Applied Thermodynamics for Marine Systems

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Lecture - 15

Basics Laws of Fluid Mechanics

We will start a topic which we can call basics of fluid mechanics. Here, we will brush up or recapitulate the fundamental laws of fluid mechanics particularly those which are very important for practical calculation and engineering practice. I will start with fluid. There is some difference between a solid and a fluid; that is why this name is given and if we like to give some sort of a definition of fluid one can define it like this. It is a substance which deforms continuously under the application of shear stress.

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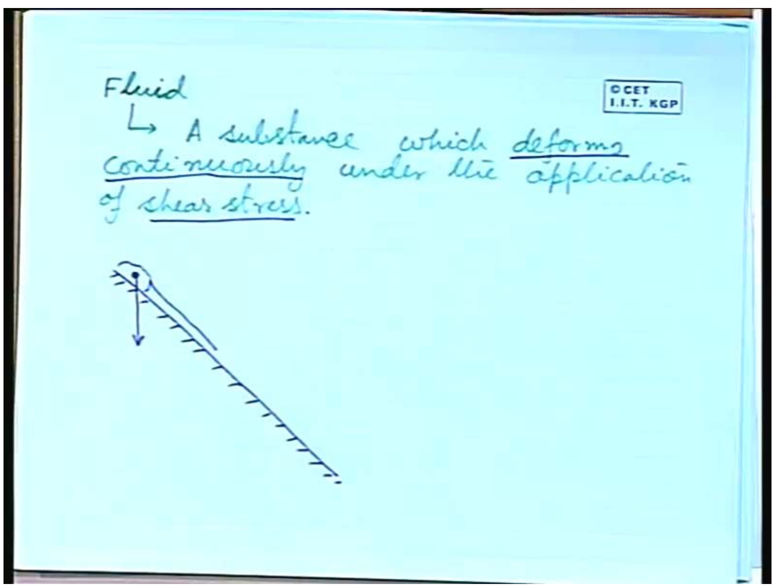

A few things are very important like it deforms continuously. In a solid if we have some applied load we will see that there will be some deformation but the solid will not deform continuously. In case of fluid if it is subjected to some shear stress, then it will deform continuously and this particular property, its manifestation, is in the form of flow. The flow of fluid we get due to this property and that is why this name fluid has come.

I will just give one example. Let's say, we have got some sort of inclined plane, this is nothing but a solid board and what we have done is we have put some water or some liquid here. We will see that it will flow like this. What happens? If we take this fluid mass, we know that its weight is acting in this direction. This weight will have two components and one component will act as shear stress or that will induce shear stress. By the application of shear stress there will be a continuous flow of the fluid. That is what I have told in the definition that it deforms continuously under the application of shear stress. We can get the property flow or flow of the fluid due to that. This is a very important difference with solid and that is how the fluid is defined.

Then, there is another very important difference between solid and fluid; we know that one important characteristic law of a solid body is the Hooke's law. There is some sort of proportionality between stress and strain. If we go for a fluid we will see that similar type of law is there but that is not identical. Stress there in the fluid is proportional to the rate of strain, so that is another difference between the solid and the fluid. This is not a typical course of fluid mechanics, I will not go on elaborating all these things, but we know what a fluid is. It will deform continuously under the application of shear stress and also we know that fluid can be broadly classified into two groups. One is a gas another is a liquid and there are some differences between gas and liquid. We will not go into this because already we have read those things in physics or in some subject of engineering. Very quickly we will go through some important properties of fluid; two, three important properties of fluid.

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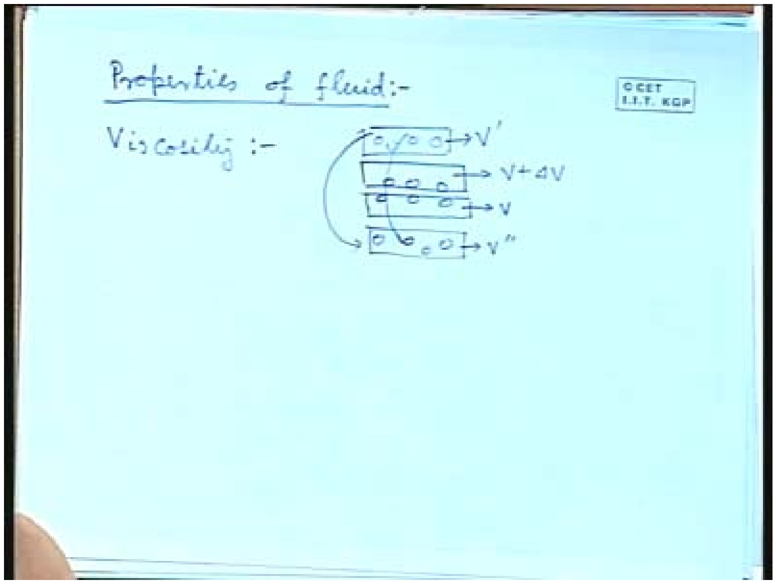

The first property is viscosity. This is one unique property of fluid which makes it different from a solid and also it is very important for understanding different fluid flow behavior or different behavior of fluids. In a nut shell if we want to describe viscosity it is like this. It is an inherent property of the fluid which tries to resist relative movement between adjacent fluid layers. The viscosity is the property which resists the relative movement of adjacent fluid layers. That means if we have two fluid layers, schematically I am showing them like this. Let us say one is moving with a velocity V and other I want to move with a velocity V plus dV. Then, definitely I will face some sort of resistance and this resistance comes due to a property of the fluid that is known as viscosity.

