^2}{2}$ and potential energy gz and this definition is made for unit mass basis.

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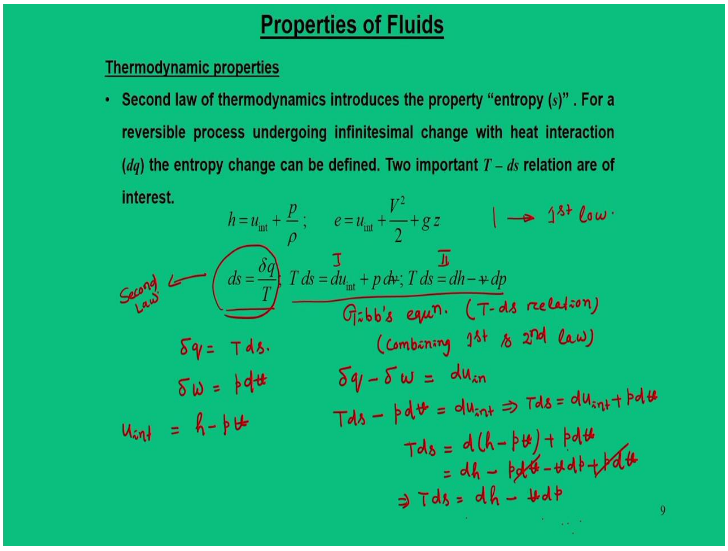

Then, moving further we will talk go to the second law of thermodynamics and the second law of thermodynamics introduces the term entropy. And, in fact, it gives the directionality of a particular systems whether a flow should occur in certain direction or not.

So, in case of entropy will essentially drive the flow in certain directions and this definition of entropy comes from the fact that when there is a heat interactions and the entropy change for a system is defined by $ds = \frac{\delta q}{T}$ that is change of heat divided by the temperature in which these change is occurring.

So, if you look at this kind of equations the first part of equation this comes from the first law; entropy part that comes from the second law and based on the first law and second law combines we get these two equations which is known as Gibbs equation. And, many a times you call this as a Tds relation. So, in fact, one can derive these equations by combining first law and second law.

$$Tds = du + pd\upsilon \qquad Tds = dh - \upsilon dp$$

Now, to do that let us talk about if let us write what is this dq from this definition as Tds. We also know that rate of work transfer per unit mass basis we can say pdv. Now, if you recall the first law which is $\delta q - \delta w = du_{\text{int}}$.

And, by putting these equations what do you say $Tds - pd\upsilon$ and so, this is nothing, but the first Tds relations. And, by putting h is equal to or internal energy equal to h minus pressure times specific volume since density is the inverse of specific volume.

$$u_{\text{int}} = h - p\upsilon$$

So, from the first ds relations when you put u as this so, what we can write is

$$Tds = d(h - p\upsilon) + pd\upsilon$$

So, this can be expanded as

$$Tds = dh - pd\upsilon - \upsilon dp + pd\upsilon$$

So, these two term gets cancelled ultimately we get the second T ds relation as

$$Tds = dh - \upsilon dp$$

So, these two relations are very essential when we deal with the compressible flow analysis.

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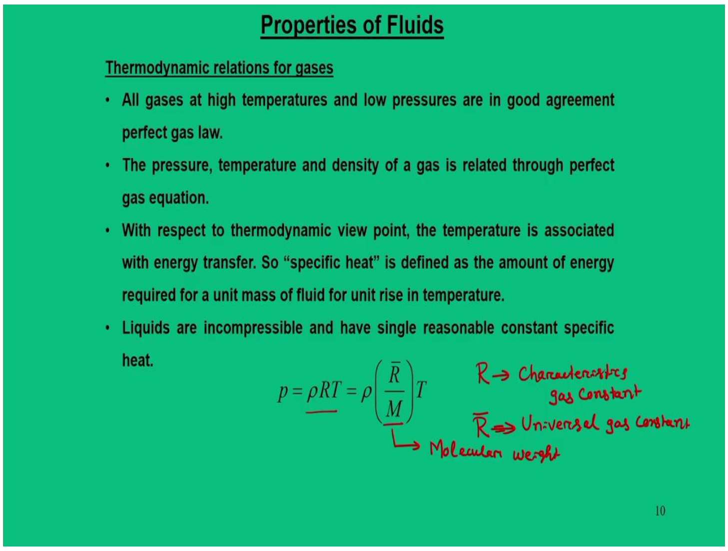

Moving further we will now talk about the equation of state or thermodynamic relations for gases and this is essentially governed as it is known thermodynamically that all the gases at high temperature and low pressures they are in agreement of perfect gas law which is $p = \rho RT$ where an R is nothing, but the characteristics gas constant and $\overline{R}$ is nothing, but universal gas constant. And, they are related through the parameter known as molecular weight. In fact, for our analysis we will routinely use this expression which is known as equation of state.

Now, apart from this we also are of the another parameter which is of more interest which is specific heat and this is related to the temperatures because essentially temperature is the main cause of heat transfer to take place. So, a specific heat is defined as the amount of energy required per unit mass of fluid for the unit rise of temperature.

