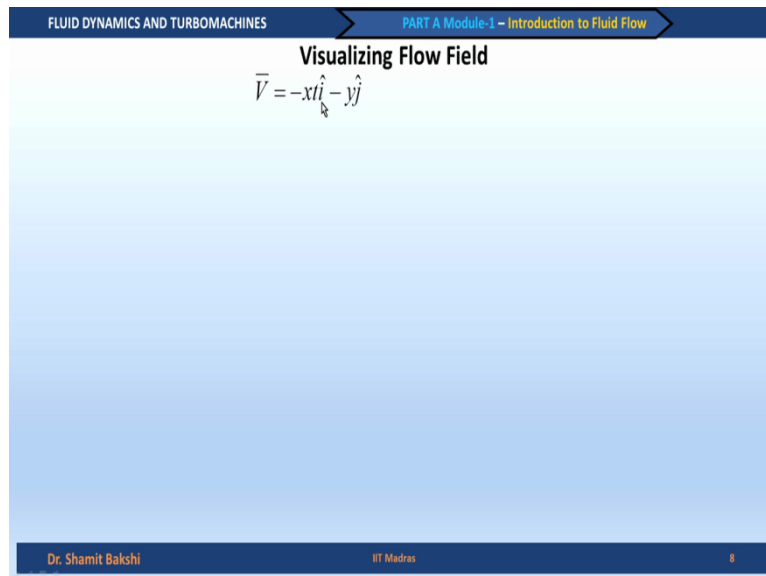


Fluid Dynamics And Turbo Machines.
Professor Dr Shamit Bakshi.
Department Of Mechanical Engineering.
Indian Institute Of Technology Madras.
Part A.
Module-1.
Lecture-2.
Introduction To Fluid Flow.

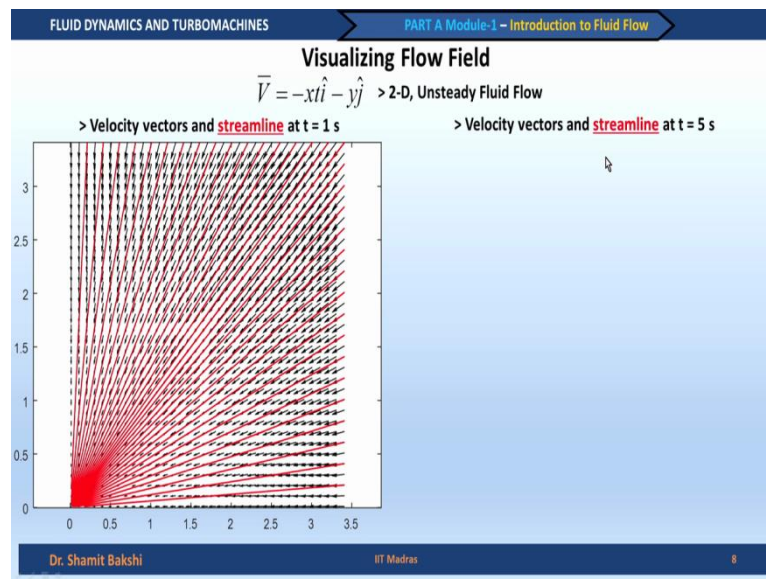
Good morning, so we will start with our 2nd lecture in the last lecture we looked at some basics of fluid flow, we defined fluid, we defined continuum and we also looked at certain fluid properties, density in the context of continuum and also the velocity field. We also introduced the concept of Eulerian and Lagrangian approaches. So, in the lecture 2, we continue with the flow field, there are different ways to visualize a flow field.

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So, let us take an example of the velocity field, now in the last case which we have demonstrated in the last lecture, the flow field was a steady two-dimensional but now we have taken a non-steady flow field. So, it has a T component here, you can see here and just to remind ourselves, the velocity is basically a velocity at the point because we are always following the Eulerian approach of fluid mechanics here. This is a velocity of a point, velocity at a point. Now, so the X component of velocity, I hat is a unit vector in the X direction, so X component of velocity at time 0, everywhere it is 0 because it is -X into T. As time increases, it increases. The Y component of velocity is independent of time but it increases in the direction of Y as Y increases.

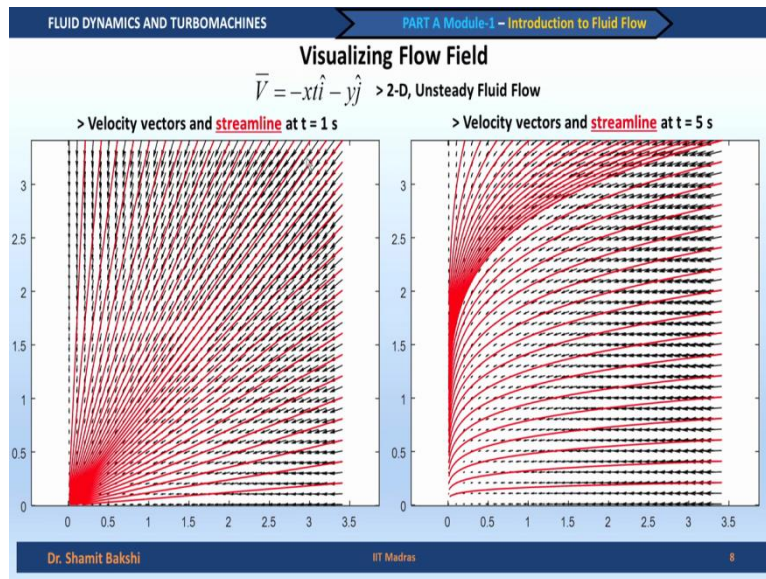
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So, it is a 2-D unsteady flow. Now, this, let us see the flow field for this slightly changed situation. The 1st thing which we can use to visualize the flow field is to look at the streamlines. We have defined streamlines in our last lecture. Basically these lines are lines tangent to these lines are actually the direction of velocity and perpendicular to these lines there is no flow because the velocity is tangential to the streamlines. Let us look at the velocity vectors and streamline at a time 1 second. So, basically few lot it, it comes like this, the velocity vectors are shown in black, whereas the streamlines are shown as red lines. In this particular situation of course these lines are straight but it need not be straight as we will see very soon.

