Introduction to Fluid Machines and Compressible Flow

Prof. S. K. Som
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur

Lecture - 21
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 mechanical principles of some fluid machines, like Pelton turbine, Francis turbine, Kaplan turbine and centrifugal pump and reciprocating pump. The characteristic features of all this machines was, that the working fluid was water and we discussed the basic principle of their operations along with the descriptions of different parts of the machines and its performance criteria or performance characteristics.

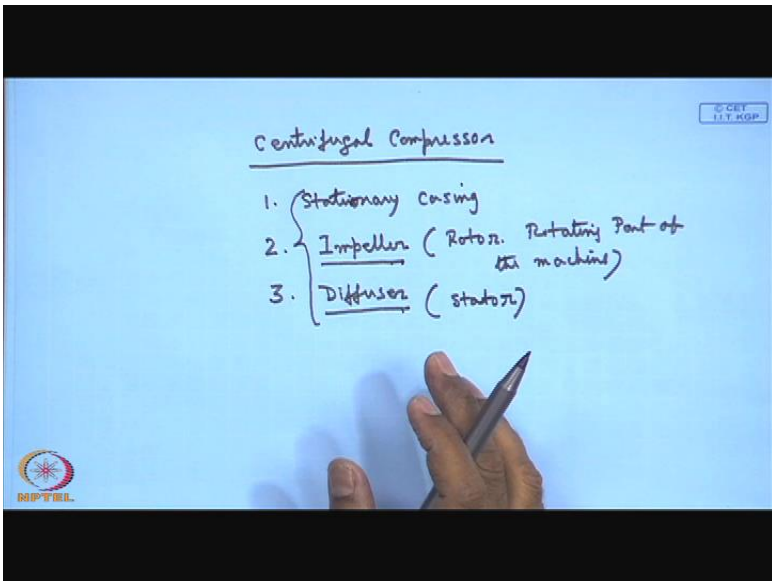
Now, there are several other types of fluid machines are available in practice or found in practice, which use air, steam or gases. Gases means, they are mixture of air and products of combustions, which are generated by the burning of fuel as required. And those machines, the basic difference is, that since use a fluid, which are not liquid, is compressible in nature in a sense, that there bulk modulus of elasticity is relatively much lower compared to that liquid. Therefore, what happens is, that the density changes with pressure as well as with temperature as the fluid flows to 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 terminologies, the turbo machines. Now, a detailed discussions 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, first we start with centrifugal compressors.

Now, centrifugal compressors is just you think is similar to that of a centrifugal pump, which we 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 to 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 we can loosely call as pressure energy and in terms of the kinetic energy that means high flow velocity. In pumps and compressors, the fluid internal energy is usually obtained in terms of higher static pressure with low flow velocity while the machine using the liquid or water is termed as pump. The machines using air or vapour are termed as compressor.

Now, today we will discuss the centrifugal compressor. I will come to that discussion why it is called centrifugal compressor. Now, the centrifugal compressor is usually, just before starting its description I tell you, it has got application today in small turbojet, turbofan, turboprop engines and small gas turbine plans. And in all those engines along with the axial compressors, which have been developed later on, this centrifugal compressors are also used. These are the applications. Now, I come to the basic of centrifugal compressors.

(Refer Slide Time: 04:38)



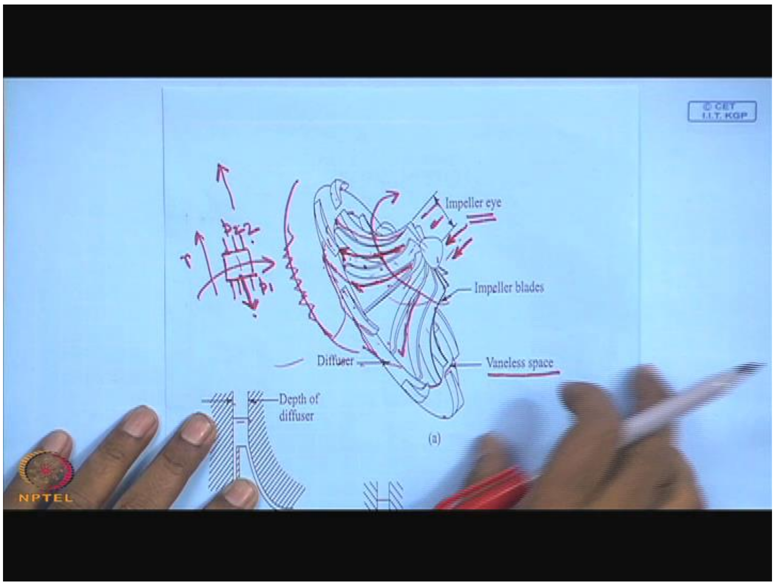
Centrifugal Compressor

1. Stationary casing
2. Impeller (Rotor. Rotating Part of the machine)
3. Diffuser (stator)

Now, you see, a centrifugal compressor, as I have told, that it uses air as the working fluid and energy is being given to the machine to raise this static pressure. Now, centrifugal compressors consist mainly of three parts, one is the casing, stationary casing; all machine basically have stationary casing. Number two 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 three is the diffuser, diffuser.

