**Fluid Dynamics And Turbo Machines.**
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**Part A.**
**Module-1.**
**Lecture-3.**
**Introduction To Fluid Flow.**

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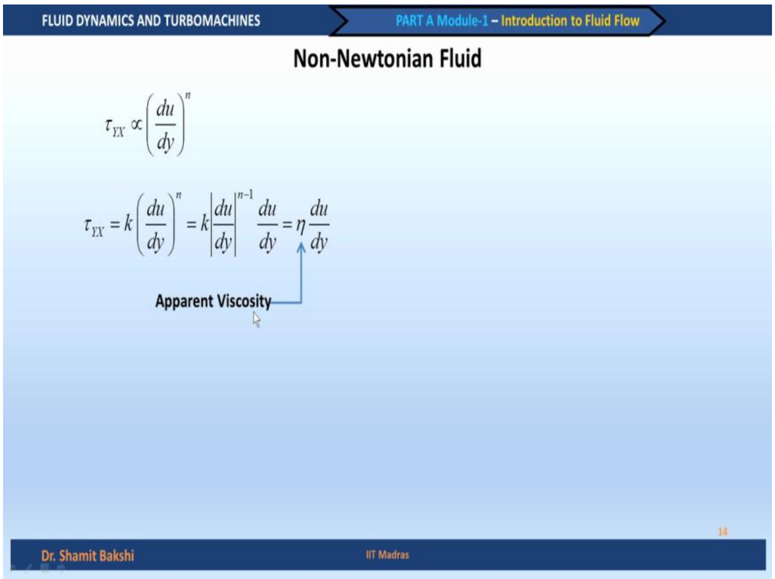


So, welcome to this third lecture, in the last lecture we looked at Newtonian fluids, in this lecture we will begin with non-Newtonian fluids. In the last lecture we introduced Newtonian fluids as those where the shear stress is directly proportional to the rate of deformation which was derived and shown to be equal to du by dy, the velocity gradient. Now it is not necessary that for all fluids, the stress and strain and linearly proportional to each other or directly proportional to each other. It may be that du by, the shear stress is proportional to the rate of deformation which is also called the strain ray raised to the power N. So N, Newtonian fluid will be a special case of this situation where N is equal to 1. So, this type of fluids are called non-Newtonian fluids.

Now we can write the same equation or same relation in the form of a Newtonian fluid and define a apparent viscosity. So, as you see here, we define tao YX, the shear stress as some constant, this is the proportionality constant multiplied by du by the gradient raised to the power N. We can now write it in this form where we take out module is of du by dy raised to the power N minus1 multiplied by du by dy. The idea behind this is to keep this expression similar to a Newtonian fluid. Now, we can write the first part K into du by dy to the power N minus1 as afferent viscosity. So, now if you look at the final equation, the shear stress is equal to eta into du by dy, it looks similar to a Newtonian fluid but with a difference that now eta is not constant, the apparent viscosity is not constant. It is dependent on the strain rate du by dy in some certain way, so it does not remain constant, so that is basically a non-Newtonian fluid.

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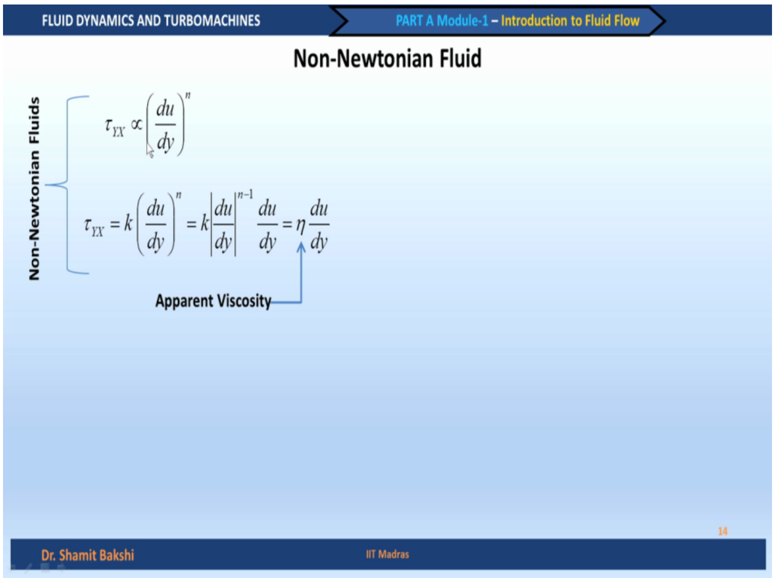


The way we have written this equation, you can see that have retained the sign of du by dy, that is also important. We have done that by taking modulus of this quantity du by dy raised to the power N minus1. This is also true because the shear stress should have the same sign or the shear stress should be positive if du by dy is positive. That means U increase, U increases in the Y direction, so the velocity is increasing in Y direction, it will apply a shear stress in positive X direction. Whereas if the velocity decreases in Y direction and du by dy is negative, then it will apply a shear stress in negative X direction. So, that is how the sense of the expression or the sign of the expression is written by using this type of expression, by expressing it in this way.