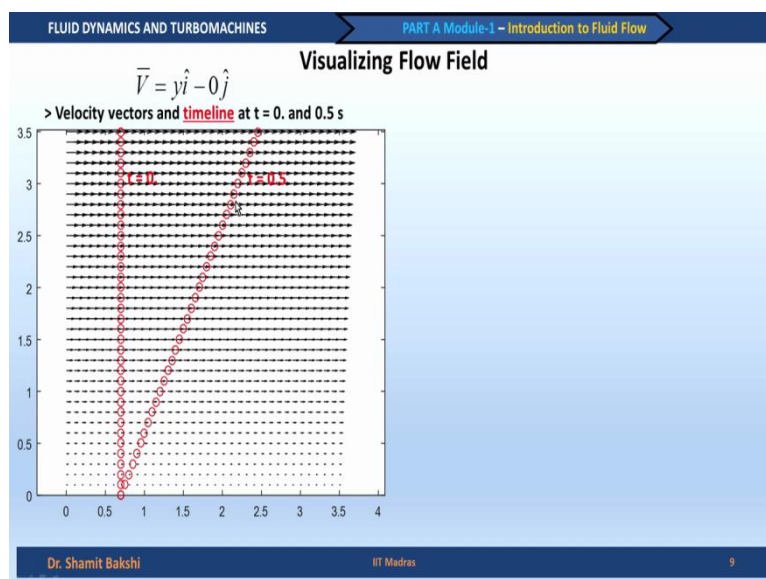
Now, everywhere you can see that if you draw a tangent to the line, it falls in the direction of the velocity vector. Again we can see here that at T equals to 1 second, this velocity, X directional velocity is -X whereas the Y directional velocity is -Y. So the velocity field is something like this, all the velocity is as we go far from 0,0 which is shown here, the velocity values increases and everything is directed towards the origin. So, this is basically the velocity field. Now, if we go to a time, a higher time, that is let us say T equals to 5 second, the velocity vectors and streamlines, let us see how it looks like.

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So, what we see is it demonstrates complete it demonstrates unsteadiness of the flow, the flow field has completely changed at higher time and the streamlines have also changed. So, that means the streamlines actually changes with time as the velocity field changes. Mostly the streamlines are used to visualize the flow field when we are doing a analysis. So, it is very useful to see the direction of the flow to look at, to understand the direction of the flow using the streamlines. It is difficult to get experimentally the streamlines. So, for doing, for getting, for visualising a flow field experimentally, we use different kinds of lines. We will see that in the next slide.

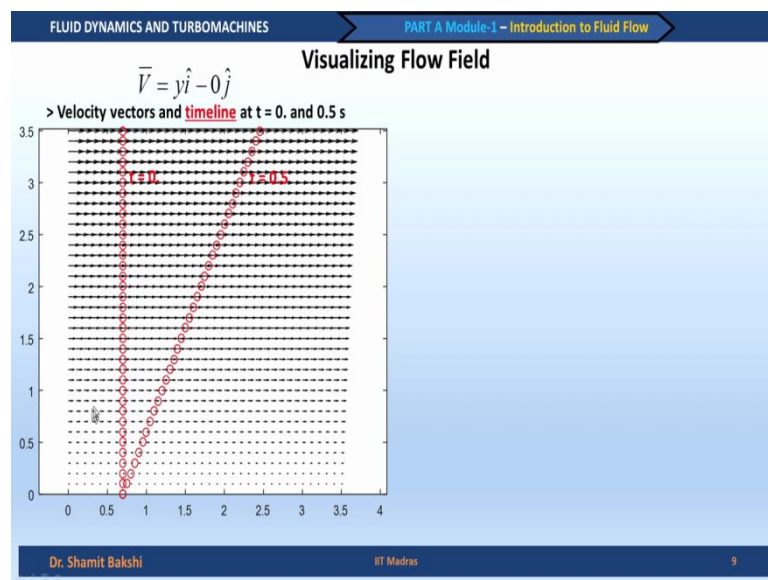
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So, one another line which is used for visualising flow field is called Timeline. So, let us look at the velocity vectors and Timeline at T equal to 0 and 0.5 second. Before we go into this, let us see, let us define what is a timeline. Timelines are basically lines introduced in the flow and looked at the line that deformation or the change in the line as the flow evolves or the as the time changes. So, you introduce a straight line for example in the flow and see how it changes as the time passes. We look at why, what is the significance of this and how we can experimentally visualize it. We have taken the example of a velocity field as shown here. The velocity field is like X directional velocity is proportional to Y, that means at Y equal to 0 the velocity, X directional velocity is 0 and as you move along Y axis, the velocity increases.

And the Y velocity is actually identically zero everywhere. Now, so let us say this is basically, if we joined this circles, the red circles we will get a line, we will say that this is one line and now at T equal to 0, if we look at the same line at 0.5 second, it will look something like this. So, this is an example of a timeline. How is it useful? If we look at the velocity variation along Y direction, the X directional velocity is linearly changing in the Y direction. It is directly proportional with in with the Y coordinate. If you look at the timeline qualitatively, it is very much representative of the velocity profile.