Diffuser is the static one, sometimes it can be told the 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 stabilized 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 in static pressure by decreasing the velocity because main object of this centrifugal compressor is to have air at high static equation. 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, which sometime is called as the diffusion process in fluid mechanics to obtain, yeah, rise in static pressure. So, these three are the important parts and consist and compresses centrifugal compression, ok. Let us now see one by one that how the parts look like.

(Refer Slide Time: 07:00)



Now, here we see, that this is the impeller, you see, this is the impeller, looks like a, looks like this, it is just like a rotating disc. You see, this is the impeller, this is the impeller, this is the impeller. Now, this is the inlet of the impeller, this is known as impeller eye. The air is being shucked, when the impeller rotates the air is being shucked like this through the impeller eye. This is the impeller eye, this is the impeller eye, this, this is the impeller eye. Now, there are vanes like this. These are the vanes, which are curved initially and that the outlet, it is more or less radial, flat and radial and the fluid which is shucked, change this direction and flows like this, try to understand, flows like this. This is a radially outward flow machine; this is the radially outward flow machine.

Now, what happens, I tell you, the air is shucked axially by the rotating action of the impeller at the impeller eye. Here is impeller eye, see impeller eye and then, the air is ultimately directed radially outwards through the rotating impeller, ok. Now, you see here, that since when the air goes 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 is 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 way, that because of this rotation a tangential velocity is imparted on the fluid and therefore, fluid obtains a centripetal acceleration, which is manifested in terms of a rising 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 has a tangential velocity, then there has to be an inward radial force due to the pressure on both the side. Let this side is 2 p 2 and this side, this 1 p 1. So, net force should be acting on the fluid in this radially inward what, 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 an inward radial force to balance this 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 then, that is the reason for which this type of machine is called as centrifugal machines and here, it is centrifugal compressor, clear.

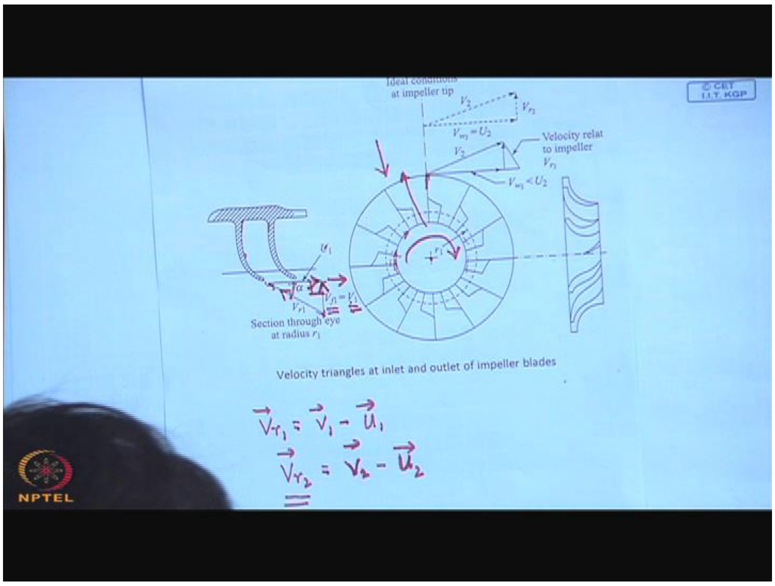
So, therefore, since it is radially outward, so pressure is automatically gained by the action of the tangential velocity, that is the centrifugal or centripetal acceleration. So, pressure rise take place and at the same time, by the action of the blade the blade imparts this velocity to this fluid because since the fluid is flowing through the passage, fluid acquires the velocity because of the rotating blade, 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 stuck axially by the impeller eye and then, goes radially outward through this impeller blade passages.

Then, what happens? When it comes out of the impeller tip, the air has got a 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 goes through some stationary passages that is being made by these vanes. These are stationary vanes and this is known as the diffusers. 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, only fluid flows in a directions where the area increases. So, what happens? Simply, the pressure is increased because the area increases 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, at the final outward periphery 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 another thing I will explain afterwards, before entering to the fixed vanes passages known as diffuser, there are some vaneless space, which is known as vaneless diffusion. Vaneless space, I will come to that afterward 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 happen by, similar thing was made by a volute casing where the fluid is decelerated to get high pressure of the water at the expense of its high velocity at the outlet of the runner. There the impeller was called, there also impeller, sorry, not runner, impeller, at the outlet of the impeller. But there we had a single volute casing without number of passages created by this type of vane, 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 shucked from this side of the impeller, from this side double action, so this is also shown like that. So, this is a double sided impeller that means, that air flows from both the sides, double side impeller. These are the schematic views of the impeller, ok.

(Refer Slide Time: 14:16)



Velocity triangles at inlet and outlet of impeller blades

$$\vec{V}_{r_1} = \vec{V}_1 - \vec{U}_1$$

$$\vec{V}_{r_2} = \vec{V}_2 - \vec{U}_2$$

Now, after this we come to this figure. Now, we have to find out the equations for energy transfer in this machines, that means, in air, ok. 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, the air comes like this axially and it goes, then is bend like this and it goes radially outward through the blade passages like this. So, therefore if you want to see, so see from the top, the blade looks like this. This is the blade, this is curved, 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 it is 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 is relative to blade because blade is a moving element.