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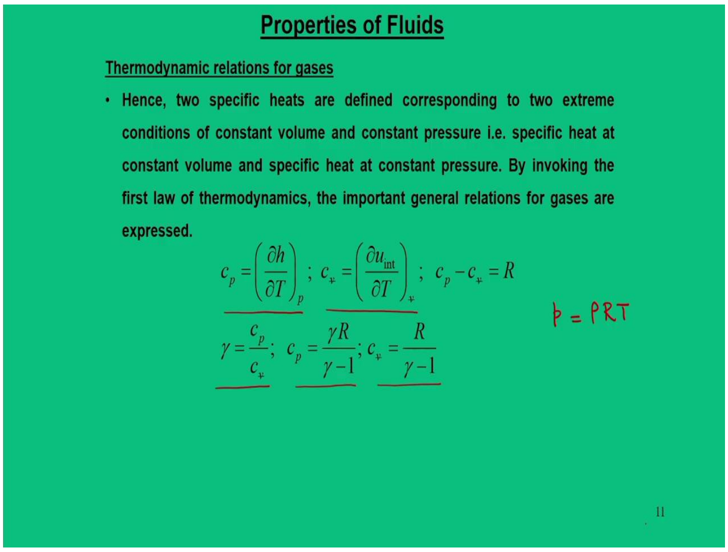

Typically liquids we do not talk about liquids because they have a single specific heat whereas, for the gases they can have two different types of specific heats because as you know the gases follow the law $p = \rho RT$. So, the change can occur at for a given temperature difference we can have change or amount of heat required we can do it by maintaining a constant pressure or maintaining a constant volume.

So, accordingly we say it is a specific heat at constant pressure C_p, other one is the specific heat of heat at constant volume. And, based on the first law of thermodynamics they have been related with enthalpy and entropy that is C_p is related to enthalpy and C_υ is related to internal energy.

So, the difference between the C_p and C_υ is nothing, but the characteristic gas constants in additions we have another parameter called as specific heat ratio γ and based on this definition the C_p can be related with the parameters is equal to

$$C_p = \frac{\gamma R}{\gamma - 1} \quad C_\upsilon = \frac{R}{\gamma - 1}$$

It is to be remembered that these two expressions we will be frequently using for the when you deal with the main compressible flow.

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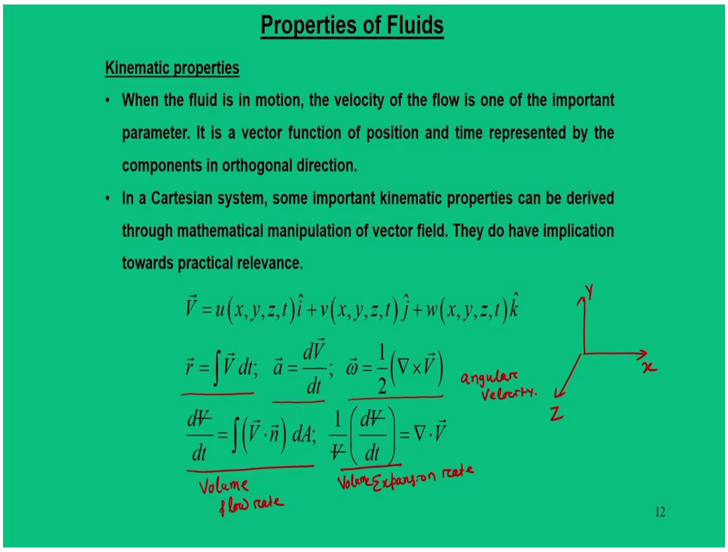

Now, we will come back again for the kinematic properties which is essentially a fluid properties. In general when the fluid is in motion it is essentially defined through a velocity vector in a particulars time and space systems or it is called as a field. So, this velocity is a vector function of position and time which is represented as

$$\vec{V} = u(x,y,z,t)\hat{i} + \upsilon(x,y,z,t)\hat{j} + w(x,y,z,t)\hat{k}$$

they are all of them are functions of x, y, z and t that is in the Cartesian coordinates and this position vectors can be found out by integrating this velocity vector with time and so, this is what you call as a position vector.

Acceleration can also be find out where differentiating the velocity vector and there is another term which we called as angular velocity. This angular velocity is nothing, but the mathematical interpretation of curl of velocity vectors.

The other parameter of interest we also define the volume flow rate $\frac{d\forall}{dt}$ and also we defined volume expansion rate. How the volume changes with respect to time and this is nothing, but the dot product of velocity vector that is gradient of velocity vectors.

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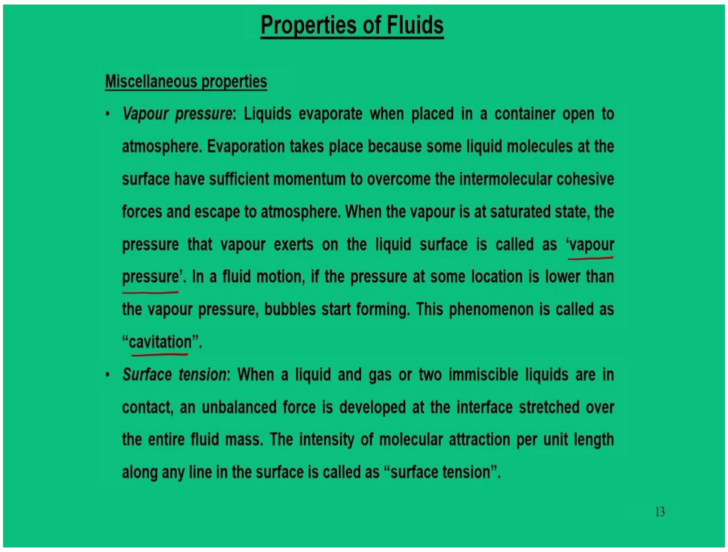

The next important properties which is are of more interest for the fluids we call these as a first properties vapour pressure and this is mainly concentrated when your fluid is a liquid. And, so, normally the liquid evaporates when it is kept on a container and open to the atmospheres. So, it is very likely that since it has a free surfaces and these free surfaces have a least energy and they try to evaporate from the surface.

So, when the vapour is at saturated state this that particular state we call this as a vapour pressures and in a fluid motion if the pressure at some location is lower than that of vapour pressure, a kind of bubbles start forming we call this as a cavitation.