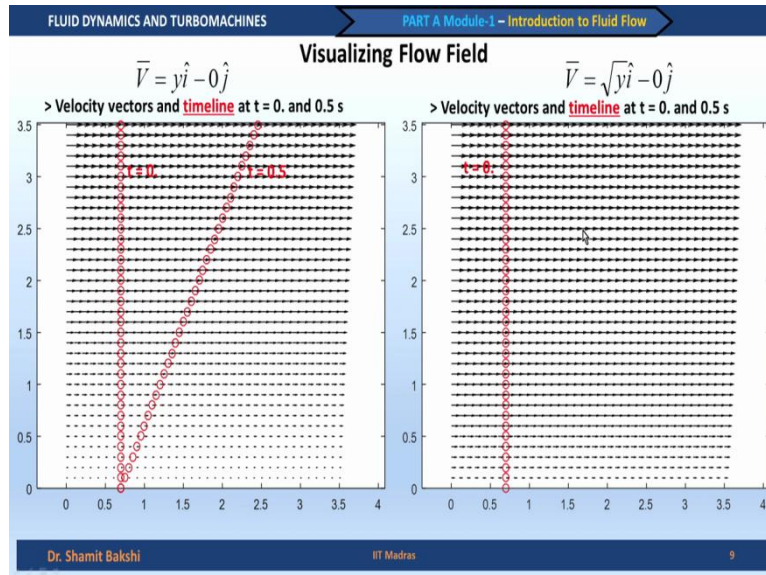
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So, experimentally actually you can generate this streamline by relieving some particles from here. Let us say we release bubbles from the bottom of a, this is a flow over a flat plate, this is very similar actually to the flow over a flat plate, not with respect to the velocity profile but with respect to the no-slip condition on the bottom wall, on the bottom surface. So, now if

you release bubbles, if there was no flow, the bubbles will actually follow this line. And when there is slow, gradually it will get shifted. The bubbles which are located very close to the wall will almost, they will not move or they will move to a very small distance, far away from the wall as the velocity is higher, so they will move through a large distance.

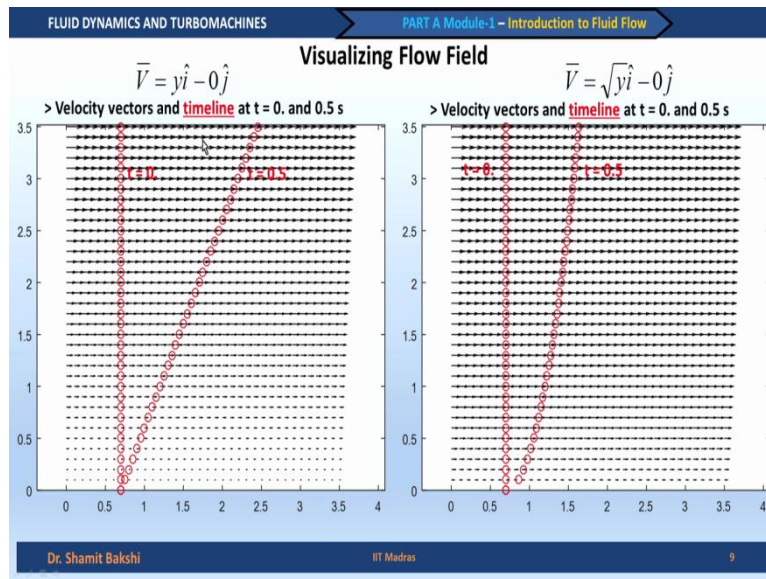
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So, if we want to get an idea about the characteristics of the velocity profile, we can use these timelines. To demonstrate this further, we take another velocity field. So, now instead of saying the velocity field in the X direction which was directly proportional to Y in the previous case, now it is proportional to square root of Y or Y to the power half. Y velocity or VY is again identically zero.

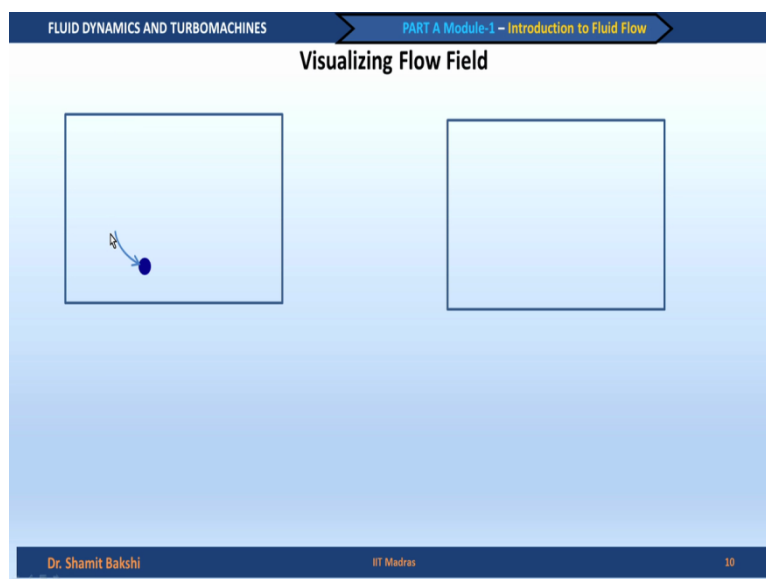
Let us see what happens to the timeline under this situation. So, now we again draw the timeline at time 0, that is the line introduced into the flow field and what happens to it after 0.5 seconds. So, this is at time T equal to 0, you can imagine it as bubbles released from the bottom of this plate and it rises in absence of, the way it rises in absence of a flow.