Now let us look at, so we did this so that we can get an expression similar to the Newtonian fluid but with a difference that now we are talking about apparent viscosity which is dependent on the strain rate. So, this class of fluids as we have already introduced are called non-Newtonian fluids.

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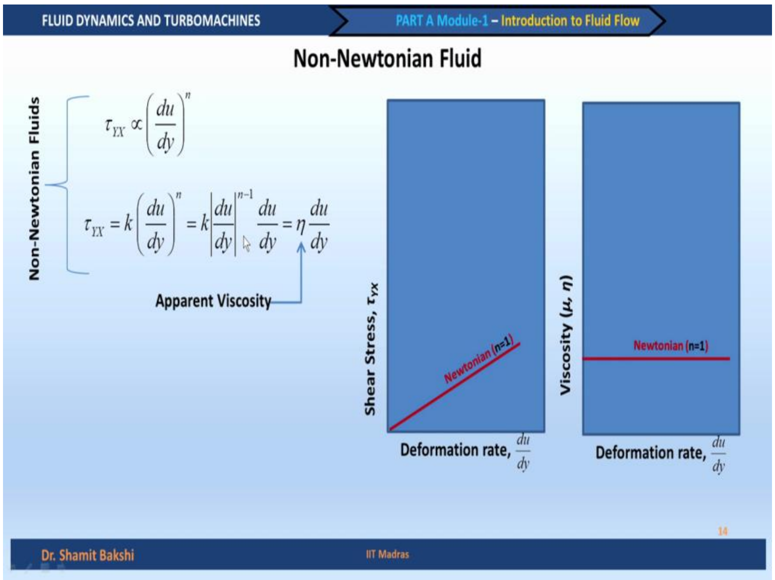


Let us look at how the shear stress arrays with the deformation rate been the case of a non-Newtonian as well as a Newtonian and fluid and how does the viscosity changes with the deformation rate. So, if we write, once we have written the equation in this form, the tao YX is equal to eta into du by dy, eta will become the slope of the variation, slope of this curve which plots tao YX with du by dy.

So, if you consider a Newtonian fluid which is the simplest of the situation that is N is equal to 1, the variation is linear, which is shown by this Red Line. Of course the viscosity remains constant with the deformation rate, with du by dy, there is no variation, there is no dependence on viscosity on this parameter, it can depend on temperature like we saw in the last lecture but it is independent of the deformation rate, so we have plotted viscosity here, the dynamic viscosity mu which is true for the Newtonian fluid or the apparent viscosity eta which is true for the non-Newtonian fluids.

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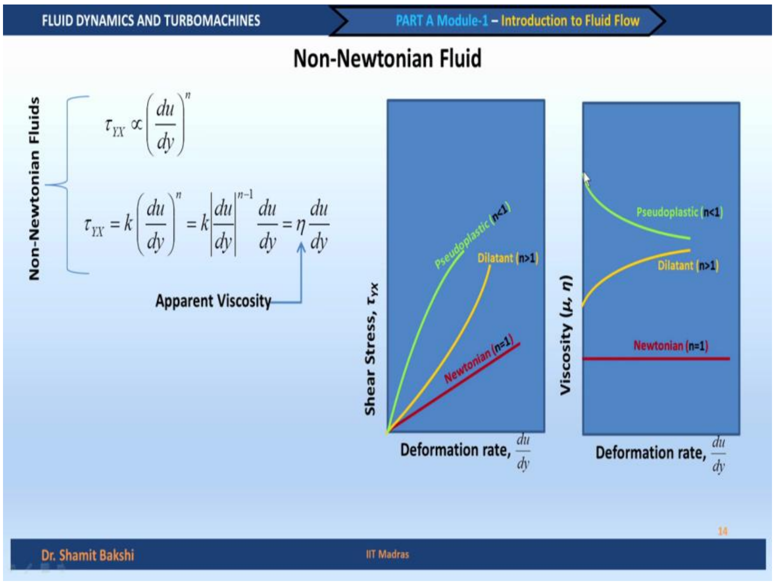


Now, depending on the value of N you can have different types of non-Newtonian fluids. So, let us see what are these different types of non-Newtonian fluids. The first possibility is, let us say N is greater than one, so if N is greater than one, what it means is this expression is increasing with the value of the deformation rate. So, that means the slope of this curve, shear stress versus the deformation rate curve will Increasing, will increase with increase of the deformation rate, that is apparent from this curve itself. We can see it more clearly if we plot the viscosity. So, if we plot the viscosity here, the apparent viscosity of course for the non-Newtonian fluid, if we plotted here, we see that for N greater than one, the viscosity is increasing with the deformation rate. So, these are called dilatant**,** type of non-Newtonian fluids.

