Fluid Machines.
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Lecture-30.
Basic Principle and Energy Transfer in Centrifugal Compressor Part I.

Good morning and welcome to all of you to this session of this course. So far we have discussed the basic fluid mechanics principles of some fluid machines like Pelton turbine, Francis turbine, Kaplan turbine and centrifugal pump and reciprocating pumps. The characteristic features of all these machines was that the working fluid was water. And we discussed the basic principle of their operations along with the description of different parts of the machine and its performance criteria of performance characteristics.

Now there are several other types of fluid machines are available in practice or found in practice which used air, steam, or gases, and gases means the mixture of air and the products of combustion which are generated by the burning of fuel is required. And those machines, the basic difference is that since use a fluid which are not liquid is compressible in nature, in the sense that their bulk modulus of elasticity is relatively much lower compared to that of liquid. Therefore what happens is that the density changes with pressure as well as with temperature as the fluid flow through the machines.

And apart from that there are other features of compressible flow found in those machines depending upon the regime of the flow. These machines are usually known as compressible flow machines and in a more acceptable and popular terminology Turbo machines. Now we detailed discussion on Turbo machines is beyond the scope of this course. We will discuss only few of such machines like centrifugal compressors, axial flow compressors, fans and blowers. So 1st we start with centrifugal compressors.

Now centrifugal compressor is just you think is similar to that of a centrifugal pump which you already discussed, which used working fluid water. Now as I already told in the beginning of this course that a pump or compressor is a machine where energy is being supplied from outside and that energy is again imparted the fluid by the machines by virtue of which fluid gains its internal energy. And that internal energy is gained by the fluid in terms of a rise in static pressure which you can loosely call as pressure energy and in terms of the kinetic energy, that means high flow velocity.

In pumps and compressors, the fluid it in an energy is usually obtained in terms of higher static pressure with low flow velocity. While the machine using the liquid water is termed as pump, the machines using air or vapour are termed as compressors. Now today we will discuss the centrifugal compressors and we will come to that discussion why it is called centrifugal compressor. In the centrifugal compressors, is usually, just before starting its discr description etion I tell you, it has got applications today in small turbo jets, turbo vans, Turbo top engines and small gas turbine plants.

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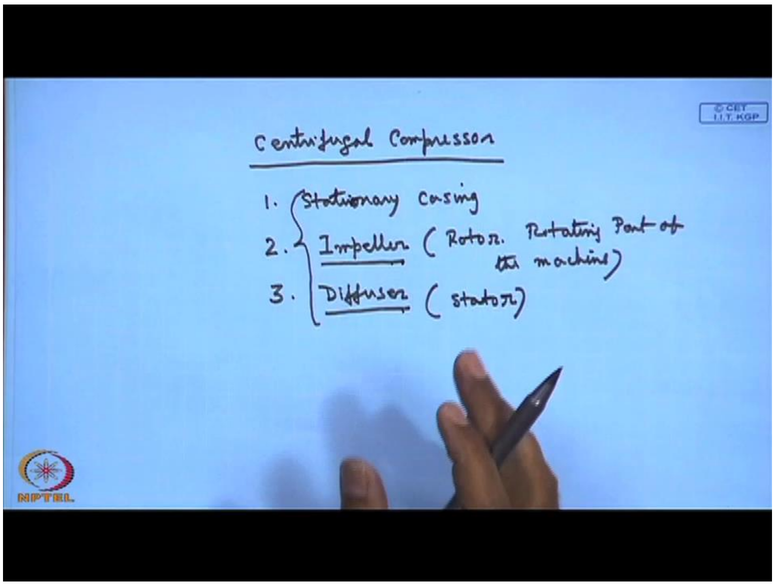

And in all those engines, along with the axial compressors which have been developed developed later on, the centrifugal compressors are also used. These are the applications. Now I come to the basic of centrifugal compressors. Now you see a centrifugal compressor as I have told that it uses air as a working fluid and energy is being given to the machine to raise this static pressure. Now centrifugal compressors consist mainly of 3 parts, one is the casing, stationary casing, all machines basically have stationary casing, number 2 is the important part, is the impeller.