So, if fluid has to glide over the moving blade means 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 relatively velocity vector must match the inlet angle of the blade or vane and blade or vane is designed accordingly. The inlet angel is designed such that the relative velocity must, the angle of the velocity, relative velocity must match the inlet angle of the blade. So, here also it is true, that is that was discussed earlier. So, for smooth entrance of the air here, so the relative velocity angel should be same as that here. We specify the angle with respect to the tangential direction. We are looking from the top. This is rotated in this direction, the impeller, so therefore this is the tangential direction. This is, this direction is the tangential direction.

Now, what happens, the impeller is designed in such a way, that it draws air, I told earlier, axially, so it draws axially. So, at the inlet, the velocity, the absolute velocity of the ((Refer Time: 17:03)) is in axial direction. So, therefore this is the velocity triangle, which is in this plane. I tell you, if you see here, which take place that means, this is in axial direction, that means, 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, ok. This is the absolute velocity.

Now, if you have to find out the relative velocity, so you have to vectorially subtract the velocity of the impeller at the inlet, that means, the relative velocity V r 1, vector is V 1 minus u 1. So, therefore this is the u 1, so this if you draw this diagram, so this will be the, this is V r 1. This is u 1, this is u 1 and therefore this is V 1. So, this is the relative velocity V 1 minus u 1. And this angle is the angle made by the relative velocity with the tangential direction while the absolute velocity makes a 90 degree 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 V 1, this is multiplied by this area, frontal area of the impeller eye will give you the mass flow rate coming to the, volume flow rate times the density, the mass flow rate going to the compressor.

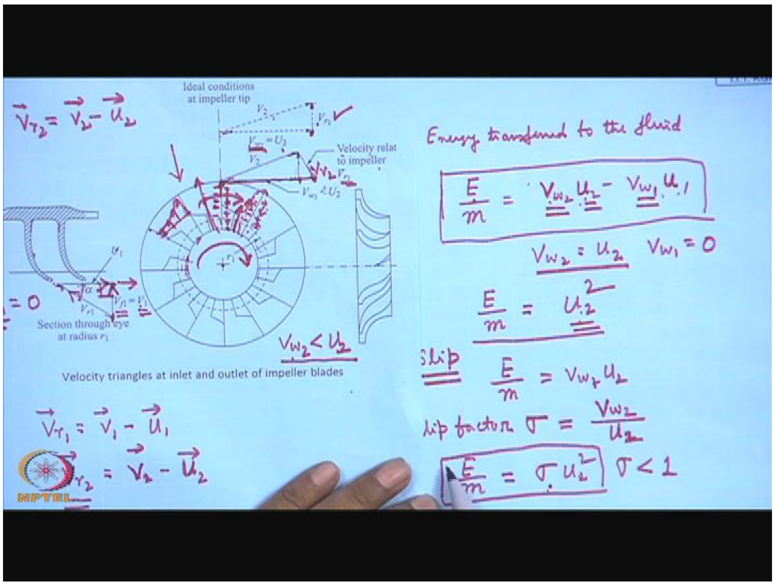
So, therefore you have to understand very clearly the inlet velocity triangle. Already you know the velocity triangle concept, earlier also we did it in hydraulic turbines and compressors, hydraulic turbine pumps. Another assumption for this, as you know already, that we always consider a uniform, because 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 azimuthal symmetric flow, so that any representative point, this 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 happened, what at the outlet? Now, at the outlet what happened? This is the blade is made radial, what we want, why the blade is radial? That means, we want, that the relative velocity, that means, the velocity, radial means, if it has to go smooth go out smoothly over this blade, the radial velocity, sorry, the relative velocity of the air with respect to the blade should be in the radial direction.

So, this is the, therefore here if you write V r 2 is V 2 minus u 2, what is u 2? u 2 is the velocity of the impeller at the outlet. Now, if we want, that the relative velocity V r 2 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 for that smooth outlet. The radial velocity should also be radial, sorry, the relative velocity should also be radial, so this is the relative velocity, V r 2. You see, this, this diagram, this diagram is better I think. This is the relative velocity V r 2, this is the V 2 and this is the u 2 because we can write this one here, that V r 2 is V 2 minus u 2.

So, you see, so with this we can draw this triangle diagram. So, this is the, so therefore what happens? This is the relative velocity, so absolute velocity is this. Since there is 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 u 2. Here, you see, the absolute velocity does not have a tangential component because absolute velocity is axial perpendicular to the tangential direction. Here the absolute velocity has a tangential component V w 2. This nomenclature you know earlier, that V w 2 is the tangential component or whirling component that is why, the w is given at the outlet. Similarly, V w 1, here you can write V w 1 is 0, that is the tangential component of the velocity, velocity of the fluid, that is, air at inlet is 0, whirling component of velocity 0, but here it is u 2.