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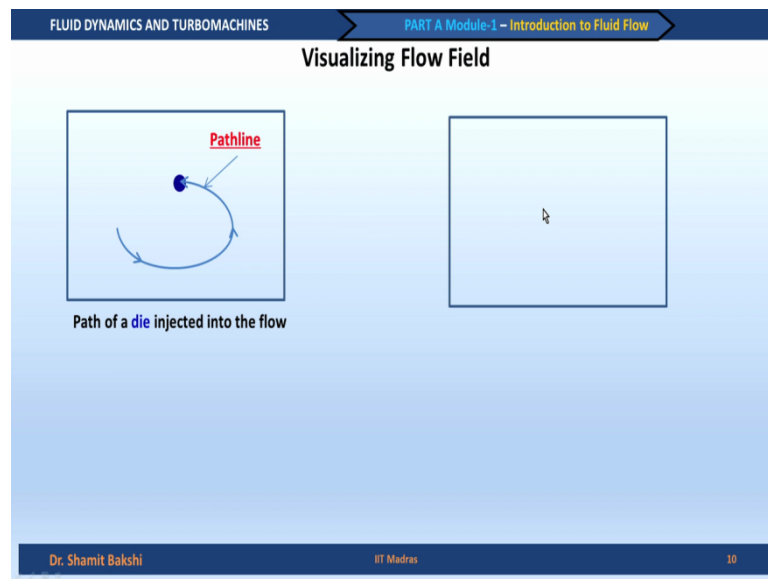
Now, as the flow starts, as the flow field is established, in that, under that condition, the bubbles move and they take the positions in something like this, which is different from the first case. So, in the second case at 0.5 seconds, the positions, the bubble, take again, is very similar, will become very similar to the velocity profile. So, this kind of visualisation actually helps us to directly look at the characteristics of the velocity profile in a flow situation. So, we have seen streamline in the last slide which is useful, more useful for visualising a computed flow field. Timeline is useful to look at the velocity profile experimentally. The other ways of visualising a flow field, so we will introduce that in the next slide.

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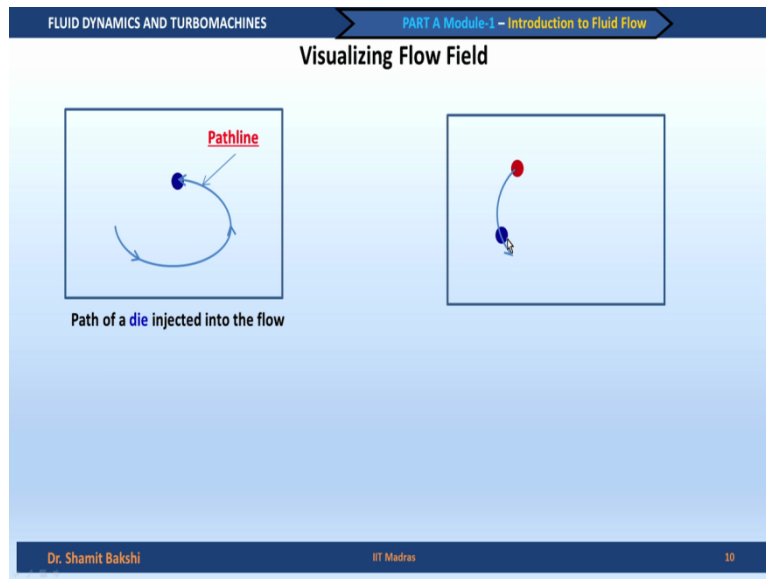
For doing that what we do is we consider this domain, this fluid domain and now we consider a particular region. So, this is basically a particular region in the flow, a small region in the flow, we consider now a fluid particle in that region. So, if we introduce a particle in this region, in a flow field which is established here it will actually start moving because there is a flow, established flow field in this domain.

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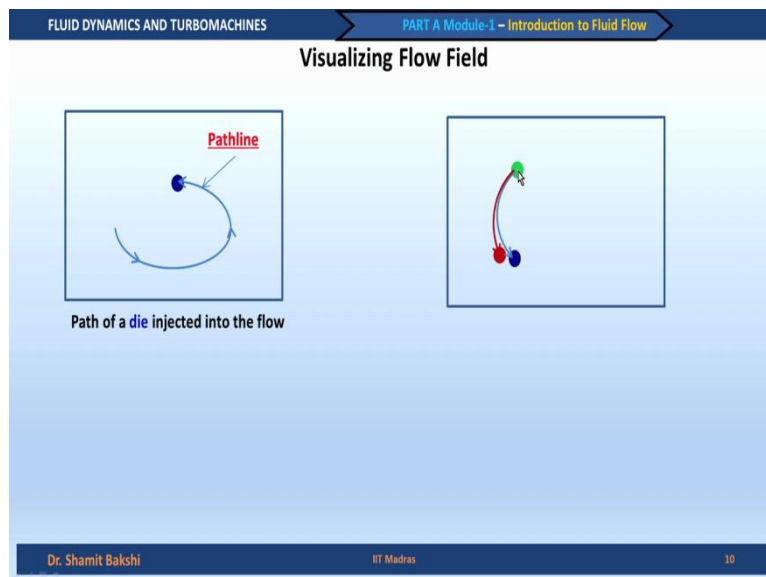
So, the particle follows the flow field and moves to the new region, then again it goes to its next position, so in this way it moves. The flow field is let us say such that it takes the particle in this particular trajectory. The line which is formed by following this particle is called a path line so, this is also useful to see how the particles are moving within a, fluid particle are moving within a flow. Experimentally it is easier to get this kind of path lines, you can inject a die like we did here, let us say this blue article represents a blue die, so we inject a die at this location and then trace, track it as it moves within the flow field. So, this gives us a path line.

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Like in the case of streamline, the path line is also in an unsteady flow, it is a function of time. For example, the particle, if it is an unsteady flow, a particle introduced at the same point at the next instant of time need not follow the same trajectory. So, the path line will not be the same. We will demonstrate this fact in this next figure. In this figure, let us now say we have this blue particle introduced into the flow. As it is introduced, it moves to its new position which is this and at that time instant, we introduce a second particle which is different in colour.