Which is known as impeller which is the rotating part of the machine, which is known as rotor. That is rotating part of the machine, rotating part of the machine, part of the machine. Where the energy is being imparted to the fluid and number 3 is the diffuser, diffuser. Diffuser is a static one, sometimes it can be told as stator, where what happens when the energy is being imparted in the rotating part or rotor known as impeller, the energy is gained both in terms of pressure that rise in static pressure and velocity, mostly in terms of velocity along with the rise in static pressure.

Diffuser is that part where the fluid is being decelerated to gain static pressure by decreasing the velocity, because main objective of the centrifugal compressor is to have air at high static pressure. So therefore the velocity which is gained by the fluid in terms of the kinetic energy in the impeller is being converted to static pressure by the deceleration, sometimes is called as the diffusion process in fluid mechanics to obtain a rise in static pressure. So these 3 are the important parts and consists and comprises a centrifugal compressor. Okay, let us now see one by one that how a, the parts look like.

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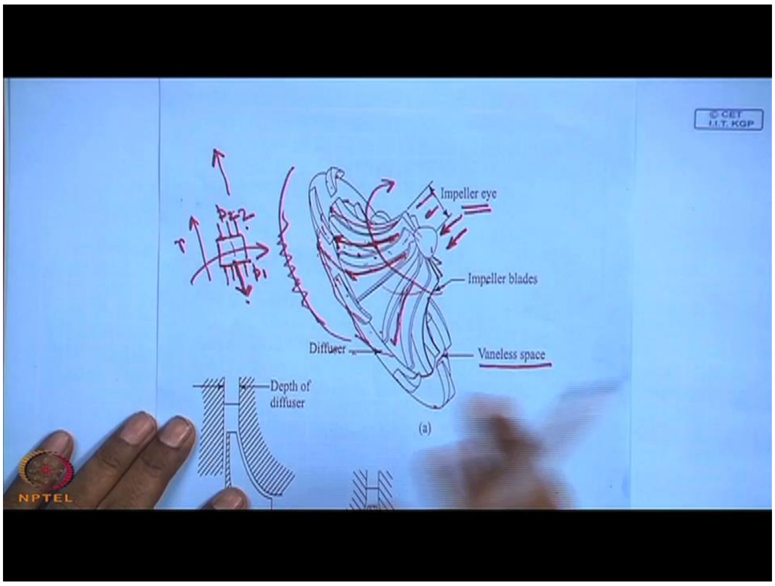

Now here we see that this is the impeller, you see, the impeller looks like this, looks like this. It is just like a rotating disk, you see this is the impeller. This is the impeller, this is the impeller. Now this is inlet of the impeller, this is known as impeller eye, the air is being sucked, when the impeller rotates, the air is being sucked like this through the impeller eye, this is the impeller eye. Now there are vanes like this, these are vanes which are curved initially and then at the outlet it is more or less radial, flat and radial.

And the fluid which is sucked changes this direction and flows like this, try to understand, flows like this. This is a radially outward flow machine, this is a radially outward flow machine. Now what happens, I tell you, the air is sucked axially by the rotating action of the impeller at the impeller eye, here it is impeller eye. And then the end is ultimately directed radially outwards through the rotating impeller, okay.

Now you see here, that since when the air go through this passage, radially outward, and at the same time impeller is being rotated, for example this is, this is the diffuser vane, I am sorry, this is the impeller, this part in rotated, this part is rotated like this, then what happens, as the fluid goes out in the radial location, its pressure increases along the radial direction. So this can be explained this with that because of this rotation, a tangential velocity is imparted on the fluid.

And therefore the fluid obtains a centripetal acceleration which is manifested in terms of a rise in pressure radially outward. Or you can see other way that if you consider a fluid element in this radial gap if you see here, if you consider a fluid element like this, this is the radial direction R. If the fluid particle as the tangential velocity, then there has to be an inward radial force due to the pressure on both the sides, let this side is 2 P2. And decide is 1 P1.