If we see bit closely why this occurs, actually there are different reasons for it and it is not fully explained. Broadly, one can say a few reasons like this that there are fluid molecules and in this there will be some sort of cohesive force. If we want to separate it, separate two layers of the fluid, that means if we want to cause some sort of a relative movement between two fluid layers then, this cohesive force will give a resistance; that is one thing.

Another thing let us say there are two layers but two layers are not adjacent. This is one layer which is having number of molecules like this and this is another layer which is also having number of molecules. Let us say the characteristic velocity of this layer, the average velocity of this layer, is V dash and let us say this is V double prime. What will happen is the fluid molecules are at random motion. So, due to that random motion some molecule will move from here; we can call them molecule or fluid particles; sometimes it is called fluid particle; that will move from here to here. When it is moving from here to here, then it is carrying some sort of kinetic energy which is due to the velocity V double prime and that kinetic energy it is imparting here. Whereas, if another particle moves from the top layer to the bottom layer that carries some kinetic energy which corresponds to V prime.

We can see that this velocity influences the movement of the top layer and the velocity of the top layer influences the movement of the bottom layer. If it is moving faster it will try to push it or pull it faster and if it is moving at a slow rate it will try to pull back the lower layer. That is why, we know or we experience that, if we try to cause some sort of a relative velocity between fluid layers, there is some sort of a resistance. These are the molecular explanations for the origin of viscosity. This is not a complete explanation. In physics, there could be a better explanation for this, but grossly this explains why there is viscosity.

Another thing one can see is that, I have told you, there is liquid and gas. In case of liquid, this adhesive force is very strong and that is mainly responsible for viscosity. Whereas, in case of gas the movement, the Brownian motion or whatever it may be, this random movement of the molecule that is mainly responsible for the viscosity.

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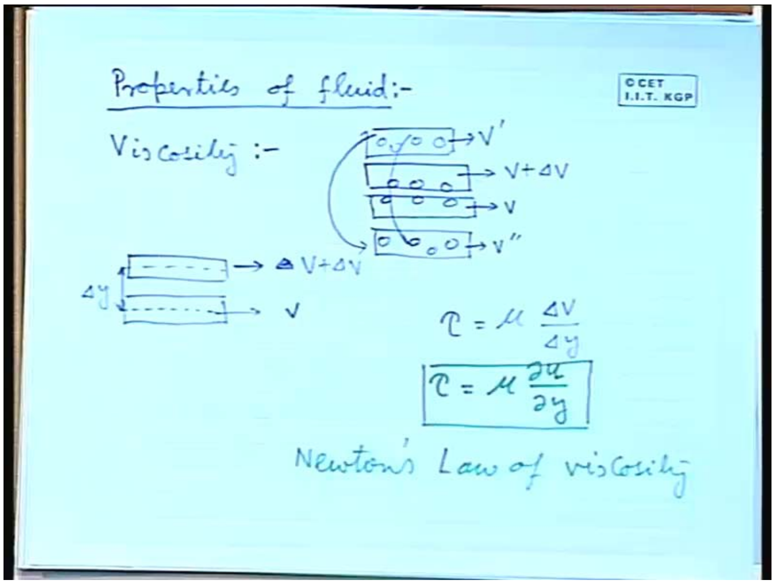

We know that if there are two layers, one is moving with a velocity, let us say, V plus del V and then another is moving with a velocity V. The relative velocity between these two layers is your del V and let us say this distance is del y. We know that between this layer there will be some sort of a shear stress and the shear stress tau is given by mu into del V by del y or more precisely in mathematical notation mu du by dy. This expression is known as Newton's law of viscosity. When we write this equation in this form, it is almost understood it that this mu is constant and when mu is constant for fluids those types of fluids are known as Newtonian fluid. There could be variation with temperature for Newtonian fluids also. But at a particular temperature mu is not a function of velocity or it is not a function of the applied force or the history of applied force like that. If these are true, then the fluid is called a Newtonian fluid. So, at a particular temperature we will get constant mu, mu is not dependent on velocity.

We will have very large number of fluids, common fluids, owing this property and they are Newtonian fluids like air, water and then number of oils; so, they are all Newtonian fluids. There are non-Newtonian fluids also. We can see there are a lot of fluids like tomato ketchup, toothpaste, etc. They behave in a funny manner; their behavior is not as simple as given by this particular equation and they are non-Newtonian fluid. We will not discuss them and only here it is important to know that this is the law of viscosity or Newton's law of viscosity. From here we can get some important information like I will give you one example.