(Refer Slide Time: 22:26)



$\vec{V}_{r_2} = \vec{V}_2 - \vec{u}_2$

Energy transferred to the fluid

$$\boxed{\frac{E}{m} = V_{w_2} u_2 - V_{w_1} u_1}$$

$V_{w_2} = u_2 \quad V_{w_1} = 0$

$$\frac{E}{m} = u_2^2$$

$V_{w_2} < u_2$

Slip $\frac{E}{m} = V_{w_2} u_2$

lip factor $\sigma = \frac{V_{w_2}}{u_2}$

$$\boxed{\frac{E}{m} = \sigma u_2^2} \quad \sigma < 1$$

$\vec{V}_{r_1} = \vec{V}_1 - \vec{u}_1$

$\vec{V}_{r_2} = \vec{V}_2 - \vec{u}_2$

So, with this blade diagram, now what we can write? We can write the energy transferred to the fluid. 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 these rotating vane, that already we derived, that energy transferred to the fluid per unit mass is given by V. This expression with the nomenclature I am telling, where V w 2 is the tangential component of the fluid velocity at the outlet of the impeller. u 2 is the impeller linear velocity, tangential velocity at the outlet, V w 1 is the tangential component, the velocity of the fluid at the inlet, which we call as whirling component of velocity at inlet and u 1 is the velocity of the impeller at the inlet because of the rotation

So, this expression was derived earlier from the use, by making use of the theorem of angular momentum or conservation of angular momentum, theorem of angular momentum, that is, for a control volume we find out the net flux of the angular momentum, which equal to the torque imparted on the control volume. So, based on this angular momentum or 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 V w 2 u 2 minus V w and it is just a recollection of the earlier thing, which we already discussed.

Now, in this case, particularly in this case V w 1, you see, that is, in this case V w 1 is 0 and V w 2 at the outlets, since the relative velocity is radial. So, V w 2, that is, the tangential component of the absolute velocity equals to u 2. So, in this case, V w 2 equals to u 2 and V w 1 equals to 0. So, therefore energy given per unit mass of the air can be written as u 2 square; simply, u 2 square. So, therefore, u 2 square is nothing but the energy given per unit given by the machine to air per unit mass.

Now, let us see, there are some other issues. I already discussed earlier, that that there is a phenomenon known as slip, which is very, very important. Slip, now I tell you what is slip. When a fluid flows through a curved vane and the vane rotates, what happens because of the combined effect of the tangential flow at and the radial flow passed the curved vanes, there is difference of pressure into sides of the vane. In the leading edge, the pressure becomes high, the fluid is decelerated and in the trailing edge, pressure becomes less and the fluid is accelerated, and there becomes a small recirculatory flow, probably you can remember, which we discussed in case of centrifugal pump. Here, let us discuss here now.

If we consider this moving in this direction, in this side. For example, here is a positive pressure, positive means higher pressure and this side the pressure is, well that means, this is because of the movement, this rotation of the blade and the flow in, pass the blade in the radial direction because of the blade curvature, it moves like that. And at the same time, the fluid flows in the radial direction. As a combination of that the fluid element here is decelerated in the leading edge. This is the leading of the blade and fluid here in accelerated.

So, what happens? There is a higher pressure, there is a lower pressure here. So, what happens? Here, I show you, this gives rise to a recirculatory flow in this direction. This is the higher pressure region, this is the lower pressure region and what happens, this recirculatory flow, if you see this passage, this happens same way in all passages, makes a non-uniform distribution of velocity and that non-uniform is skewed one. That means, this makes a distribution like this, this make, this was discussed earlier also, this makes the distribution like this. The velocity distribution become much skewed here, the velocity becomes and this side between this passage is high, here this is low. So, this way the velocity distribution changes.

So, as a whole what happens? Because of this small recirculatory flow to the difference in pressure from the leading and the trailing edge, there is a, there is a change in the direction of the velocity of the fluid relative to the blade. So, this results in this way. That means, we wanted, that the fluid go in the radial direction, rather it will move in this way. That means, the direction of the fluid relative to the blade is changed like this. So, this is velocity relative to impeller. This is the, this velocity triangle here, you see, this velocity triangle, this, this, this triangle, this is the triangle, so this is now V r 2, so this is V r 2.

And therefore, what happens? If this becomes V r 2, then this is the changed velocity triangle, it is just similar. If you recall, what we discussed in case of centrifugal pump, so what happens is, that in that case, this is the tangential component of the absolute velocity. Now, if you compare this two, this u 2, this is u 2 or obviously u 2 remain same. u 2 depends upon the rotational speed and the outer radius of the impeller, ok. So, therefore for the same u 2 at the impeller outlet v 2 is reduced and this component is reduced from that of the u 2. So, therefore as a result, what I, what we get? V w 2 is less then u 2. In this case, it was V w 2 u 2 because the absolute, the relative velocity is radially outward here.