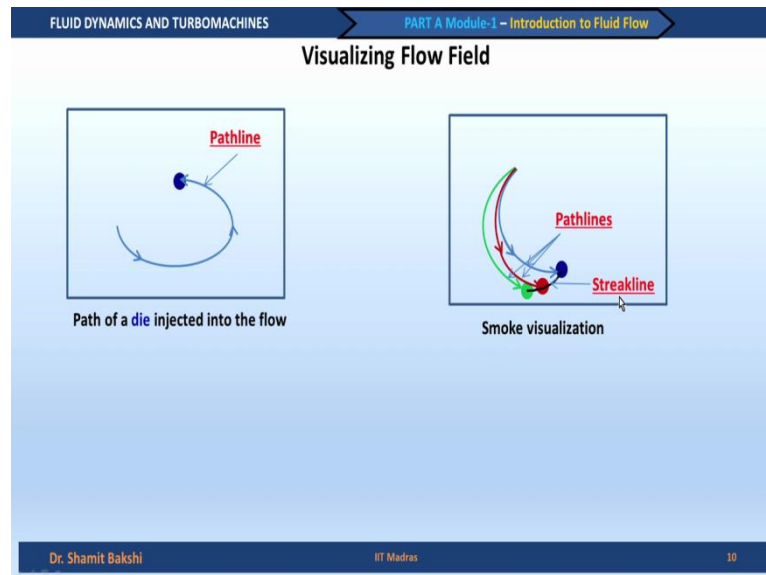
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Now, this particle which is introduced at the second instant of time can follow, if the unsteady, can follow a different trajectory, so you can have a different path line for the

particle injected at the same point. Let us say at the second instant when the first particle has again moved to its new position and second particle has moved from the first to the second position, we introduce another green particle at the third instant of time. And then we follow it, it can again go in a different way as the flow field is unsteady.

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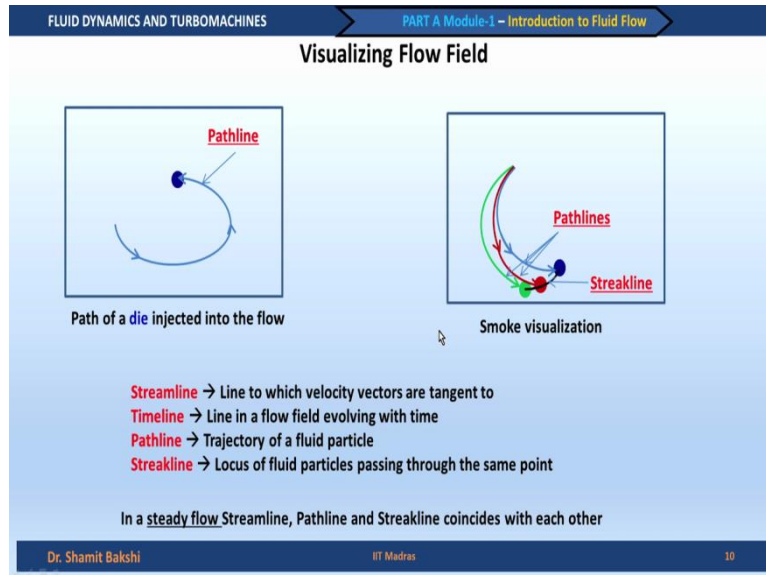
Now, each one of these, according to our previous definition of path line, is one of this is actually a path line. It is the path taken by a particle introduced into the flow, so this, all these are actually path lines. All the three lines shown by different colors are path lines. We can define another line by joining this locus of all the particles which passes through, which are introduced initially from the same point and this line is called as streak line. So, basically this is the locus of particles which has been injected at the same point.

Now, if this field was not unsteady like in the case which is demonstrated here, then this particle would have actually fallen in the trajectory of the first particle, in the path line of the first particle. The third particle which is green in colour would have also fallen in the path line of the first particle and if we joined those lines, if we join the locus, if we take a locus of all the particles, then we will actually get the path line back. So, it is, it can be seen that in the case of a steady flow, the path lines and streak lines are actually superimposed with each other.

The example, the experimental method for visualising path streak line is a smoke visualisation, that means you are in the case of path line, we inject a die, a small drop of die and see how the die, the trajectory taken by the die, whereas in the case of streak line, we

keep on injecting some seeding particles or some dye or smoke at a particular point and keep on tracking the trajectory taken by the entire smoke trajectory. So, this smoke visualization is an example of a streak line.

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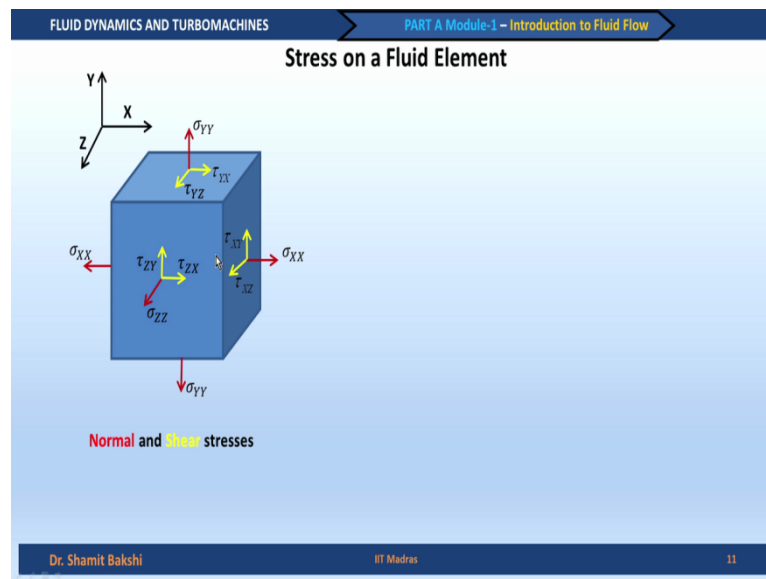


So, just to revise what we have demonstrated in the context of visualising a flow field, we have introduced the concept of streamline, the streamlines are actually lines to which the velocity vectors are tangent. Timelines basically are lines in a flow field evolving with time. So, if you introduce, this is, this need not be in a particular direction but you just introduce a line into the flow field and see how it evolves with time.