So here the viscosity increases with the deformation rate. So, these are called, also called, so by the application of more shear stress, this liquid becomes, this fluid becomes more viscous, so these are like shear thickening liquids, dilatant liquids also called shear thickening liquids. The other possibility is that where N is less than one, that means you have a situation here where the shear stress at deformation varies nonlinearly like what is shown here and the slope of this curve decreases with increasing deformation rate. Okay, if we draw a tangent to this curve, to this green line at different points, the angle of the tangent with the X axis will reduce, that means the slope of this curve as we go for higher deformation rate will become less. In terms of apparent viscosity it means that the apparent viscosity will reduce, so these are called pseudoplastic.

These are also called by application of more shear stress or more deformation rate, this becomes thinner. So, these are also called shear thinning liquids. So, we have seen shear thickening liquids, types of non-Newtonian fluids and shear thinning types of non-Newtonian fluids which are also known as pseudoplastics. There are several examples of this types of fluids like for example if you are talking about pseudoplastic material, you have paints for example, where the paint stays in the can, it is stationary, it is more viscous. When you apply shear, when you apply the paint on the wall, you are actually applying shear of the paint and then under that condition it becomes thinner, it is also helpful because by thinning it becomes easier to apply the paint on the wall.

Again the examples of dilatant fluids as well, one good example which is familiar to us is like of course cellulose and other things are also there, one very good example is wet sand. If you have experienced working on a wet sand on the beach, you will see that if you walk on the wet sand, your foot will sink. But if you jog on the wet sand, it becomes, it is more firm. So, when you are walking on the sand what happens is you are applying a normal force and the wet sand cannot, because it is wet, it gets displaced and the foot sinks. But if it is, if you are jogging, you are applying shear on the wet sand and when you apply shear with increasing deformation rate, it becomes more firm because the viscosity is more. So, these are some examples of shear thickening and shear thinning fluids.

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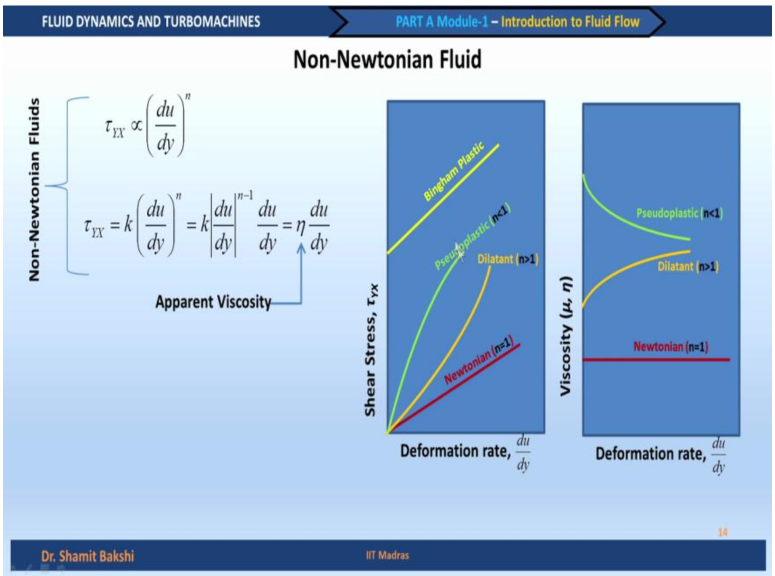


Apart from this there is something called a Bingham plastic. So, what is it, it is actually a plastic, that means it is like a solid to begin with, so what happens, what you can see here is that here this curve which shows a Bingham plastic actually does not pass through the origin, that means a certain shear stress is required, a certain value of shear stress is required for this material to flow like a fluid. It does not flow instantaneously like the Newtonian fluid like the dilatant or shear thinning or shear thickening, sorry shear thickening and shear thinning types of fluids. So, this needs an initial stress to behave like a fluid. The example of Bingham plastic, very good example is, which we are familiar with is toothpaste. See, if you, see when it is stored in the tube, even if you unscrew the lead of the tube the toothpaste does not come out or we do not intend it also to come out automatically.

So, when it, when you open it, even it does not come out even if you apply a small force, it needs some amount of force for it to come out. So in some sense at that stage it behaves like a solid, it needs some yield stress for it to flow. But after it starts flowing, it should not remain as solid because solids are elastic, so what happens, if it is, if it behaves like a solid, then once you put the pressure, it comes out and once you withdraw the pressure on the tube, it goes in because of its elasticity, this is not desirable. So, under that condition it flows, it flows like a Bingham plastic, it undergoes permanent deformation, it comes out. So, this is an example of a Bingham plastic.