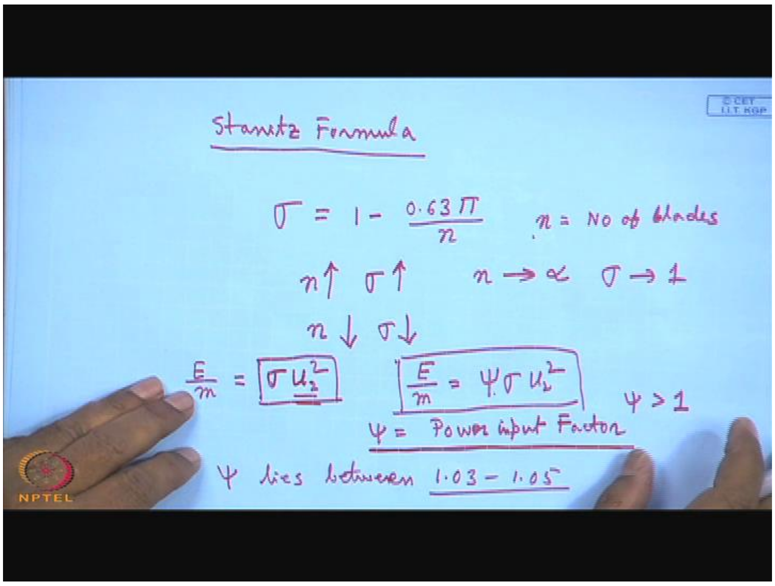
The relative velocity is like this. This is the similar thing what happen in case of centrifugal pump, so this is the slip, but you have to know the fluid mechanical principal of slip. It is because of the blade curvature and the rotation of the blade, the motion is being imparted to the blade. At the same time, the fluid flow pass the blade on the two side of the blade leading edge and the trailing edge, which creates it a sort of a circulation, circulation combined with a linear flow, which is in the radial direction, which creates this type of difference in pressure. And the local circulatory flow, as the combination of, with this radial flow outward makes a skewed non-uniform distribution of the velocity, which finally results in this type of velocity triangle where we gave the relative velocity at the outlet is not radial. As a result of which finally, we get V w 2 is less then u 2, which means, that if we see the energy transfer.

So, therefore this will be now V w 2 is u 2. So, this will be now actually E by m. If V w 1 is 0, is V w 2 u 2 since V w 2 equals to 2 we wrote is u 2 square. But now, if V w 2 is not equal to u 2, so it will not be u 2 square and V w is less then u 2, then it will be less then u 2 square. Here, a terminology is there defined slip factor. A factor is defined, known as slip factor, which is symbolized as sigma. I did it for centrifugal pump also, which is here defined as V w 2 by the ratio of the outlet whirling component or the tangential component of the fluid at outlet divide to the tangential speed of the rotor of the outlet.

So, if slip factor is defined like this, then in terms of the slip factor we can define, that the energy per unit mass is then sigma u 2 square and sigma is less than 1, sigma is less 1. And therefore, we see, because of this slip, a less amount of energy is being imparted to the fluid as compared to that if there could have been slip. So, how slip will increase?

Now, one thing I tell you again and again, which I told you while discussing the centrifugal pump, that slip is not a consequence of fluid viscosity. Slip is a consequence of the motion of the fluid, the rotation of the fluid by the action of the blades. Even the fluid is invist, the slip will occur. So, therefore, be careful. The slip phenomena is not because of the fluid friction though the slip ultimately reduces the energy from what we would have got if there was no slip. There is the formula to find out slip.

(Refer Slide Time: 32:12)



Stanitz Formula

$$\sigma = 1 - \frac{0.63\pi}{n}$$

n = No of blades

$n\uparrow \ \sigma\uparrow \qquad n \rightarrow \propto \quad \sigma \rightarrow 1$

$n\downarrow \ \sigma\downarrow$

$$\frac{E}{m} = \boxed{\sigma u_2^2} \qquad \boxed{\frac{E}{m} = \psi\sigma u_2^2} \qquad \psi > 1$$

ψ = Power input Factor

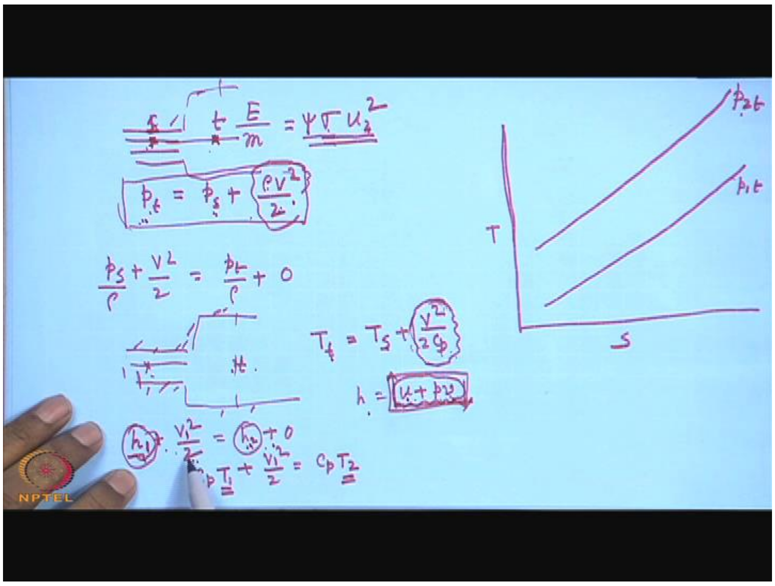
ψ lies between 1.03 – 1.05

So, this formula is known as Stanitz formula. Stanitz, from a potential flow analysis expressed the slip like this, you can get some idea from here, 0.63 pi by n, where n is equal to number of blades, where n is equal to number of blades or vanes. Now, you see here very much, that if the number of blade, so therefore you see, if the number of blades increases what happens? Sigma increases, the maximum value is 1; where number of blades tends to infinity, sigma tends to 1. There is no slip. That means, if you make small, small streams on more number of blades, infinite number of blade passages, then slip will be totally reduced, almost reduced.

On the other hand, when number of blades is decreased, slip is decreased, which means, slip will be much lower than 1 and there will be a much reduction in the energy imparted to the fluid, ok. So, therefore due to the slip, finally the energy imparted per unit mass is given by sigma u 2 square where u 2 is the outlet tangential velocity of the impeller or the impeller blade and sigma is the slip factor.