So net force should be acting on the fluid in this radially inward direction to balance the centrifugal force in the outward direction so that fluid element can rotate in the tangential part. This is the basic requirement for any tangential flow in a fluid. That means if the fluid has a tangential component of velocity, then the pressure rises radially outward. This is because this pressure gradient gives rise to a inward radial force to balance the centrifugal force.

So therefore the pressure rise obtained in the outward radial direction because of the centrifugal action due to the rotation of the fluid element and that is the reason for which this type of machine is called as centrifugal machine. And here it is the centrifugal compressor. Clear. So since it is radially outward, so pressure is automatically gained by the action of the tangential velocity, that is the centrifugal centripetal acceleration. So pressure rise takes place.

And at the same time, by the action of the blade, the blade imparts the velocities to the fluid because since the fluid is flowing through the passage, the fluid acquires the velocity because of the rotating plate which is basically the impulse action that I already explained while discussing the hydraulic machines. So this is basically the impeller part, the fluid is, the air here is sucked axially by the impeller eye and then goes radially outward through these impeller blade passages.

Then what happens, when it comes out of the impeller tip, the air has got high velocity, at the same time it has got a high-pressure but we want more pressure rather less velocity. So what happens, therefore it go through some stationary passages that is being made by these vanes, these are stationary vanes and this is known as the diffuser. This passage is known as the diffuser. So you see it is written, this is the diffuser, where what happens, when the flow takes place, there is no energy exchange amount the fluid flows in a direction where the area increases.

So what happens, simply the pressure is increased because the area including means by continuity, the fluid velocity decreases and in consequence to that, the pressure increases. This is the process by which the fluid is decelerated and its pressure is increased, so that at the final outlet, that the final outward very free of the diffuser, here, we have air at a very high static pressure but at a relatively much lower velocity. So this is impeller blades as you see and now here are another thing I will explain afterwards before entering to the fixed vane passages known as diffusers, there are some vane less space which is known as well as diffuser, vane less space, I will come to that afterwards.

And why so many number of passages are made, that also I will tell afterwards, in pump you have seen that the similar thing was, similar thing happened, similar thing was made by a volute casing by the fluid is decelerated to get high pressure of the water at the expense of its high velocity at the outlet of the runner. That the impeller was called, then also the impeller, not on, the impeller at the outlet of the impeller, but there we had a single volute casing without number of passages created by this type of vanes.

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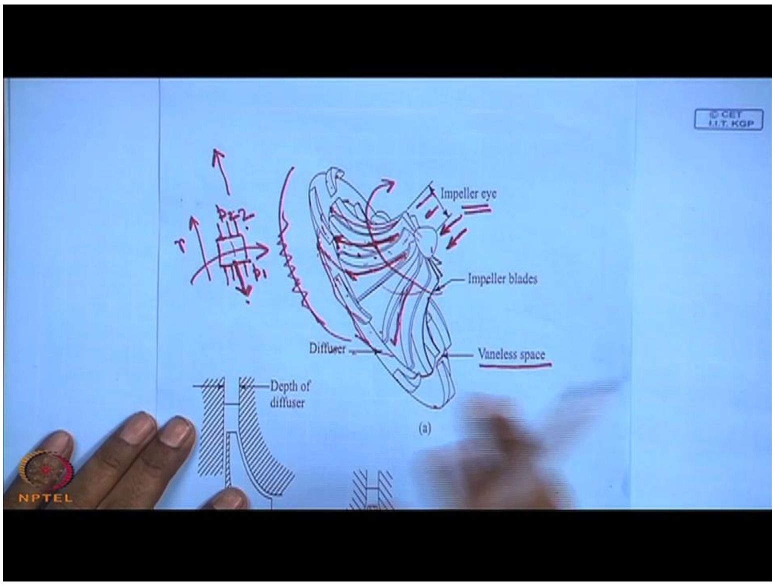

But here the vanes are there to create a number of passages to divide the flow into small passages, I will come to that afterwards. This you can have a look of this diffuser and the impeller. If you take a view from this side, you will get a view like this. So this is the impeller blade, this is the diffuser, this is the depth of the diffuser. Now sometimes, there are the impellers are both sided, that means the air is sucked from the side of the impeller, from this site, the double action.