It is useful to get if you, if you can thoughtfully introduce a line at the initial time instant, you can figure out the velocity profile by looking at the evolution of the timeline. Path line is basically a trajectory of a fluid particle. So, path line pertains to a particular fluid particle. Streak line is locus of the fluid particle passing through the same point.

Now as we have said before, you can see that in a steady flow, all these lines, no, not the timeline but the streamline, path line and the streak line, they actually coincide with each other. In an unsteady flow, like demonstrated in this second, the second part of this, part of the slide, this right part of the slide, they could be quite different, the path lines could be quite different in an unsteady flow, they will not overlap with each other.

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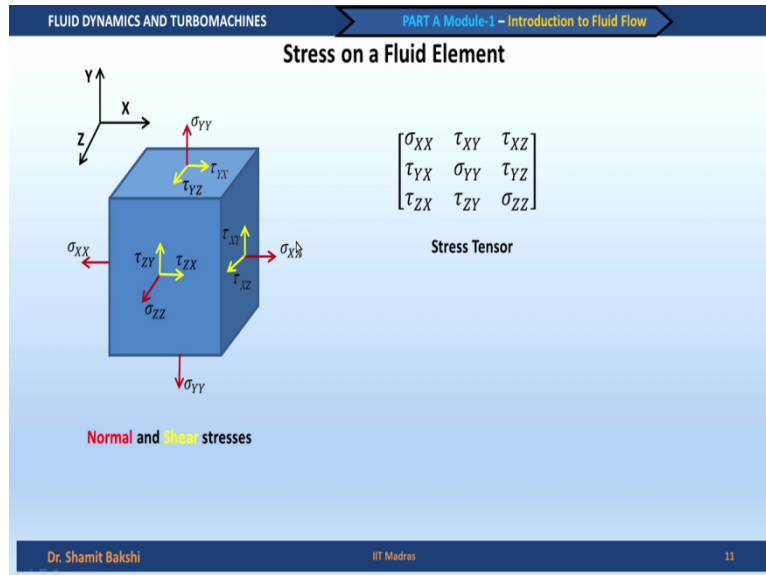
The second, so we have after introducing the continuum concept, we have looked at different field of different properties, we have looked at the velocity field, we have looked at how to visualize the flow by looking at different approaches. We let us now look at the stress on the fluid element or the stress field in the fluid. So, to look at the stress on a fluid element, let us take this as our reference system, X, Y and Z and we consider a three-dimensional fluid element as shown here. Now, if we look at the stress on the fluid element, first we talk of normal stresses, like the stresses which are perpendicular to the plane on which it is acting. Or we can say it in a different way, we can say the stress is the direction, the orientation of the stress is parallel to the direction of the plane.

What do you, what is meant by the direction of the plane? The direction of the plane is actually the direction of the normal drawn to the plane. So if you draw a, if you take this plane and draw a normal, its orientation will be same as the orientation of the normal stress. So, this is an element on which normal stresses are shown. In fact you can see the nomenclature has a certain indication. It shows, it says Sigma XX instead of Sigma X, it means that this stress acts on in the X direction and also in X plane. We will see this further when we demonstrate the shear stresses. So, now the yellow arrows actually show the shear stresses acting on this fluid element on the three planes which are visible in this view.

Let us take an example of this Tao YX. So, this Tao YX is actually acting in X direction and it is acting on the Y plane. What is meant by our Y plane? The Y plane naturally means, if you draw a normal to this plane, it will be parallel to the Y axis. So, the first one represents the plane on which it is acting, the second one, X represents the direction in which it is

acting. So, similarly you can name this as Tao YZ, Tao XY, Tao XZ and so on so forth. So, these are stresses which are acting on the fluid element. There are both normal stresses and shear stresses.

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If you have to represent the stresses in a compact way, then you can use this stress tensor. So, the stress tensor is actually it has nine components. Now, before going into the details of that, what we see is, when we represent a force actually, it is a vector quantity, it has three components. When we represent a stress, we need nine components. The reason behind this is, when we represent a force, it is just a force, whereas when you represent a stress, it is force per unit area. So, we have to bother about how the area on which the force is acting is oriented to the direction of the force. So, that actually distinguishes the stress into normal stress and shear stresses. So, even in a three-dimensional situation like, this element is that three-dimensional element, you can have three normal forces like this and you can have three shear stresses acting in three different directions.

Of course you will have complementary stresses acting in the other planes, in the parallel planes which are not visible in this view. So, when we talk about stress, we cannot explain the stress, state of stress just by using three components, if we have to use the components of the normal as well as the shear stresses. That is why we use a stress tensor rather than a vector.