The other properties of impotence is a surface tensions which is essentially the properties when these liquids and gases come in contact together and this is governed by the molecular interactions and typically known as surface tensions. However, in our philosophy we will not be going to use this property exhaustively.

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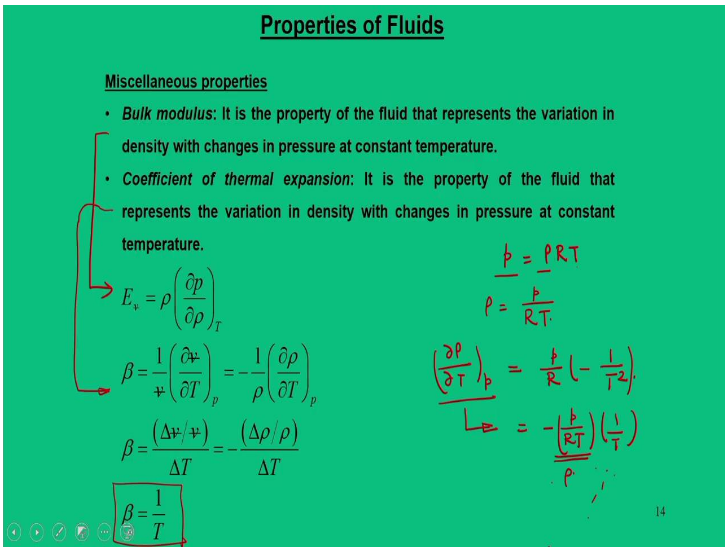

The and in fact, now we are coming to another important properties which is bulk modulus and it is the property of a fluid that represents the variation of density change with respect to pressure at constant temperatures. Ideally if you look at the equation of state $p = \rho RT$ so, we can say that the pressure can change with respect to density by keeping temperature as constant.

So, we define a parameter called as a bulk modulus E_v, this is what we say

$$E_v = \rho\left(\frac{\partial p}{\partial \rho}\right)_T$$

Another parameter of interest is coefficient of thermal expansion which we say as β how the specific volume changes with the temperatures. So, $\beta = \frac{1}{\forall}\frac{\partial \forall}{\partial T}$. And in fact, from the equation of state one can derive that beta turns out to be $\frac{1}{T}$ from the equation of states.

Now, from this equation we can write $\rho = \frac{p}{RT}$. Now, one can find out $\left(\frac{\partial \rho}{\partial T}\right)_p = \frac{p}{R}(-)\frac{1}{T^2}$. So, if you take this $\frac{p}{R} = \rho T$. So, $\left(\frac{\partial \rho}{\partial T}\right)$ reduces to $-\left(\frac{p}{RT}\right)\left(\frac{1}{T}\right)$.

So, finally, from this expression we can and this is nothing, but $\frac{p}{RT}$ is nothing, but ρ. So, after simplifications we get this turn β to be inverse of absolute temperature for an ideal gas.

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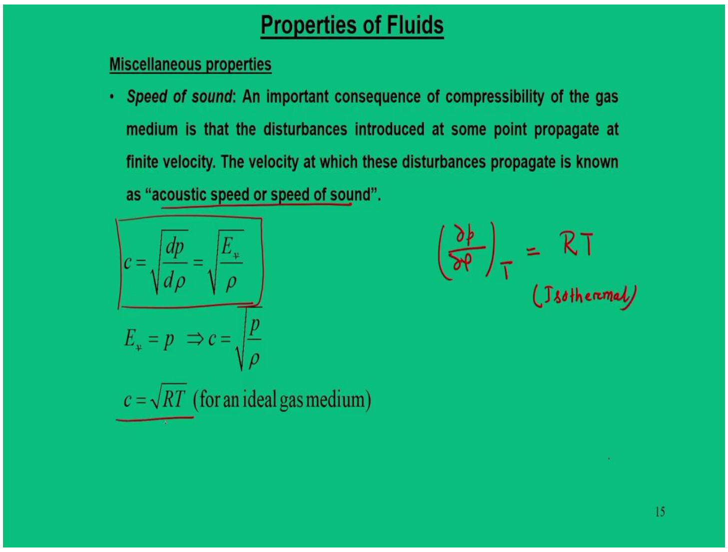

The next important properties which is called as speed of sound, this parameter we will be looking at in more exhaustive form in the subsequent class. Just for the sake of continuity I am just explaining that the one of the important consequence of compressibility of gas is the fact that when a gas moves in a medium it creates a pressure disturbance and these pressure disturbance moves at certain speed which is known as the speed of sound or typically known as acoustic speed.

This acoustic speed is defined by $c = \sqrt{\frac{dp}{d\rho}}$. This is the fundamental definition of acoustic speed. Now, if the medium is attached to be isothermal this expression reduces to $\frac{dp}{d\rho} = RT$ if it is an isothermal case.

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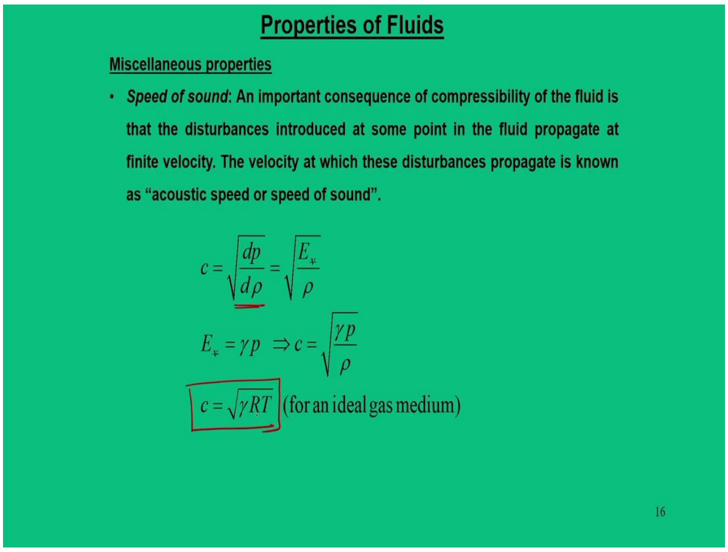

So, in such situations speed of sound becomes $\sqrt{RT}$. The now if, but that is a very unlikely event, but the most importantly when the speed of sound is approximated by keeping the medium to be isentropic for which this $\frac{dp}{d\rho}$ is calculated and that is comes out to be $\sqrt{\gamma RT}$ for an ideal gas.