So this is also shown like that. So this is a double sided impeller, that means the air flows from both the sides, double sided impeller. These are the schematic views of the impeller. Okay. Now after this, we come to this figure.

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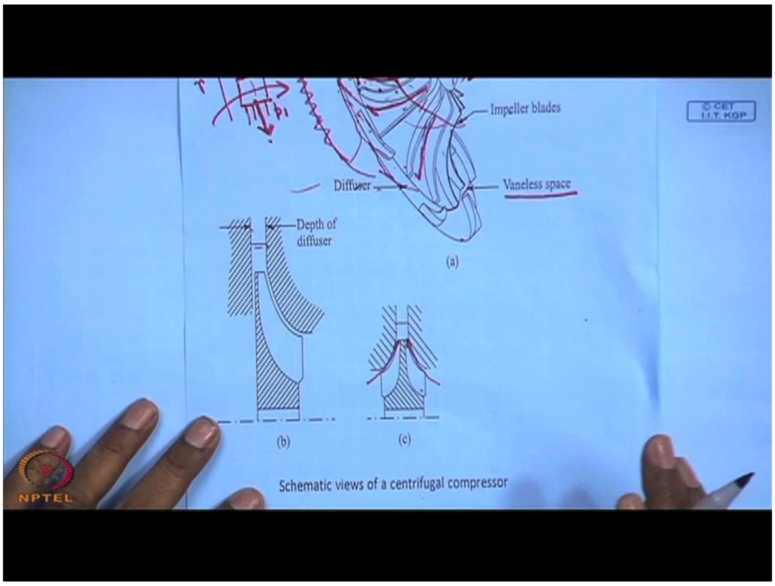