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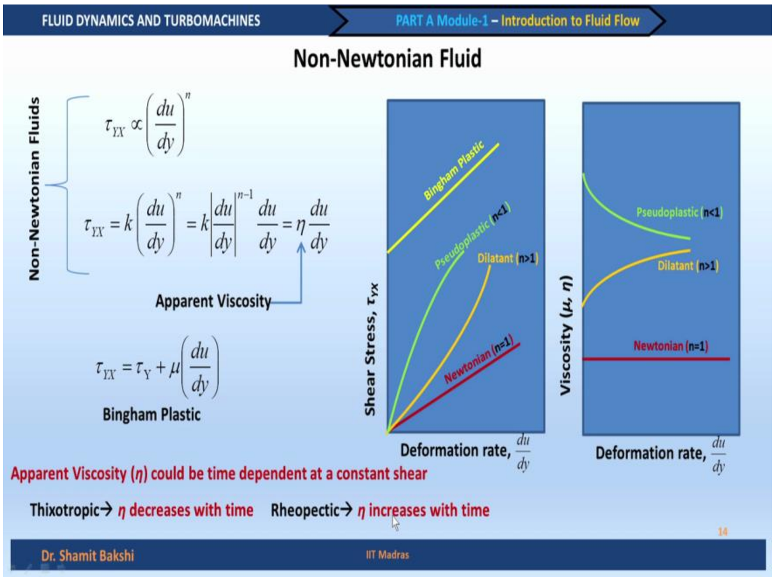


Mathematically if you want to represent it, it is little, of course it will be little different from this expression, so it is something like this shear stress, you have some constants, is now, there is a constant so that means even if the deformation rate is zero, you need a kind of yield stress for this to start flowing. So this is basically a mathematical expression for a Bingham plastic. So, the situation, so now we see that the way shear stress and strain rate relates to each other in case of fluid is quite complicated, it is not restricted to just Newtonian behaviour. Of course in this course we will be restricted to only Newtonian fluids but we should know that it can be have in various situations in a non-Newtonian way.

So far whatever we have discussed brings out the dependence of the apparent viscosity on the strain rate of the rate of deformation. But, if you see, the statement here, it says the apparent viscosity ETA could be time-dependent, that means even if the shear stress applied, applied shear stress of the rate of deformation is same, it can change with time. So, the examples, so this time dependency brings in more complicated in the type of behaviour for the non-Newtonian fluids.

The first type, of course there are two possibilities when we are talking about the time dependency of apparent viscosity, it can decrease with time, these are known as Thixotropic, many paints for example are thixotropic which helps because if you keep on applying even at a same shear rate, it becomes thinner. And it could be Rheopectic, that means eta increases with time, apparent viscosity increases with time, this is also possible.

So, in this particular slide we looked at different types of behaviour of stress with deformation rate. We looked at the stress field before in the last lecture and we also looked at the stress strain relationships, stress and strain rate relationship for a Newtonian fluid **tood** today we have introduced non-Newtonian fluids also. The next important thing for this first part of this module is how do you classify the flows. We have introduced to what is fluid and what are the different flow fields, what are the different types of **velo** parameters characterising the flow field like the velocity field, stress field, etc., how the stress field relates to the velocity field. Now there are different ways of classifying flows.

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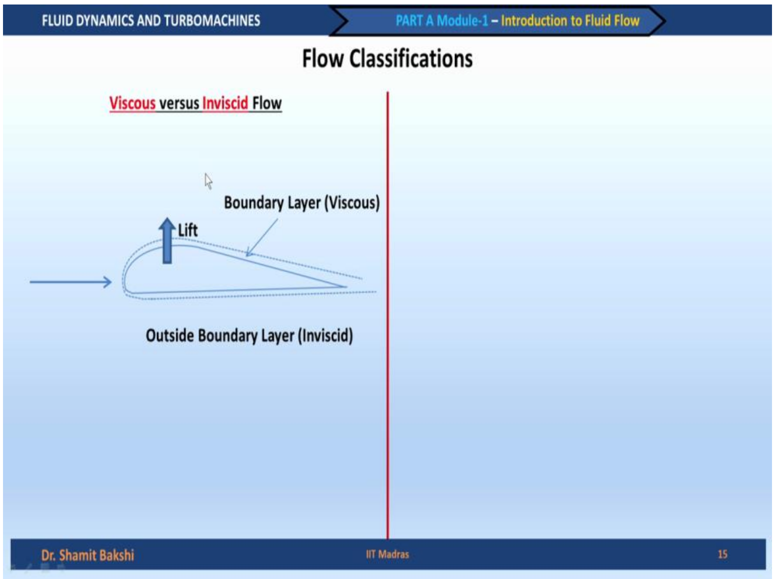


Let us look at some of these classifications. The first classification is very much related to our last discussion, we introduced this property called viscosity. Now we can talk about viscous versus inviscid flows. So, we can see the viscous flow and we can say, we can consider inviscid flows also. Of course in reality no flow or no fluid is completely inviscid, it is understandable. But then what do we mean by inviscid flow and why do we want to study inviscid flow? To look into that, let us look at this example often aerofoil, this is a particular flat bottom aerofoil. Now if you consider a flow past this aerofoil, you can consider this as hydrofoil also, that means water flowing across this particular object or air flowing across his particular object which is an aerofoil.