So, the point that I need to emphasise here is that although we call this as a speed of sound, but it is very basic definition talks about the parameters which are essentially the properties. So, even though it is a speed, but it is a property because it contains the terms γRT for a given situation or for a given gas.

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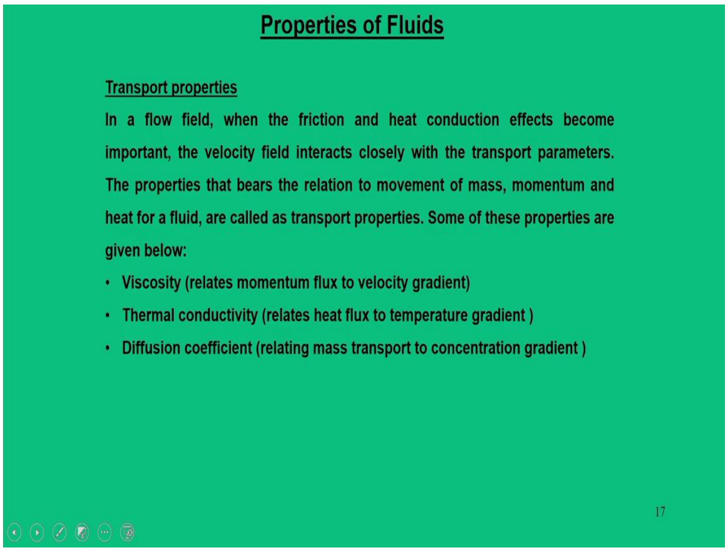

There are very other properties of some other properties we call them as a transport properties that is the friction and heat conduction effects becomes sometimes significant when the velocity interacts with these parameters. In such a situation when the fluid is in motion these properties affects the flow parameters.

So, during such situation we define some properties which is viscosity that relates momentum flux to the velocity gradient; thermal conductivity that relates heat flux to the temperature gradient; diffusion coefficient that relates mass transport to the concentration gradient.

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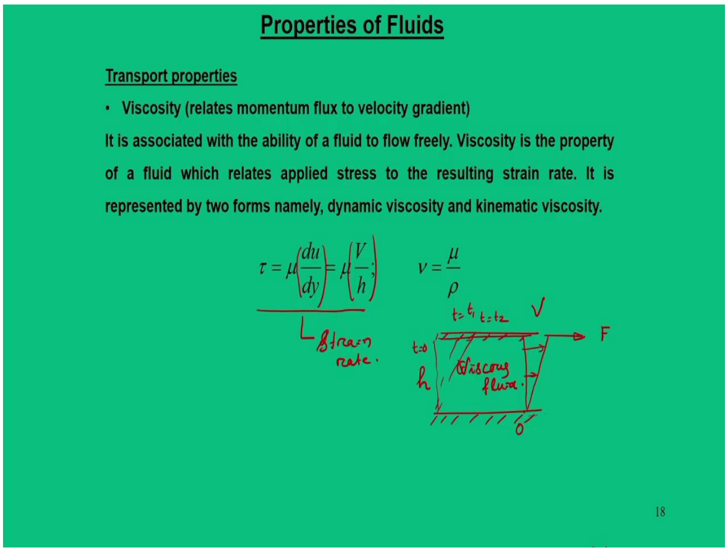

So, the first properties is the viscosity, it relates the momentum flux to the velocity gradients. So, essentially the viscosity is the term which is defined as the ability of a fluid to fluid flow to flow freely.

A classical definition goes in this way that the viscosity is the property of a fluid that relates applied stress to the resulting strain rate. So, based on that we define a term which is called as a shear stress and that relates the strain rate which is $\frac{du}{dy}$ and one can find out this $\frac{du}{dy}$ as the $\frac{V}{h}$.

So, a classical example typically is given the when there is a fixed plate and there is a moving plate and in the moving plate the force is given. And, in between the moving plate and fixed plate there is a viscous fluid. And, this plate is given by velocity V and the fluid layers gets sheared.

So, at one instance at time t = 0, at time $t = t_1$ and time $t = t_2$ the upper plate position is at these locations. So, based on that if you talk about the velocity profile it says that the top layer of the fluid undergoes maximum change whereas, velocity at the fixed one it is almost 0. So, the velocity changes from 0 to its final value within this distance h which is the separation distance between the top plate and bottom plate.