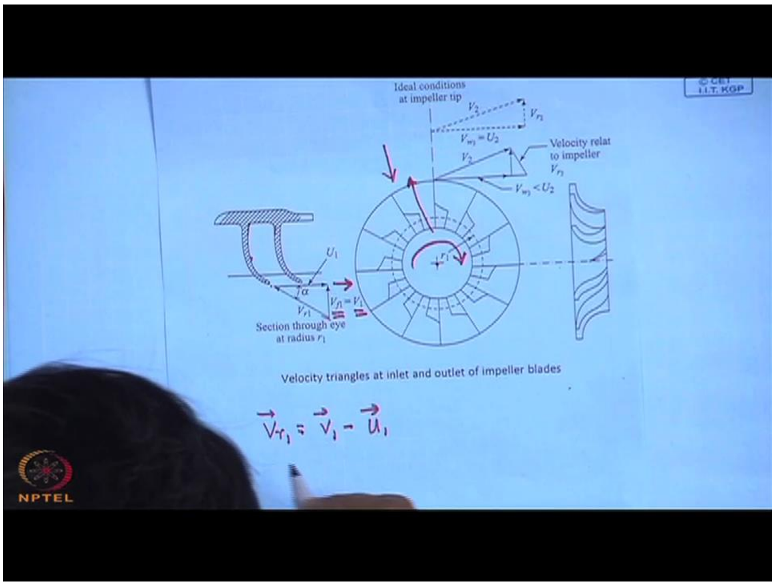

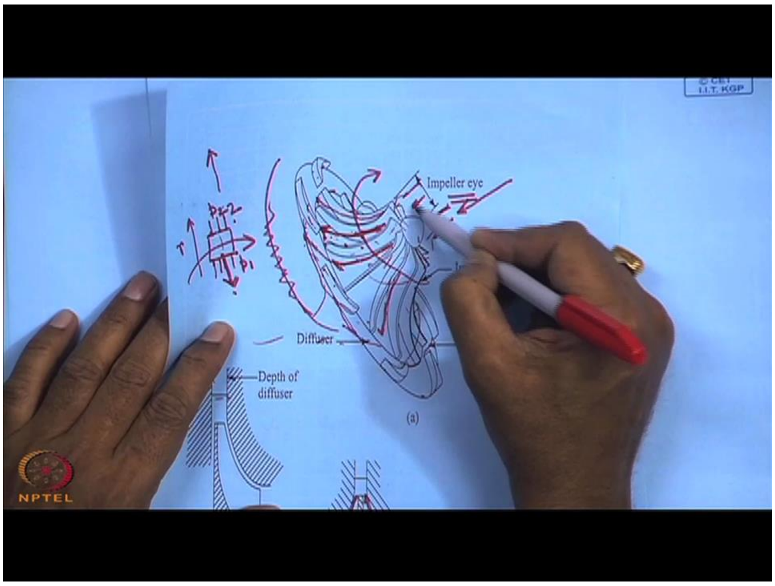

Now we have to find out the equations for energy transfer in this machine, that means in air okay. So now let us see that this figure is shown in a, rather this figure, if we have a view from this direction and if you see that front view, it looks like this. This is the blade which is radial and relatively flat at the outer periphery and curved here. So here this is the impeller tip. So this is, the air comes like this, axially and it goes then, is bent like this and it goes radially outward through the blade passages like this.

So therefore if one sees, so sees from the top, the blade looks like this. This is the blade. This is the curve, this is the curvature of the blade at the inlet, and then goes radially straight at the outlet. Now the inlet velocity is made this way that under the design condition, the fluid as I told earlier in all hydraulic machines, we always make the flow in such a way that the fluid whether the liquid or it is gas or it is air, always should flow in a way that it should glide the blade surface.

That means while it enters the blade, it should glide the blade surface. Which means that the velocity vector relative to the blade, because blade is moving element, so if fluid has to glide over that moving element, mean that the fluid velocity relative to the blade should be such that the angle should match, that means the angle of the velocity vector, the relative velocity vector must match the inlet angle of the blade or vane. And the blade or vane is designed accordingly, the inlet angle is designed such that the relative velocity must, the angle of the relative velocity must match the inlet angle of the blade.

So here also it is true, that is, that is, it was discussed earlier. So for smooth entrance of the air here, so the relative velocity angle should be same as that. Here we specify the angle with respect to the tangential direction, we are looking from the top, this is rotating in this direction, the impeller. So therefore this is the tangential direction. This is the direction is the tangential direction. Now what happens, the impeller is designed in such a way that it draws air like I told earlier axially, so it draws axially. At the inlet, the velocity, the absolute velocity of the air is in axial direction.

So therefore this is the velocity triangle which is in this plane, I tell you, if you see here, which takes place, that means this is in axial direction, that means if we see from the top, we will see this direction which is the axial direction. That means here, if you see this direction is the absolute velocity direction which is the axial direction. Sometimes this is referred as the flow velocity. So flow velocity, this is the axial direction. Okay, this is the absolute velocity, now if we have to find out the relative velocity, so we have to vectorially subtract the velocity of the impeller at the inlet, that means the relative velocity VR1 vector is V1 - U1.

So therefore, this is the U1, so this if you draw this diagram, so this will be, this will be, this is VR1, this is U1, this is U1 and therefore this is V1. So this is the relative velocity V1 - U1. And this angle is the angle made by the relative velocity with the tangential direction while the absolute velocity makes 90 degree angle because this is axial. And axial direction is perpendicular to the tangential direction.

So therefore this is the axial and this is the flow velocity at the inlet. That means if this velocity is V1, this is multiplied by this area, frontal area of the impeller eye will give you the mass flow rate coming to that, the volume flow rate times the density is the mass flow rate going to the compressor. So therefore you have to understand very clearly the inlet velocity triangle, already you know the velocity triangle concept, earlier also we did it in hydraulic turbines and compressors, hydraulic turbines and pumps.