Now, if we consider other losses, mainly the mechanical frictions, ok and then windage losses, this type of losses if you take care of, then you have to give more amount of work as given by that expression. And therefore, the energy per unit mass is written by making another term as a product, that is, psi, which is known as power input factor; psi is known as power input factor, ok, power input factor. So, this is known as power that means, this takes care of frictional losses that this frictions, the frictional losses, the disc frictional losses, the disc frictions windage losses, all this things is taken care of by the power input factor, which by physical sense will be grater than 1. Definitely, that means, this will be greater than 1, that means, this will be the energy requirement of the machine, so that out of this, this will be imparted to the fluid, which will exhibit the slip phenomena. And this value of psi usually lies between, lies between, between 1.03 to 1.05 like that. So, therefore finally, you, we arrive at this expression, that energy per unit mass given to the fluid is sigma, psi sigma u 2 square. This is the amount of energy given to the fluid.

(Refer Slide Time: 36:06)



Now, let us find out in terms of the pressure rise. Let us do something thermodynamics, let us consider, now here again I come here, let us consider, this is, this will be better here. We are not going unnecessary to this complicated figure. Let us see, that this is the inlet to the impeller section 1, this is the outlet of the impeller section 2, this is the outlet of the diffuser section 3.

Now, let us concentrate this way, that section 1 to 2 when the fluid flows, it gains the energy. So, the energy is being imparted here whose value is just now we have written, psi sigma u 2 square. This is the energy required, but actually fluid gets this energy sigma u 2 square psi. Sigma u 2 square is the total energy required, part of which is lost in friction. So, therefore this energy is being imparted in the fluid only here, so 2 to 3 there is no energy given. So, total energy between 2 to 3 remains same. There is no energy given to the fluid, there is no energy interaction.

So, therefore what happens? The energy level at 2 and 3 remains same, but there is a difference in pressure between 2 and 3 because the pressure rise takes place in the diffuser. So, now if you give this 1, 2, 3, now if we, with this can you see this 1, 2, 3? Yes, then we can draw a, in thermodynamics the T-S diagram, ok. Let us consider now the pressure here is, total pressure is p 1 t and at the end, the total pressure is p 3 t. And we show these things like this, p 1 t, and we show this thing p 2. These are diverging lines, p 2 t. What is the total pressure? Total pressure is the static pressure plus the stagnation plus the velocity pressure that means, the pressure velocity head, equivalent, pressure equivalent of the velocity head or the kinetic energy.

Now, I will not show you here, it will be difficult. Now, 1 is the inlet of the impeller, 2 is the outlet of the impeller. Now, you see one thing, that what is this p 1? p 1 now stagnation pressure, total pressure, I am just recalling again, total pressure is the static pressure p s plus rho v square by 2. For any fluid stream if you make the velocity 0 by some way, for example you make the area infinitely larger. So, therefore if you write the Bernoulli's equation, there are two points along a stream line. You can get, that p t when the velocity become 0, then p t equal to total pressure. That means, the pressure there equal to p s plus rho V square by 2 and you can write Bernoulli's equation when there is no energy, no energy added from outside, ok, and there is no dissipation taking place, no fluid friction, no dissipation.

So, therefore under ideal condition for invisit fluid this is synonymous to an isotropic flow, that the fluid is brought to rest, then we can write. For example, if this is the point 1, if this is the point t for example, where the total pressure is obtained. So, therefore p 1, that p 1 is the p s here. Let this is s, p s is this pressure here plus p s by rho plus V square by 2 is p t by rho plus 0. So, which gives rise to this, that means, that total pressure is obtained by writing the Bernoulli's equation, means, that the fluid is decelerated isentropically. Isentropically means, without any internal reversibility, without any heat transfer. Therefore, external reversibility is also not there, purely reversible and without any other energy added or taken out. So, therefore this is the concept of the total pressure. So, this is the total pressure.

Now, let us consider the stagnation temperature. What is stagnation temperature is similar to? That the concept of the stagnation temperature is the temperature, which is being gained if a fluid stream is brought to rest, but there is no concept of reversible way, that is, you can bring to rest even in consideration of the friction because the total energies conserve. For example, I just give you the recalling this stagnation temperature concept, that 1 and t, the similar way if you do that fluid stream is being returned it from point 1 to a point here t.