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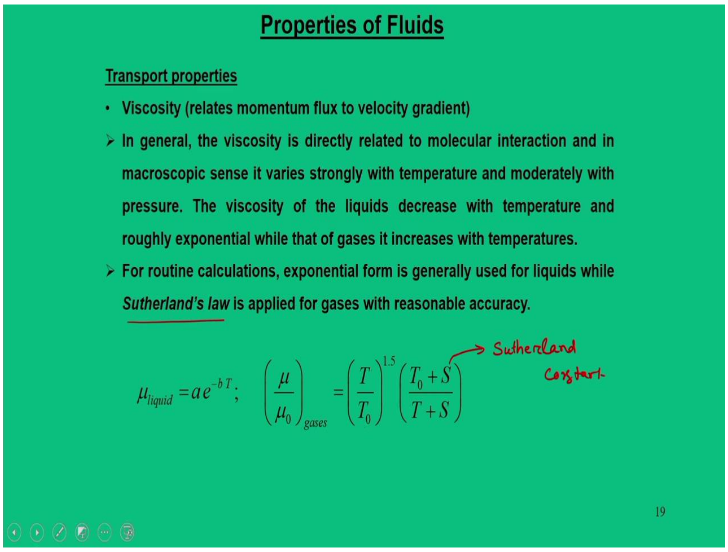

The other properties of importance which is the now when we actually calculate the viscosity for the gases, it is seen that the for gases the viscosity increases with the temperatures. So, many a times when we deal with very high temperature flow gasses, we need to find out how viscosity changes with the temperatures.

So, for that we typically refer a classical law which is called as Sutherland's law and which essentially relates the viscosity of gases at any arbitrary temperature T that is μ has to be defined at any arbitrary temperature T provided we know the viscosity value at the given temperatures. And, this is related by this expression where S is known as Sutherland's constant.

$$\left(\frac{\mu}{\mu_0}\right)_{gases} = \left(\frac{T}{T_0}\right)^{1.5}\left(\frac{T_0+S}{T+S}\right)$$

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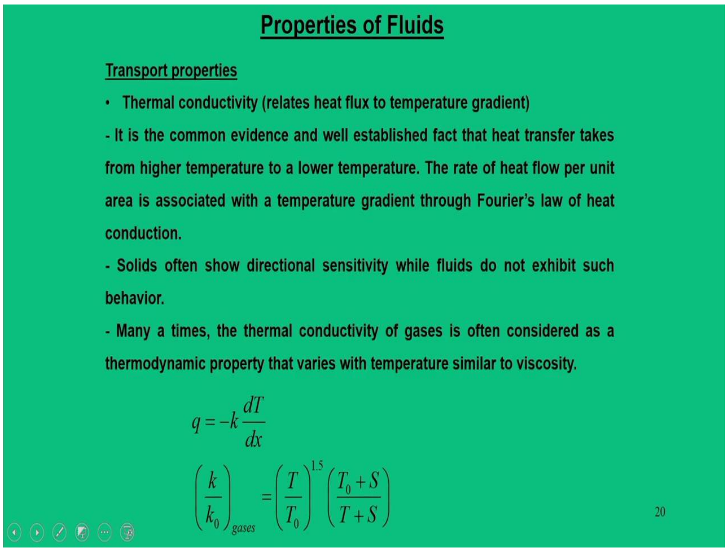

Similarly, we move on to properties called thermal conductivity. And, in fact, in our mostly in our situations the gases have least thermal conductivity and it does not exhibit very sensitive behaviour as it does with respect to solids. But, however, one can evaluate these change in the thermal conductivity with respect to temperature which is almost similar to that of a Sutherland's law.

$$\left(\frac{k}{k_0}\right)_{gases} = \left(\frac{T}{T_0}\right)^{1.5}\left(\frac{T_0+S}{T+S}\right)$$

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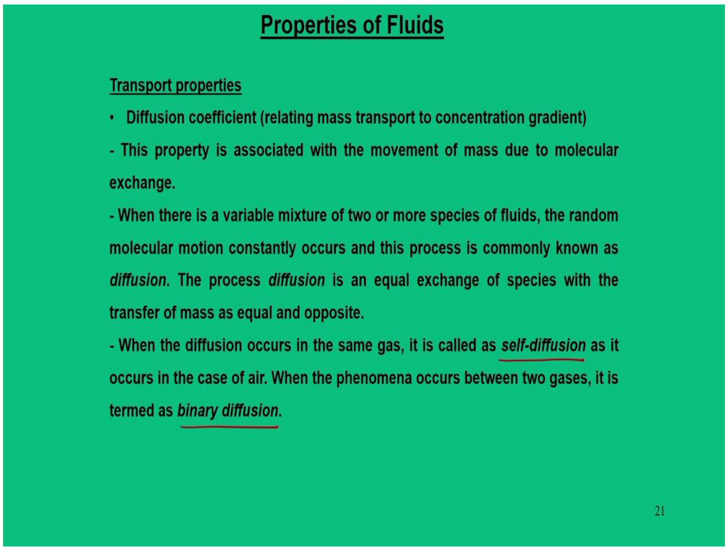

The other parameter of interest is the diffusion coefficients. Once again this diffusion coefficient is a parameter that talks about when there are two gases you have to find out how one gas diffuses into the other. So, this is something like a. So, for that we defined two fundamental concept we call this as a self either it can have a self diffusion that is a same gas diffuses into other.

That is, for example, one gas is moving very high velocity and same gas is moving at one other velocity when they mix together that means, one gas penetrating into the other then we call this such type of situation as a self-diffusion. But, similar thing if the gases are treated as a two different entities; that means, one gas tries to tries to diffuse into other, then we call this as a binary diffusions.

And, in fact, more and more we can have the concept of multi diffusion; that means more and more species gets diffused into other, but that is not of our interest.