Another assumption for this, as you know already that we always consider a uniform, because the variation in this direction is neglected, the circumferential direction. So therefore we always consider a uniform velocity distribution along the circumference, that means it is a azimuthal symmetric flow. So that any representative point is velocity at any azimuthal location is the representative of the velocity of the entire periphery. So with that we can show the inlet velocity triangle at the for this impeller.

Now what happens, what at the outlet, now at the outlet what happens, this since the blade is made radial, what we want, why the blade is radial? That means we want the relative velocity, that means the velocity, radial means if it has to go smooth, go out smoothly over this blade, the radial velocity, so the relative velocity of the air with respect to the blade should be in the radial direction. So this is, therefore here if you write, V R2 is V2 - U2, what is U2?

U2 is the velocity of the impeller at the outlet. Now if we want that the relative velocity VR2 should be such that it must match the angle of the blade at the outlet and since the blade is made radial, this is deliberately made radial so that for that outlet, the radial velocity should also be radial. Sorry the, relative velocity should also be radial. So this is the relative velocity VR2, you see this, this diagram is better I think, this is the relative velocity VR2, this is the V2 and this is the U2.

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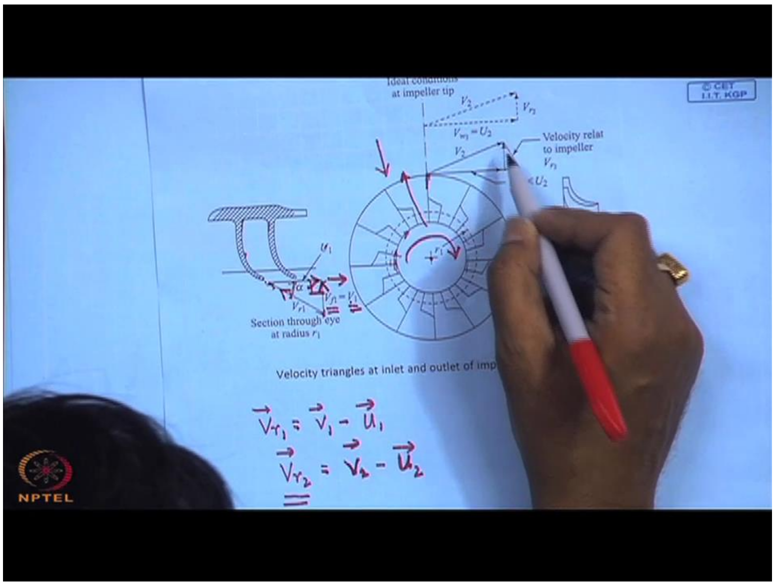

Because we can write this one here, VR2 is V2 - U2. So with this we can draw this triangle diagram. So therefore what happens, this is the relative velocity, so absolute velocity is this. Since the relative velocity is in the purely radial direction, so absolute velocity does not have, sorry the absolute velocity does have a tangential component, the absolute velocity does have a tangential component which is equal to U2. Here you see the absolute velocity does not have a tangential component because absolute velocity is axial, perpendicular to the tangential direction.

Here the fluid velocity has a tangential component VW2, this nomenclature you know earlier that VW2 is the tangential component of whirling component, that is whether the W is given at the outlet. Similarly VW 1 here, you can write VW 1 is 0. That is the tangential component of the velocity, velocity of the fluid that is air at the inlet is 0. Whirling component of velocity is 0. But here it is U2. So with this blade diagram now what we can write, we can write the energy transferred to the fluid.