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FLUID DYNAMICS AND TURBOMACHINES PART A Module-1 - Introduction to Fluid Flow

Stress on a Fluid Element

$$\begin{bmatrix} \sigma_{XX} & \tau_{XY} & \tau_{XZ} \\ \tau_{YX} & \sigma_{YY} & \tau_{YZ} \\ \tau_{ZX} & \tau_{ZY} & \sigma_{ZZ} \end{bmatrix}$$

Stress Tensor

For Solids → Hooke's Law of Elasticity $\sigma = E \epsilon$

For Fluids → 2D Element subjected to shear stress

$$\begin{bmatrix} \sigma_{XX} & \tau_{XY} \\ \tau_{YX} & \sigma_{YY} \end{bmatrix}$$

Stress Tensor for a 2-D Element

Elastic Modulus

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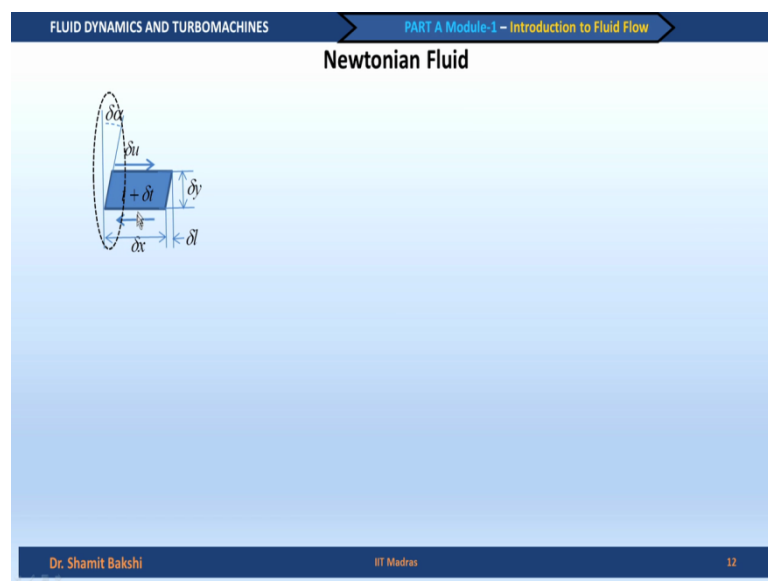
If we talk about a stress tensor for a 2-D element, of course we will not have the normal stress in the Z direction and the shear stresses acting in the Z direction. So, basically if you see this is the normal stress σ_{ZZ} in the Z direction and these two are the shear stresses, either in Z plane or Z direction. So, we do not have this in a 2-D element and the shear, and the stress tensor looks like this. Now, you have a stress filled within the fluid, within the entire fluid like which is demonstrated in a fluid particle or a fluid element. The important thing to consider now is how this stress, how the stresses which are shown here, demonstrated here, how do they relate to something which we can talk about in terms of a flow like fluid velocity. For solids, we know that the stress is related to the strain by using the Hook's law of elasticity, of course within the limits of, within the elastic limit, that stress and strain are linearly proportional.

Let us see how it transforms, this law transforms in the case of a fluid. We have seen in our first lecture that the fluid behaves differently than a solid when I shear force is applied to the fluid. Here, let us see how the stress relate, how can we express stress in terms of something like velocity or what is the complementary part of Hook's law for fluid. Of course this is, I already told that stress and strain our proposal and E is basically the elastic modulus. So, E is basically a property of the, it is a property of the solid which characterises its elasticity. We also said that solids are elastic whereas fluids are viscous. So a similar property should be there for fluid which can correlate the stress with something like deformation.

So, we will see that, before going into that lets look at a 2-D element instead of that three-dimensional situation which is more complicated. So, for fluids, let us look at a 2-D element

subjected to shear stress. We have only considered shear stress here because the normal stress is important only when the compressibility comes into picture. We will talk more about towards the end of this first part of the introduction to fluid flow about compressible flow but essentially the part relates, normal stresses relates more to the compressibility. Let us see the shear part, how does the shear part relates to the deformation of the fluid because under the action of a shear force, the fluid constantly flows or it, so let us see how or constantly deforms, so how that deformation can be linked or what is the law defining the relationship between the shear stress and the deformation.

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So, we take this element at a time T , a force acts on this 2-D fluid element, of course it will deform, means its shape will change at $T + \Delta T$ and we can take $\Delta \alpha$, the angle made by the edge of the fluid element with this, with its initial direction as the deformation, so it gets deforms. The question is how we can relate this to stress, shear stress. Okay. We will soon see what is a Newtonian fluid but we come back to our discussion of the element. We have taken the element fluid, two-dimensional fluid element introduced in the previous slide for time $T + \Delta T$, when the fluid element is already deformed. Let us say the top part has a velocity ΔU and the size of the fluid element is ΔX and ΔY , ΔL is the deformation, the linear deformation of the fluid element.

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FLUID DYNAMICS AND TURBOMACHINES PART A Module-1 - Introduction to Fluid Flow

Newtonian Fluid

$$\delta\alpha = \frac{\delta l}{\delta y} = \frac{\delta u \delta t}{\delta y}$$

$$\text{Rate of deformation} = \frac{d\alpha}{dt} = \frac{du}{dy}$$

For Fluids \rightarrow 2D Element subjected to shear

$\tau_{IX} \propto$ Rate of Deformation

Newton's Law of Viscosity $\left\{ \begin{array}{l} \tau_{IX} \propto \frac{du}{dy} \\ \tau_{IX} = \mu \frac{du}{dy} \end{array} \right.$

Dynamic Viscosity

Fluid	viscosity (Pa.s)	viscosity (cP)
Water (20°C)	10^{-3}	1
Water (90°C)	0.3×10^{-3}	0.3
Air (0°C)	1.75×10^{-5}	0.0175
Air (27°C)	1.86×10^{-5}	0.0186
Glycerol(20°C)	1.2	1200
Propanol (25°C)	1.95×10^{-3}	1.95

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Now let us look at this part separately, so if you look at it, you can take this part, this angle is delta Alpha, this side, this is the initial edge of the fluid element, this is delta Y and delta L is the linear deformation. So, you can write relationship between these three parameters provided delta Alpha is small. So, you can write delta Alpha is equal to delta L by delta Y. Okay, this angle, this arc, for small values of delta Alpha, this is like a arc, so this arc by this radius, again for small values, this difference between delta Y and this edge can be is negligible. You can write delta Alpha is delta L by delta Y. Delta L deformation can be written as delta U into delta T, delta T is the time spent and delta U is the velocity of the top edge of the fluid element. And so now you can write that d Alpha by dt that is the rate of deformation can be related to the velocity, the velocity gradient.