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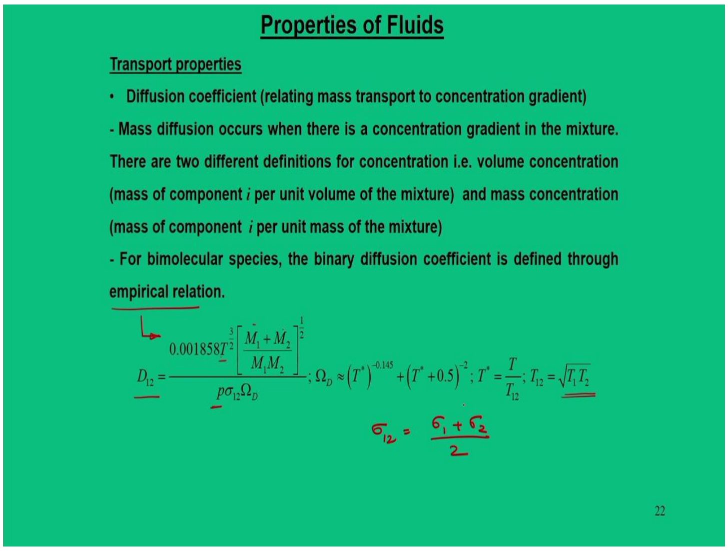

But, however, one particular interest we want to say that when you deal with the high speed flow of gases of then when a one gas tries to diffuse into other, then we would call this as a coefficient called as a binary diffusion coefficients which is calculated by this expressions D_{12} and, it is empirical relations.

$$D_{12} = \frac{0.0018583T^{1.5}\left[\frac{M_1+M_2}{M_1M_2}\right]^{0.5}}{p\sigma_{12}\Omega_D}; \Omega_D \approx \left(T^*\right)^{-0.145} + \left(T^*+0.5\right)^{-2}; T^* = \frac{T}{T_{12}}; T_{12} = \sqrt{T_1T_2}$$

Of course, we do not need to remember, but just to say that that one that is just the way of evaluating a diffusion coefficients that talks about how a gas diffuses into other. So, in these expressions there are parameters which is of interest is that we want to find out the diffusion process occurring at certain pressure p.

Other parameter of interest since we have two species we have two molecular weights M_1 and M_2 and these all pressure also happening at we want to find out diffusion process at certain temperature and certain pressure. Apart from these there are other parameter of interest which you know which you should know is that what is the temperature of species 1 or what is the temperature of species 2. These are absolute temperatures.

And, apart from that we also need to know a parameter which is called as effective collision parameter. This effective collision parameter which is $\sigma_{12} = \sigma_1 + \sigma_2$ and in fact, σ_1 is nothing but the molecular diameter of 1 and σ_2 for the second gas.

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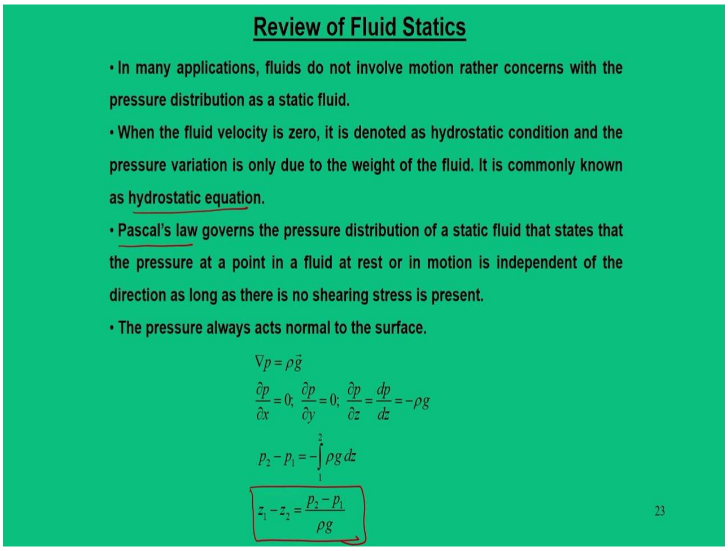

Now, after having defining all these things so, if you just read out something about fluid statics that means, if the gas is not moving at all so, we treat this term as a fluid statics. Under that behaviour we commonly refer these hydrostatic equations and the law that governs these things is known as Pascal's law. And, the equation of hydrostatic equation which is fundamental definition is $z_1 - z_2 = \frac{p_2 - p_1}{\rho g}$

So, but the very basic definition in our analysis whenever you will be using this whenever there is the term the potential energy which is associated with the flow this parameter makes of importance. In fact, it is a very fundamental aspects when you start the fluid mechanics course or fluid statics.

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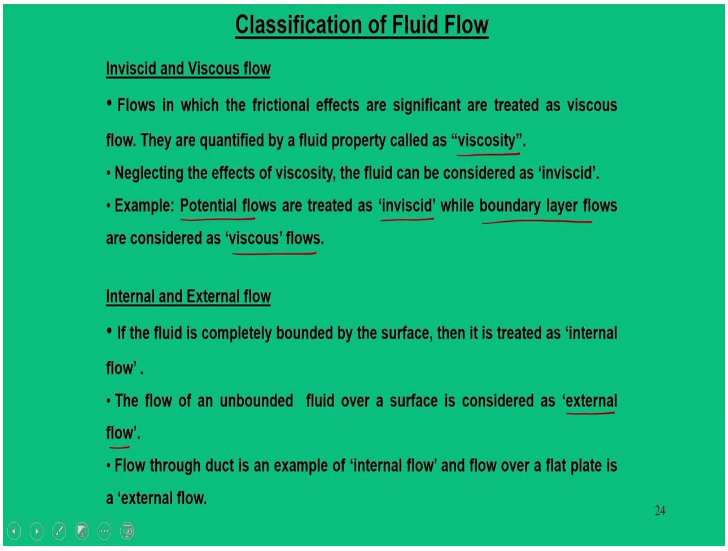

And, the last segment of this lecture is the classifications of the fluid flow. Essentially all these things are been covered as the fundamentals in the UG level.