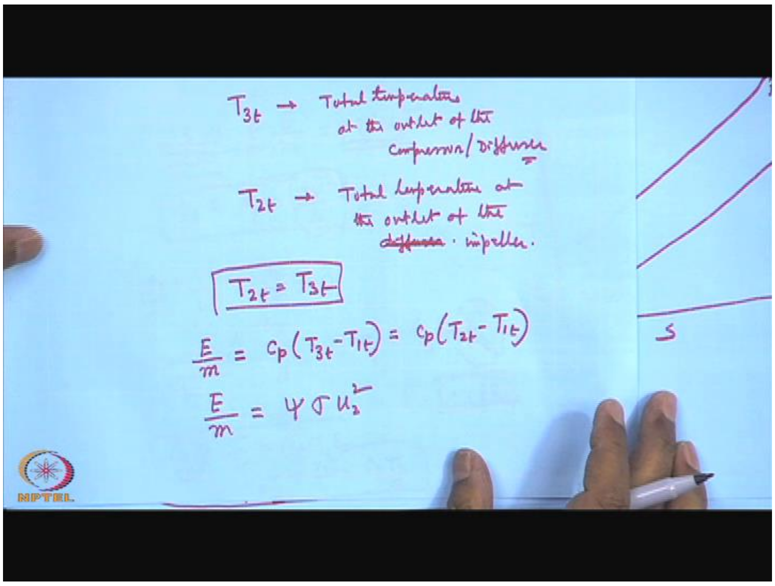
And if we write this energy equation, the steady flow energy equation, h 1 plus kinetic energy V 1 square by 2 and if you consider, that it is done adiabatically, that means, no energy interaction, either in the form of heat or in the form of work takes place, then we can write h 2 plus 0. So, this equation is the steady flow energy equation where we neglect the change in potential energy. So, there is no other form of work transfer, either from outside or from the system, outside to the system or system to the outside, then therefore for this control volume system is steady flow energy equation, gives rise to where the friction is not coming into the picture.

So, therefore here this h 2, the h 1 is what C p into t 1. This is the section 1, for example, plus V 1 square by 2 and h 2 is C p into T 2. So, this T 2 corresponds to the stagnation temperature of T 1. You understand? So, therefore a stagnation temperature if you write, the T t is equal to what? It is equal to T s, this is known as the static temperature, plus V square by 2 C p. In general, that means, this is the velocity or kinetic energy equivalent velocity head or kinetic energy equivalent of the temperature. This is kinetic energy equivalent of the pressure, this kinetic energy equivalent of the pressure is realized, if this is being, this is done in a reversible way without any dissipation, absence of friction. But this is purely energy conversion. So, therefore this is the temperature, this is the velocity equivalent or the kinetic energy equivalent of temperature added with static temperature, gives the total temperature where the fluid velocity is reduced to 0 without any restriction whether friction is there or friction is not there. This is because the friction takes care of the pressure, but here the friction does not come into picture. I just explain it again for your concept to be clear, that h is probably, you know, u plus p v.

So, whenever we make this difference, this balance, that h 1 V 1 square by 2 is h 2, so within the h this u and p v and just mainly made by the friction. That means, whether friction is there or friction is not there, that will depend upon this distribution within u and p v. They will adjust, the friction is there, u will be more, the internal energy will be more because of the friction, whereas where p v is less. The reverse is there if there is no friction. This u will not be changed because internal molecular energy will remain same because of the temperature and p v will get as proportion to h, change in h.

So, therefore it is the conversion from u and p v, that will depend upon the friction, but h 1 minus h 2 is V square by 2 or h 1 plus V 1 square by 2 is h 2. The velocity is 0 or any other velocity may be there. This is a steady flow energy equation, which is independent of whether there is friction or not. This is recapitulation of this total pressure and the total temperature.

(Refer Slide Time: 44:24)



$T_{3t} \rightarrow$ Total temperature at the outlet of the compressor / Diffuser

$T_{2t} \rightarrow$ Total temperature at the outlet of the ~~diffuser~~ · impeller.

$$\boxed{T_{2t} = T_{3t}}$$

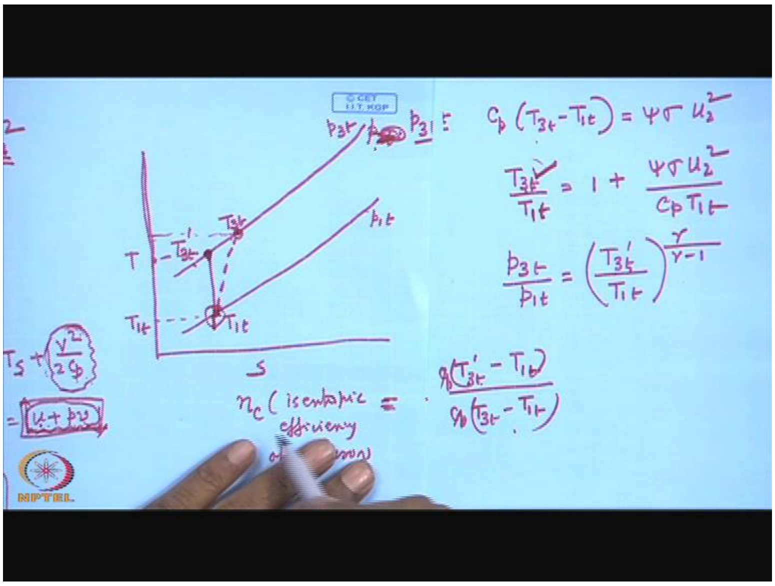
$$\frac{E}{m} = c_p\left(T_{3t} - T_{1t}\right) = c_p\left(T_{2t} - T_{1t}\right)$$

$$\frac{E}{m} = \psi \sigma U_2^2$$

Now, come to the point, if we consider the point 1, that is, the inlet to the impeller at point 1 where we have got the total temperature, is a total temperature T 1 t and if we get a total temperature T 2 t. Now, let us, before that let us consider this way. Now, sorry let us consider this way, that ok, let us consider this way, that if T 2 t 3 is the total temperature, total temperature at the outlet of the compressor, at the outlet, at the outlet of the compressor, at the outlet of the compressor, at the outlet of the compressor, that means, at the outlet of the, at the outlet of the diffuser, then T 2 t, if we write T 2 t is the total temperature or the stagnation temperature, total temperature at the outlet of the diffuser.