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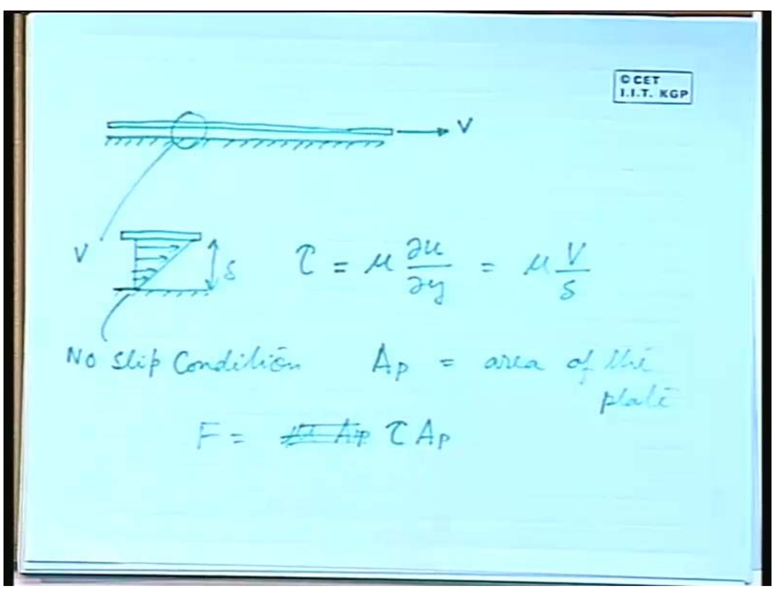

Let us say, we have got a fixed plate. We want to move another plate at the top of this fixed plate and the gap between them is filled up by some sort of lubricating oil. Here I want to draw this with some velocity; with some velocity V, I want to draw this particular plate. How much effort will I have to put that I can determine from Newton's law of viscosity. How do I determine this? If we see an exaggerated view of this particular phenomenon, then this is the velocity distribution in the gap; that means velocity at the fixed wall is 0. This is a very important observation. If there is a solid surface and on the top of it if some fluid is resting and then if there is a movement of the fluid, the fluid can move with any velocity but just at the interface that means where the fluid touches the solid surface there the velocity is 0. If it is in contact with a stationary solid surface then the velocity at that point is equal to 0. This we call no slip condition. That means there is no slip between the fluid and the solid.

As this gap is very small we have taken a linear velocity distribution. So, tau, shear stress will be equal to mu into du by dy. If this difference is delta, this is equal to mu V by delta. This is our shear stress and if I know the area of the plate A_P, then we can calculate force is equal to tau into A_P. Tau we have calculated or Tau we can determine from this equation and if A_P is known, then we can calculate what is the force required to move this plate. A similar example can be taken, like we know journal bearings.

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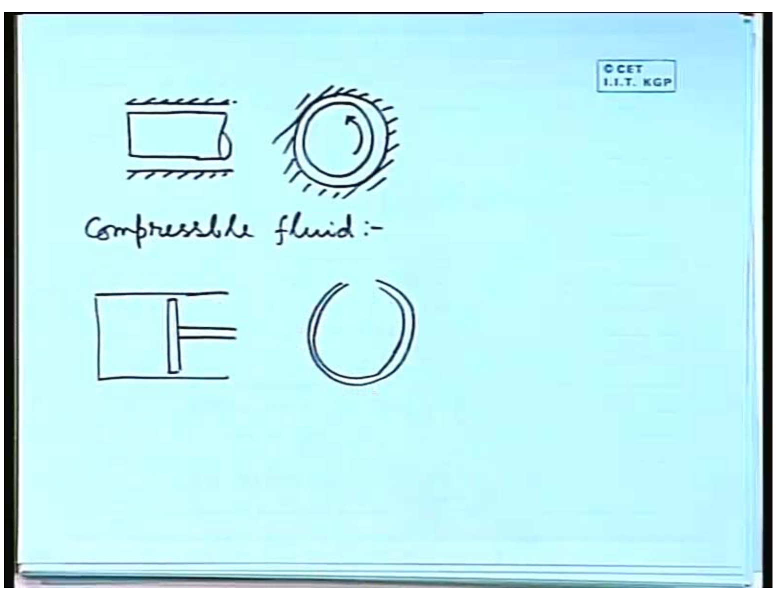

In a journal bearing part of the shaft which is known as journal, that is inside the bearing. It is like this and this is the bearing and this gap is filled up with lubricating oil. If we see from the end we will have some sort of a view like this and the journal is moving and we have got the bearing like this. Here also if we know the rpm of the shaft, if we know the gap, then we can calculate what amount of force is required to overcome the resistance. Where that effort is going? That effort is dissipated in overcoming the viscous resistance. The amount of mechanical energy we are supplying, as energy cannot be destroyed, it is getting transformed into another form of energy which is not recoverable and it is getting transferred into thermal energy. Why I am telling this is we can also know how much thermal energy or how much heat is generated. In the next step if we have to keep the bearing at a particular temperature that is important, because unless we do that the lubricating property of the fluid will get destroyed; so, we have to keep the bearing at a particular temperature. How much cooling is needed also we can calculate from this exercise?

Step by step, one has to first calculate what the shear stress is and then what the force is and then what torque is. Then torque multiplied by velocity will give us the power and that is the power which we have to extract because that power will get converted into thermal dissipation. We know how much cooling water or whatever it may be is needed; may be some heat transfer calculation will also involve in it. This is the utility of the equation which I have shown here, the direct application of this equation.