So, now if we consider a flow, we can define a region which is shown by this dashed line and this region is the region where the viscous behaviour is only important. That means the fluid behaves in a viscous way. What we mean by that? So, it means that the viscous stresses are important only in this region which is a thin region around the aerofoil. What happens outside? There is still a flow outside, okay. So, this region where the viscous forces are important or viscosity is important is known as the boundary layer. We will talk about powder layer later in this first module of this course but for the time being we can just take it as a region where the viscosity plays an important role within a flow. Now, outside boundary layer what happens? Outside the boundary layer on the flow is inviscid.

So, this brings in the importance of viscous and inviscid flow. Essentially an inviscid flow does not mean that the viscosity of the fluid is zero, it means that the viscous forces are not so important to consider there. For example, if this is a aerofoil and air is flowing across past this aerofoil, the viscosity is uniform with is same within and outside the boundary layer. Within the boundary layer or outside the boundary layer. The same viscosity or if it is a hydrofoil, then, let us say water is flowing across this hydrofoil, the same viscosity is there for the fluid water inside and outside the boundary layer. But what is different is the behaviour in terms of viscous forces. We can neglect the viscous stresses or viscous forces in this region, in the inviscid flow, in the inviscid flow region, but within the viscous boundary within the boundary layer, viscous forces are dominant and they have to be considered.

So, this is the first classification and, yah, this inviscid flow is very important to analyse because often we can see particularly in Aerodynamic application, we see that you can actually explain the lift just by considering the flow to be inviscid. So, what decides, Majorly decides lift is the flow outside the boundary layer, not inside the boundary layer. So, that is why inviscid flow has its own importance of study.

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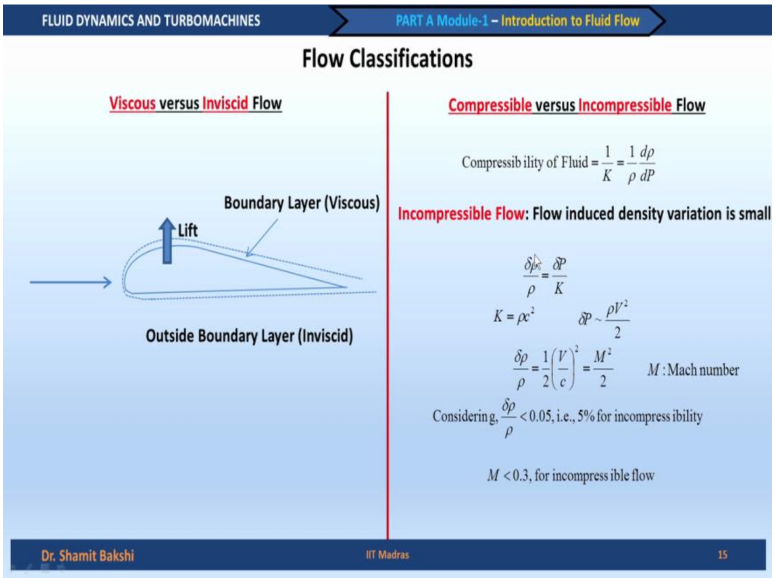


The next classification is based on the fact whether the flow, whether it is a compressible or an incompressible flow. Now, we have, we have introduced compressibility of the fluid in terms of bulk modulus in our first lecture. Let us extend that discussion to make this distinction between the compressible and incompressible flow. So, this compressibility of the fluid, it was defined before as the reciprocal of all modulus, K is the bulk modulus and if you try to write it now, it means that this is given as the relative change in density divided by the applied pressure. Now, if you look at this expression for compressibility, we had also introduced in during the previous lecture that if you take an example of air as a fluid, it has very low value of bulk modulus and it has, that is why it is highly compressible, whereas water has higher value of bulk modulus, it has, it is less compressible, compressibility is less.

But that does not mean that whenever we consider air, we have to consider the flow to be compressible, the flow can still be incompressible but the fluid can be compressible. Now what is meant by this? This actually means, this actually brings us to the definition of a compressible flow or an incompressible flow. So, an incompressible flow means that the flow induced density variation is small. So, there is density variation in the flow, let us see the flow is that of air, it is highly compressible fluid but even that fluid, the flow of that fluid could be incompressible if the flow induced density variation is small. Now, what do we mean by flow induced density variation?

What is meant by that is that we are talking of, let us look at this definition, so we are talking of this pressure if this change in pressure is brought about by the flow itself and that variation is less, then you can consider the flow to be incompressible. So, let us do it little bit more mathematically. From this definition of compressibility of the fluid, we can write this expression, we can write delta rho by rho is dell P delta P by K, directly from this expression we can write, so that means any change in density is due to a change in pressure. And this change in density and pressure are related through this expression. Now, bulk modulus can be also related to the velocity of sound through that fluid.