So delta d Alpha by dt can written as du by dy. So, why are we doing all this? We want to get an expression for rate of deformation in terms of velocity because for the flow field, by the flow field we mainly mean the velocity or its gradient. So, we finally want to relate stress with velocity or its gradient. So, for fluids, a 2-D element subjected to shear, we can, the law says like the Hook's law, this law says that the shear stress is actually proportional to the rate of deformation. Okay. So, rate of deformation is du by dy, so that means the shear stress is related to the velocity gradient as du by dy. And you can make, write this also as an equation by introducing a constant mu, so you can write tao YX as mu into du by dy. This mu is the viscosity of the fluid.

So, this is very similar in the case of solid, the property which or the constant which related the stress with the strain was elastic modulus, here we have viscosity because the fluids are

viscous, whereas solids are elastic within its elastic limit. Of course this is called dynamic viscosity and this law is called Newton's law of viscosity, which is a complementary part of Hook's law applied to fluids.

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FLUID DYNAMICS AND TURBOMACHINES PART A Module-1 - Introduction to Fluid Flow

Newtonian Fluid

$\delta\alpha = \frac{\delta l}{\delta y} = \frac{\delta u \delta t}{\delta y}$ Rate of deformation = $\frac{d\alpha}{dt} = \frac{du}{dy}$

For Fluids \rightarrow 2D Element subjected to shear

$\tau_{IX} \propto$ Rate of Deformation

Newton's Law of Viscosity $\left\{ \begin{array}{l} \tau_{IX} \propto \frac{du}{dy} \\ \tau_{IX} = \mu \frac{du}{dy} \end{array} \right.$

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Glycerol (20°C)	1.2	1200
Propanol (25°C)	1.95×10^{-3}	1.95

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The property viscosity, of course it has a different unit than elastic modulus because elastic modulus you see, it is, it relates stress and strain, so it has the, the strain has no unit, so elastic model is has the same unit as stress, it is Pascal. Whereas this actually it relates, viscosity relates shear stress with rate of deformation, the rate factor is there. So, this unit of du by dy is 1 by second, so unit of dynamic viscosity is, this is Pascal, so Pascal seconds. So, we have demonstrated here the viscosity of some familiar fluids. Let us take a little, little look at the values of the viscosity.

So, let us take water at 20°C, the viscosity in Pascal seconds is 10 to the power -3, of course Pascal is actually I am sorry is actually SI unit, certain newton per metre square. So, water at 20°C has a viscosity of 10 to the power -3 Pascal seconds, you can also represent this in the CGS unit which is shown here. The viscosity of water at 20°C is 1 centi poise, poise is actually dyne second per centimetre square. And if you, we write it as centi poise, that is 10 to the power -2 into poise, 10 to the power -2 dyne second per centimetre square, because the value of water becomes one if you write it as centi poise. So, it is very remember also, water at 20°C is 1 centi poise which is 10 to the power -3 Pascal seconds. This also gives us, helps us to remember the relationship between century poise and Pascal seconds.

Now we take water at 90°C, it has lower viscosity, so what we see for liquid, the viscosity, the property which we got from the relationship between stress and the rate of deformation, we see that this is also a function of temperature, as the temperature increases, the viscosity decreases. But this is only true for liquids where the inter molecular force loses if you go to higher temperature. Let us take an example of air at 0°C, so you can see it is very Inviscid, of course we know that air is much Inviscid, so to look at the value, it is 100 times, 1 by 100 times that of water. So, what is 100 times viscous then air.

So, it is about 1.75×10^{-5} Pascal seconds or so much centi poise. But one important thing to note here is the same air at 27°C actually has little higher viscosity, not very significantly different but the trend is different from that for liquid. So, this is the characteristics of gases that they have, for them the viscosity actually increases with increasing temperature. We can, we have taken some other familiar fluid, we have taken the example of glycerol at 20°C, you can see it is highly viscous, it is 1.2 Pascal seconds. So, if you take water, it was one meal a Pascal seconds, whereas glycerol is around 1 Pascal seconds, so 1000 times that of water.

Okay, so similarly here it is 1 and 1200, so you want to this is useful if you want to study the effect, experimentally study the effect of viscosity on certain process or certain, certain things, then you can use this combination, you can glycerol, repeat the process with same maybe other conditions with glycerol, then you can see what viscosity does to that effect, to that particular parameter. In fact we can define some parameter, another parameter called surface tension. This is a useful information for an experimentalist that you see, if you, if you look at the surface tension of glycerol, it is very close to that of water. So, if you want to keep the surface same and study the effect of viscosity, you can do the same experiment using water and glycerol, you will know what viscosity does to them.

Of course this is little out of context but this is useful to know. Experimentally it is very difficult to keep other it is difficult to change only one property to see the effect of that property because if you change the fluid, then lot of other properties also change. Another example is propanol, so this has a very, this is another hydrocarbon and it has very similar viscosity is water as you can see here. So, we saw that fluids are basically dissipative and they show display viscosity, some of the values of viscosities are displayed here.

So, this brings us to the end of the second lecture, in this lecture we have looked at velocity field and different types of parameters to define a velocity field like the streamline which is

useful for visualising a fluid flow, then path line, timeline, streak line. We saw that path line, streamline and the streak line becomes the same in the case of a steady flow. We also looked at the stress field, the stress on a element, on a fluid element, we looked at the stress tensor and then we have also introduced how stress relates to rate of deformation in the case of a fluid and which is also known as Newton's law of viscosity and the fluids which obey this law of, Newton's law of viscosity are called Newtonian fluid. In the next lecture we will begin with non-Newtonian fluids which do not obey the Newton's law of viscosity. Thank you.