Then, I am going to another property of fluid which is compressible fluid. We cannot compress a solid. We may put enough amount of load but the change in volume of the solid will be very small. So, a solid is practically incompressible. If we give more and more load, the solid may get crushed but change in volume before crushing will not be much. The same thing applies to liquids also. We can put a large amount of load but the change in volume of the liquid is not very high. In case of a gas, it is not true. We know that if we have got a piston cylinder arrangement we can compress the gas. We can inflate a balloon by sending gas inside it.

Let us now take some other example. Let us say something like a balloon but with a solid or non-deformable wall. We can put more and more gas inside it; we can put a small amount of gas, also we can put larger amount of gas inside it. So, the meaning is that that we are able to compress the gas inside this volume. That means we can see that there are certain fluids which are incompressible and all the liquids are taken as incompressible. There are certain fluids whose density may change with pressure or whose density may change with temperature. In case of liquids also there is a change in density with temperature but that is small. In case of gas we will see that there is a large amount of change of density. So, fluids we can again divide them as compressible fluid and incompressible fluids. Like, before we had classification of Newtonian and non-Newtonian, here also we can have compressible and incompressible fluids. I will not elaborate much in this regard. Let us look slightly into fluid statics:

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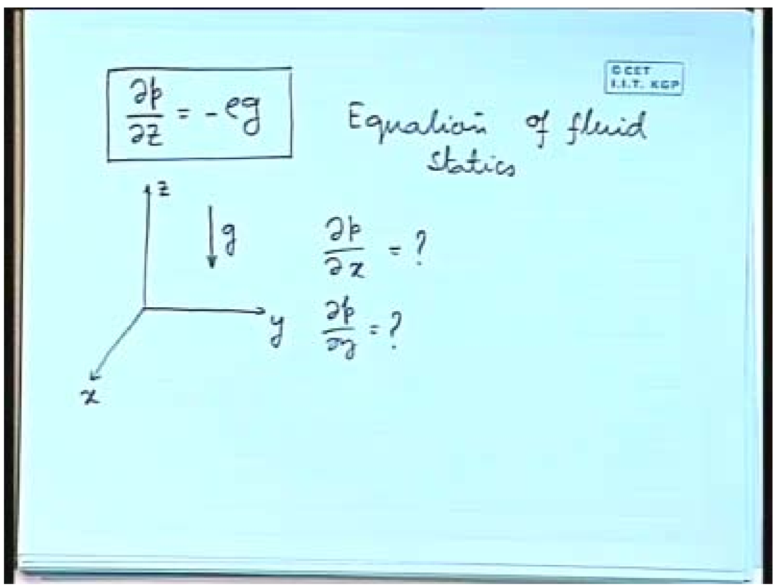

In a fluid, if it is stationary, we can get d_p by d_z is equal to minus rho g. This can be proved. This is equation of fluid statics; $d_p d_z$ is equal to minus rho g. It is like this. We have got a Cartesian coordinate system xyz and g we have taken in this direction. In that case this equation is valid means we have got a particular direction of z and particular direction of g. In a stationary fluid we will have this. Then people may ask, if the fluid is stationary, then what is d_p by d_x and what is d_p by d_y. d_y, I have drawn it. I have taken the coordinate system; both these are 0 and so in x direction and in y direction there will not be any variation of pressure. We will have pressure variation only along the z direction or in other words in a stationary fluid, the planes which are normal to the direction of gravity they will be isobaric planes, constant pressure plane. From here one can also draw some sort of a conclusion that the constant pressure surfaces will be always normal to the direction of acceleration. Those things I do not have time to discuss but this is one of the important equations which one must remember while he is dealing with fluid mechanics or fluid behavior. From this equation, we can again do lot of things; means suppose there is any submerged body we can determine the pressure on the submerged body. I do not know; maybe these types of equations are dealt in detail, when you are doing your …. design or things like that; I do not know.

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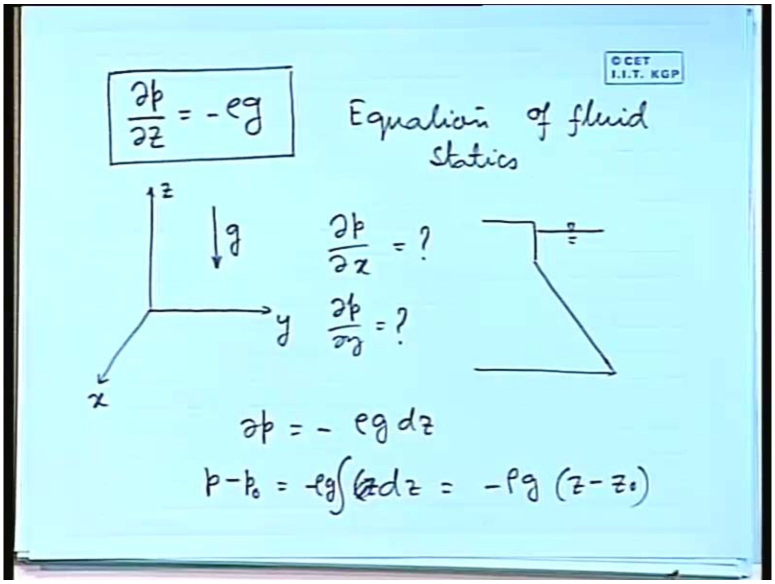

Suppose, there is some sort of a dam like this and we want to calculate what the force on this dam is, we can calculate by the application of this equation and if we do the integration then we get d_p by d_z is equal to rho g. d_p is equal to minus rho g d_z; p minus p_0, let us say we can have minus rho g, we will have d_z. This is d_z and then minus rho g z minus z_0. One can accordingly determine the pressure. That means, if you know pressure at a particular location, at a particular datum level, that is your p_0 if it is known pressure then, you can determine any other pressure at any other point. This is a very simple case, where rho remains constant. If rho varies then also one can determine it. I will go to the movement of fluid motion.