So, velocity of sound through a particular fluid is given by square root of K by rho, that means K, that is bulk modulus can written as rho into C square. Of course we saw bulk modulus has a unit of, we can check the consistency of units here also, K has a unit of pressure and rho into velocity square, also you can check it yourself as a unit of pressure. Okay, so K is rho into C square, C is the velocity of sound through the medium, through the fluid which we are talking about, for which we are ascertaining whether it is a compressible or an incompressible flow. Now, we will introduce this later but actually you can write delta P, if it is, that means the flow induced delta P pressure variation can be written, can be scaled with rho V square by 2. Okay.

So, in the next chapter we will actually next to next chapter we will be introducing this relation. So, delta P can be related to rho V square by 2. So, if the velocity in the fluid is V, then the pressure variation can be estimated from there using this relation. The pressure variation will be rho V square by 2. If you plug in these two expressions in this equation, what you get is like this. You get delta rho by rho is basically, so you plug in delta rho, delta

P as rho V square by 2 and K as rho C square, rho cancels out and we get half V by C whole square. V by C is defined as Mach number. So, this is basically the velocity of the, velocity in the fluid divided by velocity of sound through the fluid.

Now this can be, dell rho by rho can written as then M square by 2, Mach number square by 2. Now, let us say dell rho by rho, this is just another option that if we see that we can call the flow as incompressible if the percentage change in density relative change in density is more than 5%, less than 5%. We can call it compressible if it is more than 5%, the relative change in density is more than 5%. So, here as we are trying to find out the criteria for incompressible flow, we can see delta rho by rho should be less than 5% or 0.05. So, 0.05 for the flow to be incompressible.

Now if we use this expression here, we can get a value of Mach number. You can directly plugin here, you can get a value of Mach number should be less than 0.3 for an incompressible flow. So, even if the flow is, even if the fluid is highly compressible like air, the flow could be incompressible if the Mach number is less than 0.3. And the reason for this 0.3 value is a well accepted value for 5% change of density, relative change of density. This is a well accepted value in different, in the academic by the fluid dynamists. So, this is, this can be applied as a criteria and you can find out if you know the velocity, say the maximum velocity in the flow and you know the velocity of sound through that medium, you can find out what is the Mach number and you can say that if it is less than 0.3, you can simply use incompressible flow assumption even for a compressible fluid.

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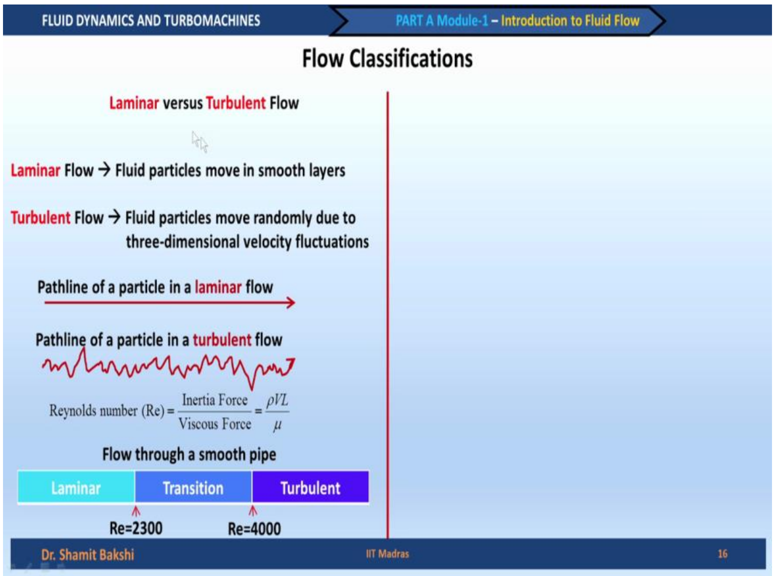

So, this is the second type of classification for flow, whether it is compressible or incompressible. There are further flow classification, one is laminar versus turbulent flow. So, let us see what is laminar flow and what is turbulent flow. We just introduced these concepts here. So, a laminar flow means the fluid particles move in smooth layer, they are, they move in laminas. How do you know that it moves in lamina? We will show that quickly. But before that the turbulent flow is one in which the fluid particles move randomly because there is a lot of fluctuation, velocity fluctuations, three-dimensional velocity fluctuations in the flow. So, now let us see how you can visualize this. So, if you consider a path line of a particle, we already defined a path line, a path line is basically the line traced by a particle introduced at a particular point in the flow.

So, if you draw a path line of a particle in a laminar flow, if the flow is straight like this, it is smooth like this, it need not be straight, it can be curved also but it is smooth. What do you mean by this smoothness? We can easily see it if we see the path line for the case of a turbulent flow. So, for a turbulent flow, for a similar type of turbulent flow, let us say flow through a pipe, the pipeline will be something like this. It will be very rough, it will move through, it will move haphazardly through the flow. Of course there are the experiments for this were done by, the pipe flow experiment, you may be familiar with, what done by Osborne Reynolds and those experiments according to the name of Reynolds in like we defined Mach number four compressible flow and incompressible flow, we define Reynolds number to ascertain whether the flow is laminar or turbulent.