Since there is no at the outlet of the impeller, sorry, at the outlet of the impeller, that is, outlet of the compressor, that means, at the outlet of the diffuser, at the outlet of the diffuser, then we can write T 2 t is equal to T 3 t, because the total temperature remains same because there is no energy at the, in the diffuser. So, therefore we can write, that energy added per unit mass, that work done per unit mass or energy added per unit mass is equal to C p, specific heat, into T 3 t minus T 1 t or is equal to C p into T 2 t minus T 1 t, clear, that we can write very well. This one, C p T 3 t minus T 1 t is equal to C p T 2 t minus T 1 t. Now, this becomes equal to what? Again, E by m we have got, is equal to psi sigma u 2 square.

(Refer Slide Time: 46:43)



$$C_p(T_{3t} - T_{1t}) = \psi\sigma u_2^2$$

$$\frac{T_{3t}}{T_{1t}} = 1 + \frac{\psi\sigma u_2^2}{C_p T_{1t}}$$

$$\frac{p_{3t}}{p_{1t}} = \left(\frac{T_{3t}'}{T_{1t}}\right)^{\frac{\gamma}{\gamma-1}}$$

$$\eta_c \text{ (isentropic efficiency of compression)} = \frac{C_p(T_{3t}' - T_{1t})}{C_p(T_{3t} - T_{1t})}$$

So, therefore what we can write? Now, we can write, we will come to this afterwards. I will do something else here, we will come to it afterwards, before that I will do something here, that we ultimately get E by m is what. Now, here E by m is what? Again, E by, E by m is this, yes, then we can write from this, from this we can write, C p let us write here, T 3 t minus T 1 t is equal to psi sigma u 2 square. So, therefore we can write simply, T 3 t by one step is equal to this becomes 1 plus psi sigma u 2 square by C p T 1 t. So, a ratio of temperature T 3 t to T 1 t we get.

Now, this is the T 3 t outlet temperature, this is the T 1 t. Now, you come to this, if this is the one. Now, if we have an isotropic expansion, we get a point here. This is the V to t, ok. So, therefore we can get this point l, sorry, this is not p 2 t. I write, it is, this is the final pressure of the compressor, thus total pressure of the compressor p 3 t. This is, sorry, p 3 t. Now, here is the point. This is the isentropic, actual T 3 t is not at this point because the actual process is not isentropic. This point we denote as T 3 t dash that means, this temperature.

So, therefore if this temperature I know, then I can write the pressure rise, the expression for pressure rise I am interested to know, T 3 t dash divided by, this is T 1 t, that the inlet temperature to the compressor, T 1 t to the power gamma by gamma minus 1. This is the isentropic process relation between pressure and temperature, but actual T 3, that is the temperature at the outlet of the diffuser, that is the outlet of the compressor, is different from that of the, that of the isentropic process. Actual process is not isentropic. So, what will be the actual process? Actual process will not be vertical. So, there may be two options, the process may be like this or process ((Refer Time: 46:06)) towards left. As we know, that the adiabatic process, that means, a process without heat transfer, but with friction or internally reversibility entropy, always increases.

What is an isentropic process? Isentropic process is a process, which does not have any heat transfer with the surrounding. The system does not have any heat transfer with the surrounding. At the same time, there is irreversibility side, there is no friction, even no heat transfer within it, temperature is almost uniform at any instant, so that internal dissipation or internal irreversibility is 0. At that same time there is not heat transfer, external irreversibility is 0, so process is totally irreversible and at the same time, adiabatic entropy remain constant. That you know from thermodynamics. But if the process is adiabatic, but you cannot avoid the friction, so this is the known as adiabatic process with internal irreversibility for which we know from the principle of increase of entropy, that entropy always increases because of the internal irreversibility. So, therefore the actual process is shown, it is recapitulation of your thermodynamics.

So, actual process is shown like this, that is, T 3 t. So, therefore this, this temperature lies here, so therefore this is the actual temperature. Here, we define a terminology known as isentropic, isentropic efficiency of compressor, isentropic efficiency of compressor, which is defined as the ratio of these two temperatures in a way, that T 3 t dash minus T 1 t divided by

T 3 t minus T 1 t. Actually there is a C p, this cancels out, this ratio is what? Physically, that it is the actual work that is required divided by the ideal work. Actual work is always more, T 3 t is more than that. This is because of friction and temperature increases because of the increases in the entropy due to internally reversible.

So, therefore actual temperature rise can be written in terms of this, in terms of the isentropic efficiency eta c, isentropic efficiency of the compressor eta C. So, therefore what we can write, T 3 t minus T 1 t is, therefore we can write is eta C, eta C into C p into what is this, T 3 t dash, this is eta C, is equal to this. So, T 3 t, T 3 t dash we can write, this is T 3 t dash. So, one eta C that means, we can write.

Now, C p T 3 t minus T 1 t is this. Here we have is, T 3 t, T 3 t dash by T 1 t is this. Therefore, we can relate this T 3 t dash by T 1 t in term T 3 t minus T 1 t in terms of this through this eta c and we can find out the pressure rise. However, today’s time is over. I think, I will discuss it tomorrow, ok, next class.

Thank you.