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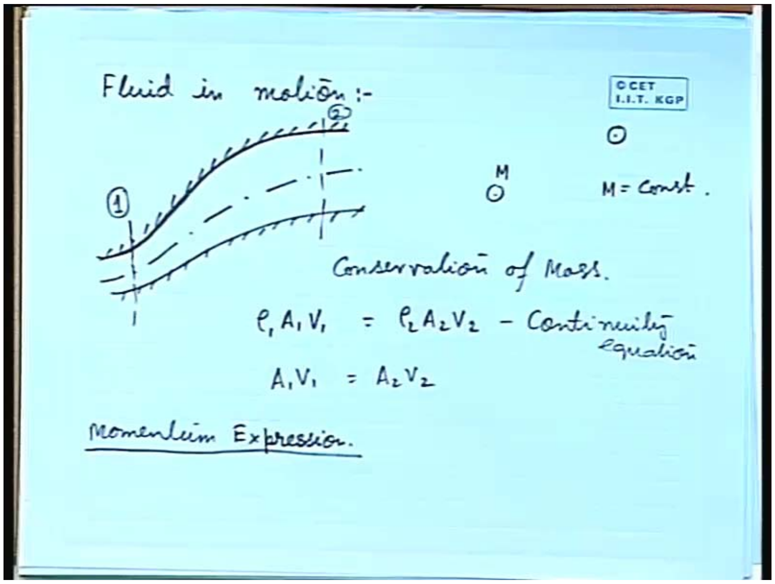

When a fluid is in motion then the behavior will be different. But, whatever laws of motion are applicable for solid body, they are also applicable for fluids. That means Newton's laws will be applicable for fluids. The only thing is that as the fluid is somehow different from a solid body so the end expressions of these basic physical laws are slightly different. That is the difference between the solid and the fluid. Because, in a solid What we can do is we can identify the solid. Once we identify the solid, we can define its centre of gravity or cg and based on the cg we can define its motion. In case of a fluid it is not possible we cannot identify separate identity of different fluid particle. A fluid is taken as a continuum and what we do is, in case of a fluid instead of tracking a particular fluid particle, we focus our attention on the space and on the space how the velocity is changing and how the properties are changing we try to analyze that. The end expressions of the equations are slightly different.

Anyway, if we take any fluid motion let us say this is any arbitrary duct through which the fluid motion is taking place; the basic equation, the first conservation equation or the basic equation of physics which we have to first satisfy for this fluid motion is the conservation of mass. If there is a movement of a solid object, let us say the mass of this object is m; we can simply write m is equal to constant. But here it is slightly different, as I have told you. We can take any two cross-sections. Let us say, this is 1 and this is 2 and we can write $rho_1A_1V_1$is equal to $rho_2A_2V_2$ for the fluid; that means rho is the density, A is the area and V is the velocity. This is how we can write the conservation equation and this equation is also known as continuity equation. If the density is constant then we can get simply $A_1V_1$is equal to A_2V_2. We can get the momentum equation. Momentum equation, I will not write the expression because this, one can write depending on the situation. But, basically change of momentum is equal to force. What we have got in case of solid mechanics, the same equation will be valid here also.

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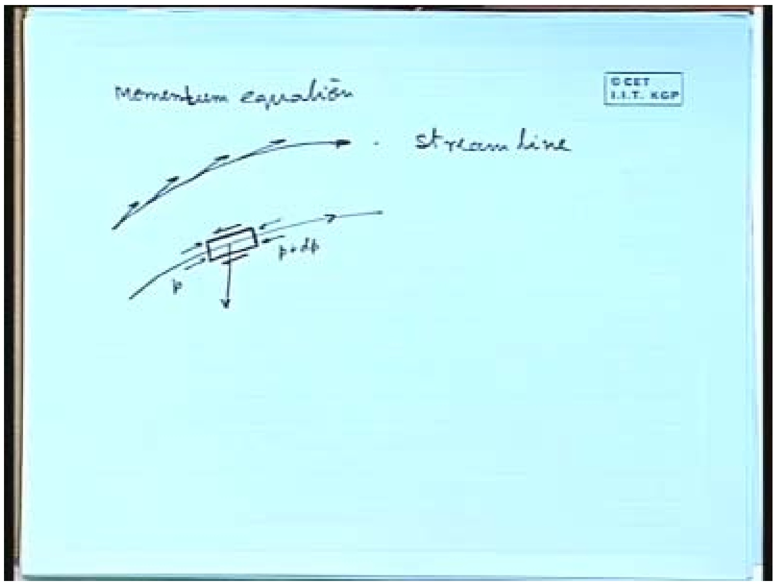

Let us say, we want to analyze or we want to do the momentum balance for a fluid flow problem. Let us say, the fluid motion is denoted by this line which is known as stream line. You see the movement of a solid body it is clearly visible or observable, so we can describe it. This means we can describe it by the locus of the cg, as the solid body moves from point to point. But in case of a fluid we have to have some different technique. If we define it like this, let us say, fluid particle is moving and number of particles is there; it is moving in space which is known in the language of fluid mechanics as the flow field. In the flow field if we have instantaneous direction of velocity like this, if we have instantaneous directions of velocities and I draw a line in such a manner so that this line is tangent at every point to the velocity vector, then this line I will call as the stream line.