So, first is whether the flow is viscous or inviscid. So, viscous or inviscid means that during the flow whether there is a role of viscosity that is affecting the nature of the motion. Other way is that, flow is completely inviscid; so, that means, in which the for viscous flow frictional effects become fluid dominant and also we need to take into parameter viscosity of the gas taken into account. And, in our day to day life we typically call potential flows are inviscid nature of flow and the boundary layer flow as typically governed through this viscous flow.

The next category of the flow is internal flow or external flow. So, whether a flow occurring in an medium which is completely enclosed. For example, the flow through a pipe a gas is moving in a pipe through certain pressure difference or a duct. So, these particular things we call this as internal flow and if the flow does not have any bounded surface, for example, flow of over an aircraft there is no bounded surface so, this is treated as a external flow.

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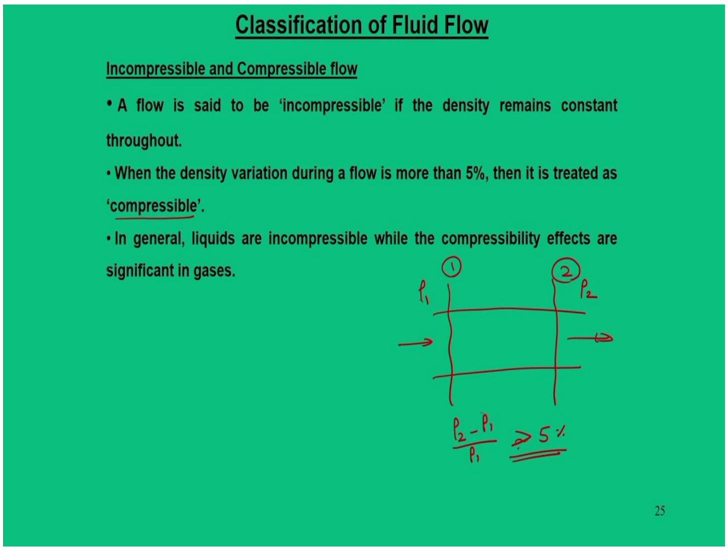

Here our main focus comes into it which is incompressible and compressible flow. So, essentially in our entire domain we will be mainly looking at the flow nature which is the compressible. So, under what circumstances we say the flow to be compressible whenever there is a flow occurring in a system or in a duct system and are two arbitrary locations.

If you try to evaluate density and try to see if there is a change in the density more than 5 percent such a case we call this to be compressible. So, we will talk more about this when you actually deal with the situations why the density is going to change. But, in the other extreme of this flow which is incompressible typically it is meant for liquids.

But, one point I need to emphasise here that when you talk about gases these gases under certain conditions they behave in two manner whether they in they exhibit the nature of incompressibility or they exhibit the nature of the compressibility is the question mark. That is essentially decided under what pressure difference this flow is occurring.

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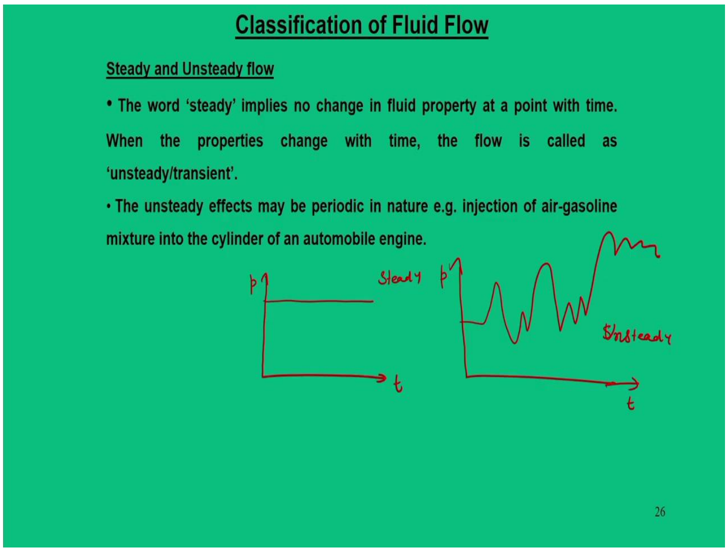

Other type of flows that is steady flow and unsteady flow: so, when you say steady flow when you say steady flow we essentially see how the parameter is any fluid parameter which is changing with time. So, let us say pressure we are, but let us say I am plotting pressure with respect to time, at any in a space medium so, I will see that the pressure do not change. So, it is a steady.

Now, in that same domain if I try to see that there is a some variation of pressure, then such a things we say unsteady. So, here in the nature of unsteadiness your time axis is very important because at every instant of time the pressure values are different.

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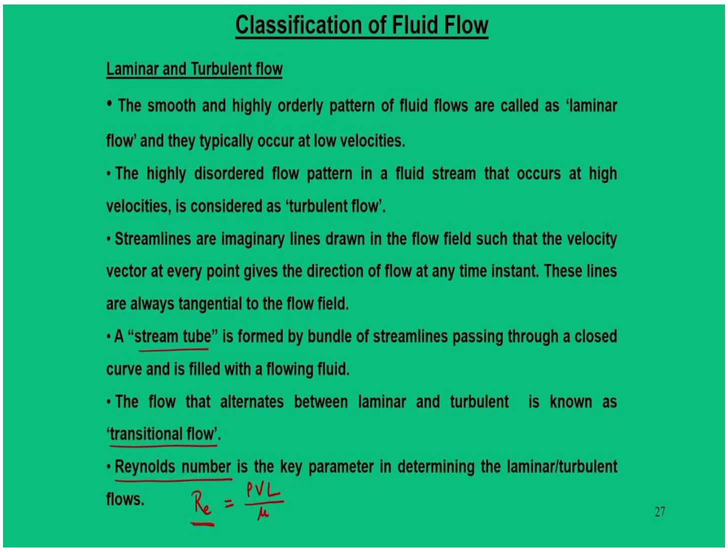

The other classical stuffs that are of interest is laminar flow and turbulent flow. In general laminar flows are orderly flow and turbulent flows are disordered nature of the flow. In fact, laminar flow follow a streamline pattern whereas, we do not see any streamline or pattern for a turbulent flows.