So, the Reynolds number is defined as inertia force by viscous force. You can show that it becomes, this ratio of the forces comes out to be mathematically in this way rho, density, velocity, length scale, so for a pipe flow, the length scale will be the diameter of the pipe. For a flow over a flat plate, it is the length of the plate divided by dynamic viscosity. Of course this is a non-dimensional number and the value of this number will say whether the flow is laminar or turbulent. So for example in the case of a flow through a smooth pipe, we can distinguish between the laminar and turbulent flow in this manner, this region, that means less than Reynolds number, less than 2300 is known as a laminar flow, is a laminar flow, of course if you have a rough pipe, these numbers may change.

And it is not like that if it is more than 2300, immediately the flow becomes fully turbulent, It goes through a transition region, roughly at a value of 4000 more than 4000, it becomes, the flow becomes fully turbulent for the case of a flow through a smooth pipe. One thing I forgot is that what is the rationale behind the definition of this number inertia force by viscous force, how is that able to determine whether the flow is laminar or turbulent. So, a very simple answer to this question is that the inertia force is something which tries to make the flow haphazard or random, like what is shown in the path line of turbulent flow. Viscous force, viscous is a damping as we have seen while defining a fluid, so because the damping nature of the viscosity, it tries to reduce this kind of fluctuation.

So, a relative value of inertia and viscous tells us whether the flow is laminar or turbulent. If the inertia is more, then it becomes, it tends to become more turbulent, if the viscous force is more, then it moves towards a laminar flow. That is a very simple explanation for the fact how Reynolds number can be used to classify laminar and turbulent flows. Apart from this there are further ways you can classify a flow

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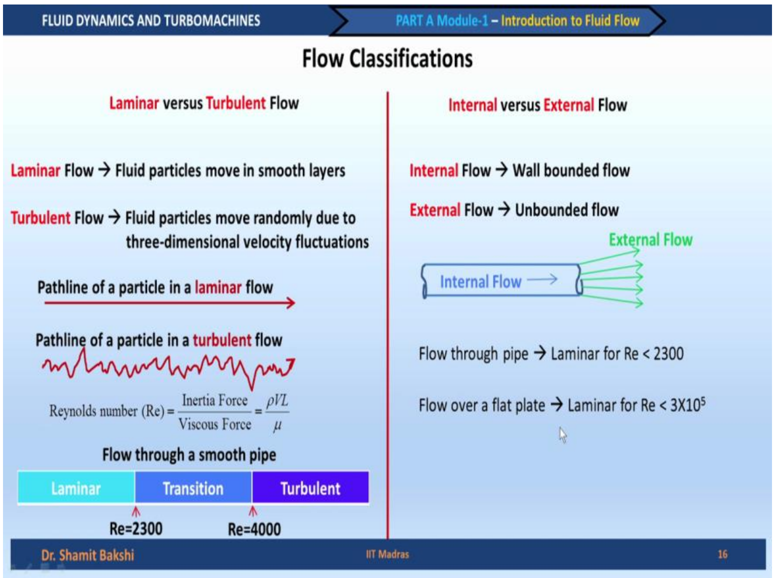


One thing is quite useful in fluid mechanics is internal versus external flows. So, what we mean by internal flows? Internal flows are basically wall bounded flows, that means the flow is surrounded by a wall. External flow are unbounded flow. So, why do we need to classify these two flows? Before going to that let us take an example. The example is again this pipe flow, so the flow inside the pipe is the actually an internal flow. When it comes out, it forms a jet here, this jet is an example of a external flow. Inside the pipe, it is bounded by the walls of the pipe, outside the pipe, it is unbounded, so this flow takes place in this, it extends everywhere. So, there is no boundary, so this is called an external flow. Now, why, so this is internal flow and this is external flow.

Now, why do we need to classify these two flows? I can explain that using what we have just now talked about, we talked about laminar versus turbulent flow, so if we take an example of internal flow through a pipe, as we saw here, the laminar foray, the flow to be laminar, the Reynolds number should be less than 2300. Let us consider a flow over a flat plate, for this flow to be laminar, so this example of flow over a flat plate is again and unbounded flow because although you have a plate on one side, the other side is unbounded. As you go perpendicular to the plate, there is no boundary, if you put a plate on the top, it becomes a flow through a channel but if you do not put, it is just a flow over a flat plate, it is an unbounded flow.

So, if you take an example of flow over a flat plate, you can see for the flow to be laminar, the Reynolds number should be less than 3 into 10 to the power 5, of course Reynolds number is defined using different length scale for which is the length of the late in the case of a flow over a flat plate but you can see that the first, these two flows are, flows have very different characteristics, that is why we need to study this flow in a different way. The number designating the transition from laminar to turbulent, that is Reynolds number in these two case have very different values for an internal flow and an external flow like this. So, we need to distinguish and study them separately.