I will explain once again. In a flow field, there are motions of fluid particles in different directions. If I draw a line such that at each and every point the velocity of the fluid particle is tangent to that line then that line will be called a stream line. This concept is important. If there is a stream line and let us say there is a fluid body in the stream line like this and for this we want to do the momentum balance. What should we do? What are the forces we will consider and the momentum change?

What can we do? Here some sort of pressure will act and here also some sort of pressure will act. We can write p, we can write p plus d_p. This is one force; here shear stress Let us say the velocity is in this direction. In these two phases shear stress will act because, the other fluid bodies are moving at different velocities; may be more than this velocity may be less than this velocity. The shear stress will come and then we can have the weight of this fluid element. These are the forces acting on this fluid body and we can take their component in a particular direction and mass of the fluid body into acceleration in that direction could be equated to that force. Whatever, we do in the solid mechanics I am not writing completely because our course does not allow that much of time. But this way we can do the momentum analysis or we can write down the momentum equation for a fluid also.

From the momentum equation, I will come to the energy equation. Basically the laws of fluid mechanics, they come from this thing. First thing is your conservation of mass, conversation of momentum and conservation of energy. Over and above, we should have second law of thermodynamics satisfied. If we do all these things, then any type of fluid motion we can analyze. It may be complex fluid motion, the analysis may be complex, complicated, difficult; but it is possible. We go to energy equation.

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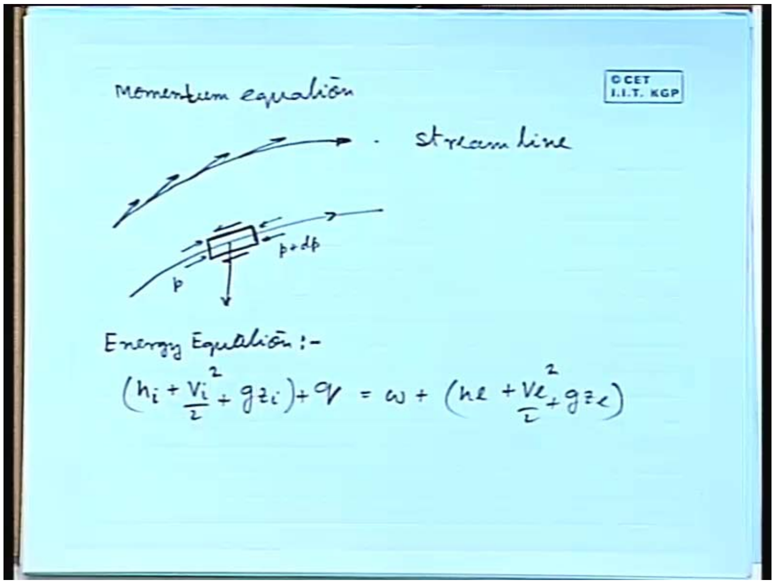

Here, I like to remind you, or I like you to note that the energy equation which we have studied in thermodynamics, which is the first law of thermodynamics that is also valid for any fluid motion and that we can apply. If we see the first law of thermodynamics for steady state what we have done there is, if you remember, $h_1$or h_i plus V_i square by 2 plus gz_i plus q that is equal to w plus h_e plus V_e square by 2 plus gz_e. This equation for steady state is valid for any fluid flow. But when we are discussing fluid flow, in most of the fluid flow, we will find number of situations where there is no exchange of thermal energy and we will also find situations where there is no mechanical work done. In that case, the generalized form of energy equation is applicable but we can get a simpler form of energy equation. The simpler form of energy equation, what we get in a large number of fluid flow situations is known as Bernoulli's equation.

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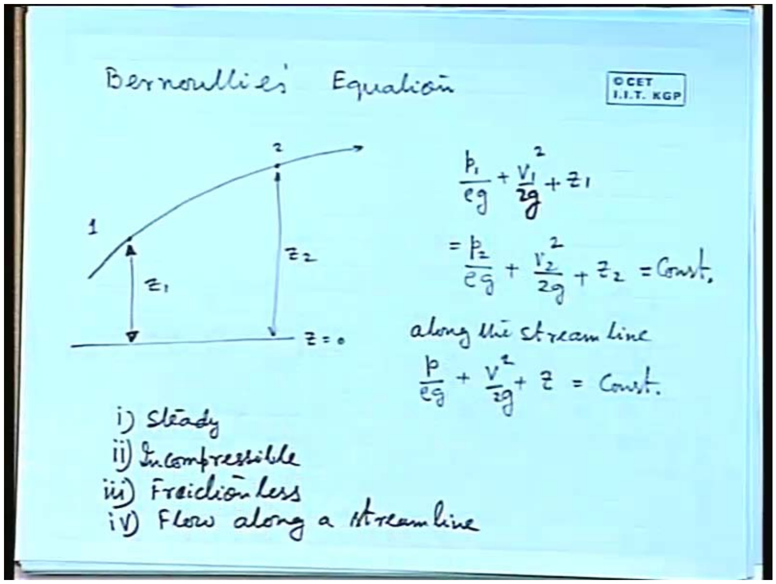

Bernoulli's equation actually comes from the momentum equation. One can derive it, but we are not interested in that. I will just write the final form of the Bernoulli's equation.