When we say streamlines, these are the lines which are drawn in the flow fields such that at any instant if you draw a tangent at that point it will give you the velocity vector. So, on the basic of streamlines in a certain volume if you consider an array of streamlines and enclosed in a certain volume we call this as a stream tube. More details of this analysis we will talk about in the subsequent lectures.

Now, when the flow changes its states that is if the flow tries to attend from laminar to turbulent or if it tries to attend from turbulent to laminar; that means, how it can do if you change the upstream and downstream conditions this type of change can occur. In such cases with the flows that are treated as a transitional flow.

Now, to decide whether the flow is laminar or turbulent, we define the term which a non-dimensional term which is a Reynolds number R_e and it is related to ρ, velocity V and L that is the characteristics length by μ it is the fluid viscosity; that means, a single domain defines a non-dimensional number Reynolds number that says that under what conditions we can define the flow to be laminar or turbulent. This we have already seen in our classical fluid mechanics course what is the role of Reynolds number in laminar and turbulent flow regimes.

$$R_e = \frac{\rho V L}{\mu}$$

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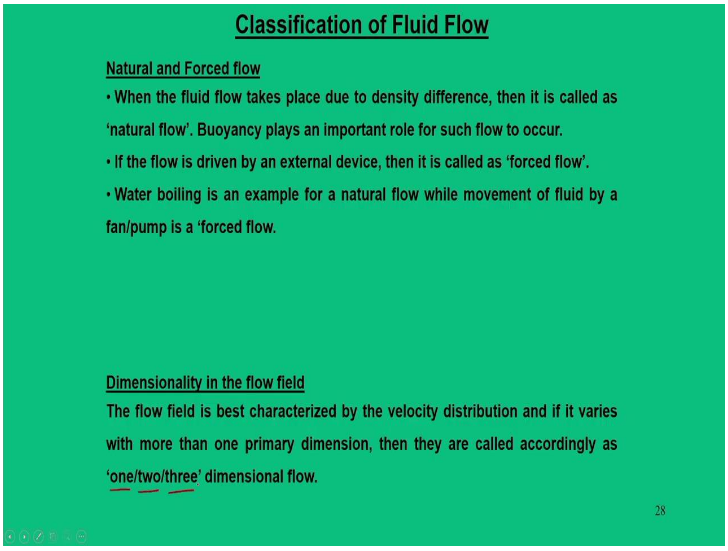

The other type of flows are of interest many times is a natural flow. Natural flow and force flow; natural flow is normally buoyancy driven for example, water boiling is a kind of a natural flow and when the fluid is driven by some external agency that means, whenever there is a pressure difference mechanism which is being put so that the flow can occur. So, such a flow we call this as a force flow.

Now, having said this one can also think the dimensionality in nature of a flow field. So, one can view the flow field phenomena occurring in a particular direction or not. So, traditionally orthogonal coordinates are the right approach which decides the flow in a given directions. So, based on that we say whether the flow is 1-dimensional, 2-dimensional or 3 dimensional in nature.

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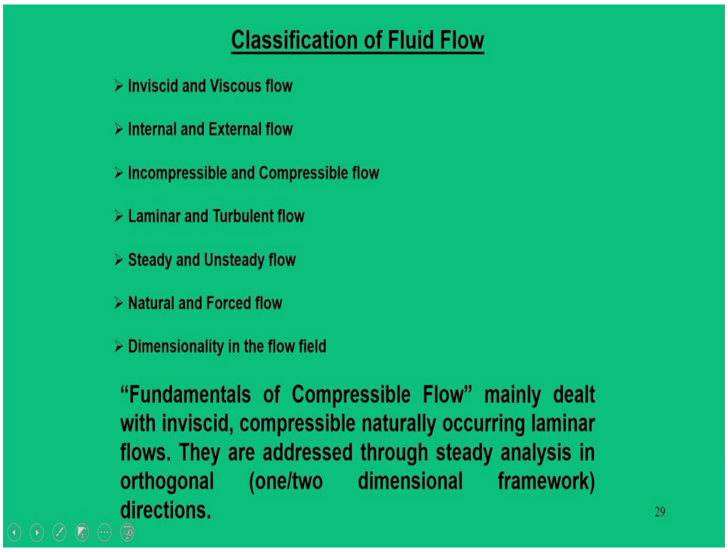

Now, having said this the last part of this lecture if you just summarize that we have talked about inviscid flow and viscous flow; we have talked about internal and external flow; we have incompressible and compressible flow; we have laminar, turbulent flow; steady, unsteady flow; natural and force flow and 1-dimensional, 2 dimensional or 3 dimensional flow.

Now, having said this, we can say that any type of combination is possible. So, one can have a viscous flow which is occurring in a pipe which is internal and this viscous flow can be compressible or incompressible so, any combination of and that flow may be steady in nature or unsteady in nature. So, any combination of these things is possible. So, it is also left to the analysis in what framework we are going to do.

And, as far as our main fundamental things as far as our concentration is fix that in this particular flow we will talk about or the fundamentals of compressible flow is mainly dealt with inviscid compressible flow which is naturally occurring and its a laminar flow. And, we will address them typically for a steady analysis in orthogonal coordinates, and in particular our focus will be in the one and or two-dimensional framework. So, with this I conclude this lecture for today.

Thank you.