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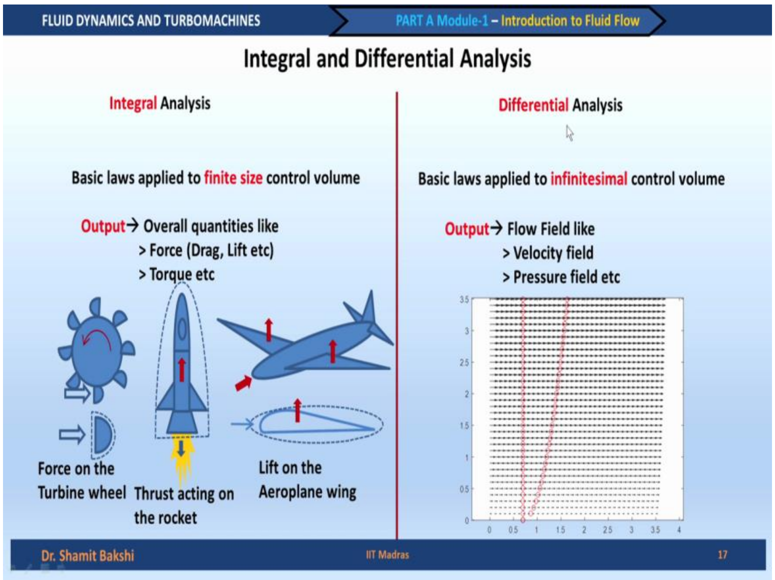


Before ending this first part we also want to use the concept of the integral differential analysis because this is what we are going to do in the next two chapters of our study of fluid dynamics. So, there are, these are two main ways of analysing fluid flows. So, what do you mean by this integral and differential analysis? So, we just list the characteristics of integral analysis here and differential analysis on the right hand side. In the case of main difference is that in the case of an integral analysis, the basic laws, conservation laws which we will introduce very soon are applied to finite size control volume. We will give example of this finite size but in the case of a differential analysis, these basic laws are applied to infinitesimal control volumes, very small control volumes.

So and what happens to do this different consideration of the size of the control volume? What happens is the output here, we try to do this analysis where we intend to get output like overall quantities like the force, force in terms of drag on a plate or drag on a aeroplane or lift on a hydrofoil, whatever it is torque, things like this. So, these overall quantities are the parameters of interest. Whereas in the case of differential analysis, the parameters of interest are different because we have taken very small control volumes, we can get flow field, so we can get velocity field, we can get pressure field and so on and so forth, temperature field etc.

So, the depending on what we want to get from the analysis, if we are interested in these overall quantities, we go for an integral analysis, if you want to get detailed information like the feel information, slow field information, we go for a structural analysis. We take an example of this, some examples of where they can apply integral analysis. So, Pelton turbine and then we can see, if you take, so this is the direction of the flow, it is hitting this turbine blade and the turbine is rotating. Now if you consider just one of this, you can consider a control volume across this and you can find out force on the turbine wheel, this is very useful because this will help us to find out from the, how the torque generated in the turbine is related to the velocity of the flow hitting the turbine blades, by using a control volume analysis.

So, the control volume, actually we will introduce in the beginning of the next chapter but it essentially means this is a fixed region in space which can exchange both mass energy with the rest of the space. So, by doing this analysis we can find out force like this. For this case, let us say we have a rocket and we can take control volume like this in the rocket and find out the thrust acting on the rocket. Similarly we can take an aeroplane and we can take the wings of the aeroplane, the aerofoil section, the flow across the aerofoil section and we can find out the lift on the aeroplane wing.

So, this kind of information definitely are very useful to us, these are just three examples and for you can go on like this and then these are very useful to us. On the other hand, this is also useful, differential analysis is also very useful when we want to look at the details of the flow, like say the flow field. This is an example, like flow over a flat plate, we want to see how the velocity varies along the Y direction, this is the velocity profile like we demonstrated this before while introducing a timeline. So, this is like how the velocity varies, if you go in that direction perpendicular to this one. So, when we want this detailed analysis and how does it vary along X direction also. So, when we won the detailed velocity field, we do a differential analysis.

So, this brings us to the end of the third lecture. In this lecture we have looked at, we have just started with what we ended with in the last lecture where we introduced Newtonian fluids in the in this lecture we started with non-Newtonian fluids, different types of non-Newtonian fluids, their behaviour, how the stress and the rate of deformation are related for different types of non-Newtonian fluids and we looked at flow classifications like compressible versus incompressible flow, viscous versus inviscid flow, then so and so forth, internal versus external flow, laminar versus turbulent flow, these 4 classification we looked at. These are the major ways of classifying fluid flows.

There could be more ways also but these are the main ways generally we classify fluid flows. And we have also looked at 2 different types of analysis and this is very pertinent to us in terms of what we are going to talk about in the next 2 chapters. In the next chapter we take up integral analysis and then we will take up differential analysis in the 3rd chapter. Thank you.