Let us say, there is a stream line and on the stream line we have got two points again point 1 and point 2. We will have Bernoulli's equation in this form. $p_1$by rho g plus V_1square by 2g plus $z_1$is equal to p_2 by rho g plus V_2 square by 2g plus z_2 is equal to a constant. This is your z_1, this is your z_2 and this is z equal to 0.That means we have selected a datum plane or datum line and then in the flow there are number of stream lines. So, in this stream line we can have two points 1 and 2 and we can write this equation. Along this stream line p by rho g plus V square by 2g plus z is equal to constant. I have not derived the Bernoulli's equation but it is important to note at which situation Bernoulli's equation is valid.

For Bernoulli's equation, we have got some assumptions. The assumptions are: first thing, the flow is steady; with time there is no change. Then the flow is incompressible. For this particular form of Bernoulli's equation, we have got incompressible flow or rho is equal to constant. The third assumption is that flow is frictionless or there is no effect of viscosity and the fourth one which I am telling from the very beginning is flow along a streamline.

We have got these four assumptions. Then, we can write down Bernoulli's equation. If we look into Bernoulli's equation you see there are three terms and if you see the dimension of these three terms, then they are having the dimension of length and this z actually you see, this is the height of the point 1 from the datum line. They are sometimes called as head or most often they are called head; z is called head. Similarly, the other terms are also called head. Like, $p_1$by rho g is known as pressure head, V_1square by 2g is known as velocity head or kinetic head and $z_1$is known as the static head. Along this streamline then the summation of all these three heads will remain constant. They can be also expressed in such a form that they represent energy. Basically this is energy equation, I told. So, they can be represented as energy.

Let us say g, I replace from every term. So, what we get is V_1square by 2. So, this is the kinetic energy associated with the unit mass of fluid; it represents the kinetic energy. Then gz_1 represents the potential energy of the fluid with respect to a datum plane and $p_1$by rho or p_1 into 1 by rho, 1 by rho is nothing but the specific volume; so p_v basically. What is p_v? We have done it earlier. That is flow energy or flow work, so flow energy. Somebody calls it loosely pressure energy but there is no term like pressure energy. So, this is the flow energy. Flow energy, kinetic energy and potential energy; so, summation of these three is constant along a stream line. Along a stream line what can happen?

Along a streamline, only interchange or transformation between these three forms of energy can occur. But whatever transformation may occur the summation of these three forms will remain constant. Sometimes this equation is also called mechanical energy equation for the fluid. This Bernoulli’s equation is the mechanical energy equation of the fluid; sometimes it is called like that. Because here you see that no electrical or chemical energies are there; even thermal energy is also not present. So, this is sometimes called the mechanical energy of the fluid.

Now I will go to extending the scope of Bernoulli’s equation.

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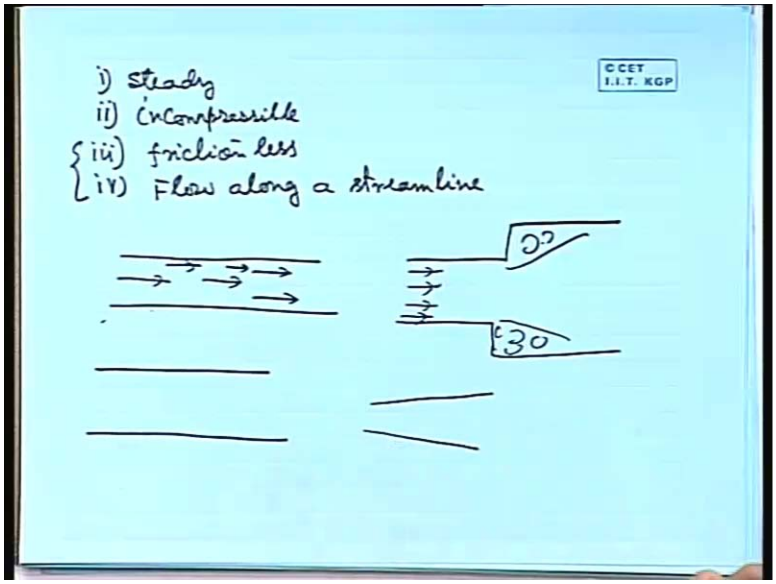

Quickly let me write, Bernoulli's equation for steady, for incompressible, for frictionless and then for flow along a stream line. We can relax almost all the assumptions and we can have modified form of Bernoulli's equation. But I will not do that; I will concentrate mainly on the last two conditions.