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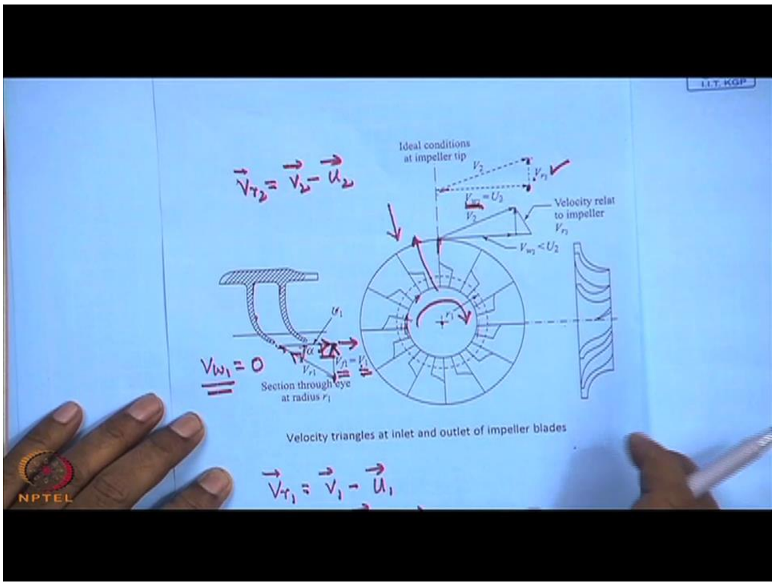

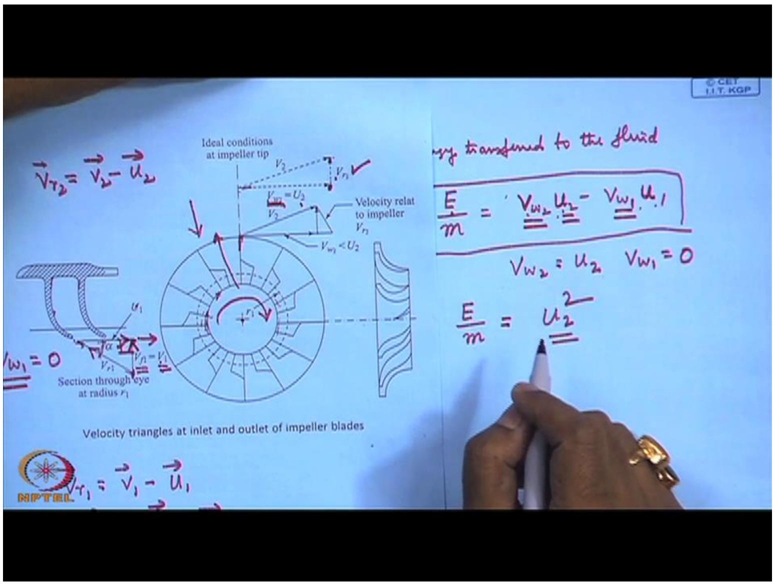

Now energy which is transferred to the fluid, energy transferred to the fluid, now energy transferred to the fluid takes place by the action of the rotating vanes. That already we derived that energy transferred to the fluid per-unit mass is given by with this expression, whether nomenclature I am telling where VW2 is the tangential component of the fluid velocity at the outlet of the impeller. U2 is the impeller linear velocity, tangential velocity at the outlet.

VW 1 is the tangential component of velocity of the fluid at the inlet which we call as whirling component of velocity at the inlet. And U1 is the velocity of the impeller at the inlet because of its rotation. So this expression was derived earlier from the used by making use theorem of angular momentum or conservation of angular momentum. Theorem of angle of momentum, that is for a control volume, we find out the net, the flux of the angular momentum which equals to the torque imparted on the control volume.

So based on this angular momentum of the momentum momentum theorem, we derived that the energy which is transferred in this case, this expression equals to the energy given by the machine to the fluid VW2 U2 - VW 1 U1, it is a, just a recollection of the earlier things which we already discussed.

Now in this case, particularly in this case, VW 1 you see that in this case, VW 1 is 0 and VW2 at the outlet, since the relative velocity is radial, so VW2, that is the tangential component of the absolute velocity equals to U2, so in this case VW2 equals to U2 and VW 1 equals to 0, so therefore energy given per-unit mass of the air can be written as U2 square, simply U2 square. So therefore U2 square is the nothing but the energy given per unit, given by the machine to wear per-unit mass, thank you.