Let us see flow along a streamline. Flow along a stream line - it is very easy to say that, but thing is that I want to apply Bernoulli's equation for practical problems and practically when there is a flow it is very difficult to identify this streamline. What is the streamline? If I have to apply Bernoulli's equation along a streamline, first I have to identify the streamline, so that becomes almost impossible. Actually it is like this. Suppose there is a pipe flow; we will assume that the flow is streamlined. There are streamlines, so we can apply between two points. It can be proved mathematically that if the flow is irrotational, again one may ask the question, as to what irrotational is. If I have to discuss that we have to do slightly more of fluid mechanics which this course does not permit. If the flow is irrotational, then irrespective of the streamline we can apply the Bernoulli's equation between any two points of the flow field. I can give one example.

There is a duct like this. In the duct there is a sudden expansion in area, sudden enlargement in the area. So we will find, at the inlet the fluid motion can be denoted by this streamline. But when it goes like this, here there will be ……. Here, the flow is not irrotational. Here we cannot assume the flow to be irrotational. Definitely, if we want to apply Bernoulli's equation between these two points, we will be at fault. But in general, when there is a straight duct or when there is a very gradual increase or decrease in velocity, in these cases we can assume the flow to be irrotational and apply Bernoulli's equation between any two points. This flow along this stream line is not a very stringent requirement always. We can identify the flows where the flow is irrotational, large number of cases are almost irrotational and we can apply Bernoulli's equation between any two points of the flow field. That gives us certain advantage.

Then, we come to frictionless. We know that all the fluid will have viscosity; however small or large it may be there will be effect of friction. Bernoulli's equation, how can it be valid? Due to friction what happens is there will be some dissipation of energy. Dissipation of energy means some energy will be converted into a form which cannot be recovered back, either in the form of flow energy or in the form of kinetic energy or in the form of potential energy. If we can account for this loss, then again we can write down the Bernoulli's equation. So, Bernoulli's equation can be applicable for certain type of flow where frictional losses are there, by adding a loss term.

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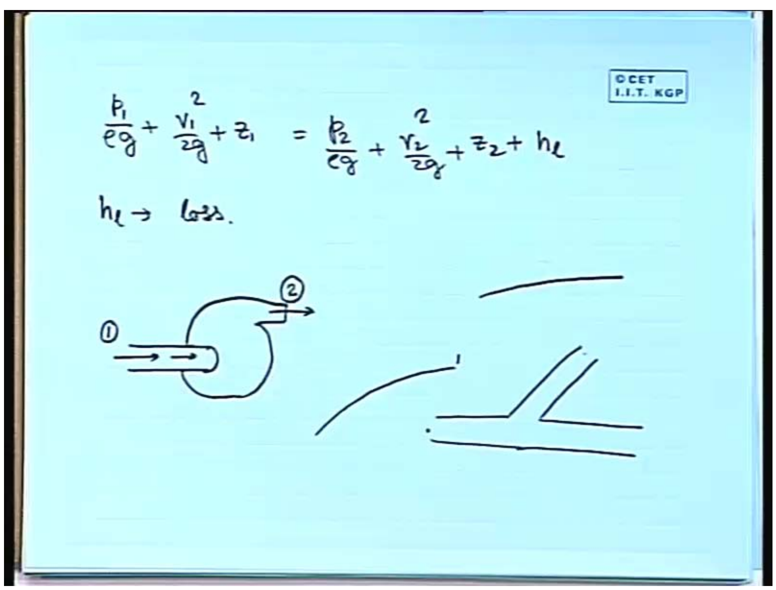

We can write p_1 by rho g plus V_1square by 2g plus $z_1$is equal p_2 by rho g plus V_2 square by 2g plus z_2 plus h_1, where h_1 is the loss. So this is the correction, which we can make to take care of the frictional loss. I will come next how to determine h_1, but before that I like to give some sort of a caution that where should we not apply Bernoulli's equation and what type of watch should we make before applying Bernoulli's equation?

Bernoulli's equation is either valid along a stream line or on some sort of a flow field where the flow is irrotational. Let us say, we have got a situation like this. This is a fluid machine. Let us say this is a centrifugal pump. The flow is entering like this and fluid is going out like this. The outlet let us say we are giving point 2 and inlet we are giving as point 1. Can we write down Bernoulli's equation between point 1 and point 2? The answer is no because there is some sort of energy input. Let us say there was a stream line. Along this stream line we had some sort of energy which is constant mechanical energy. As soon as this energy input is there, streamlines we will get with some other energy constant. So, we cannot write the summation of flow energy, kinetic energy and potential energy here is equal to the summation of flow energy, kinetic energy and potential energy at the outlet of the machine.

In a nut shell, whenever there is a mechanical energy input, we cannot write down Bernoulli's equation taking a point upstream of that and downstream of that; we cannot do it. When there is heat input, then also we cannot do it taking two points upstream and downstream of the heat input. When there is a large deviation from irrotational flow just like I have told that it is a sudden expansion kind of a thing, there also we cannot write down Bernoulli's equation. Let us say we have got a pipe line and branching of pipeline, something like this. If we have to apply Bernoulli's equation between these two points we have to be careful, because here the continuity equation is not valid. The mass flow rate here and mass flow rate here they are not the same. It can be done but with some sort of a caution one has to do it. These are the situations, where we should be careful in applying Bernoulli's equation.

I will stop here today, but I will elaborate on h_1, which is the main part of this lecture in the next class.