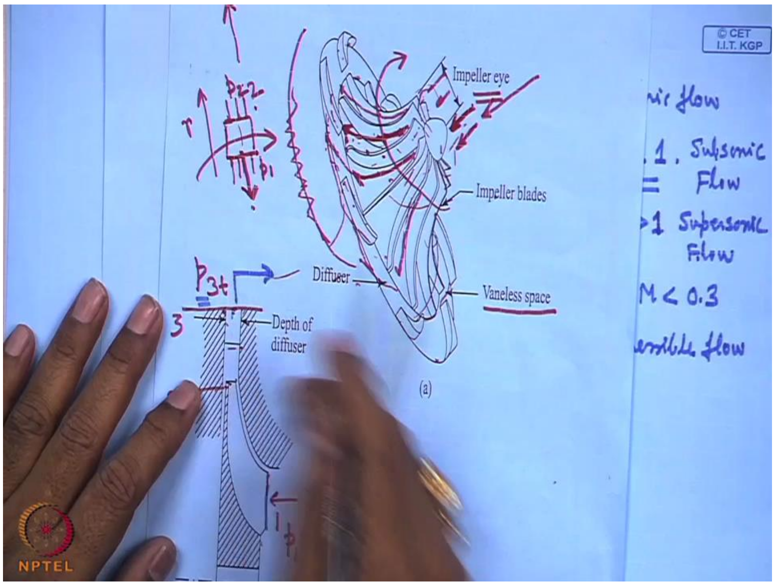
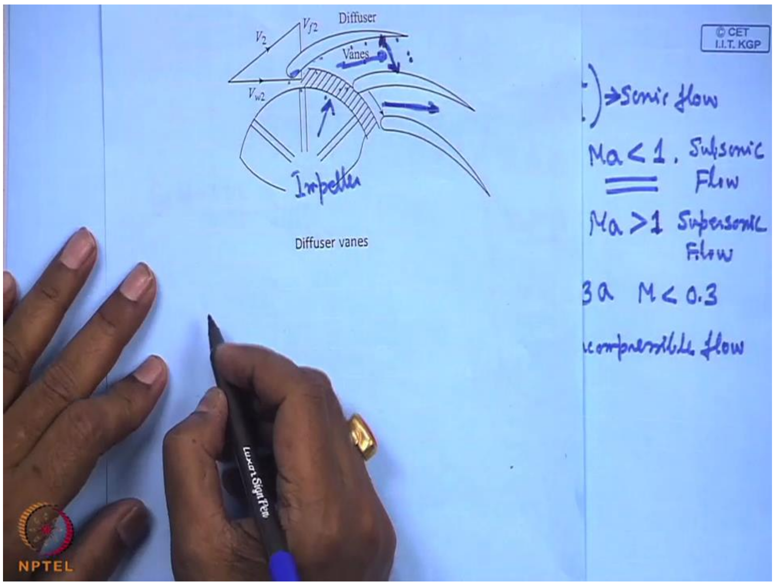
Fluid Machines.
Professor Sankar Kumar Som.
Department Of Mechanical Engineering.
Indian Institute Of Technology Kharagpur.
Lecture-33.
Basic Principles and Energy Transfer in Centrifugal Compressor Part IV and Losses in Centrifugal Compressors.

(Refer Slide Time: 0:52)





Good morning and welcome you all to this session of the course. Now next is this diffuser. Now I come to the next part, that is the 2nd component diffuser. Now what is diffuser? That is same as that of your centrifugal pump diffuser. Now we know that impeller and diffuser are the 2 important parts. This is impeller, impeller, this is impeller. Now what happens, energy is added to the impeller, so when air comes out of the impeller, what happens?

The air acquires energy by the momentum transfer, transfer of angular momentum by the rotating action of the blade which we have done how to find out the increasing, sorry, how to find out the work input to this. Now what happens when it comes out of the impeller tip, the energy is stored in the form of both kinetic energy, velocity of the fluid and the static pressure. The impeller passages are made diverging, so that the pressure will increase in the direction of the flow.

But we want finally from the outlet of the compressor that means if you see this diagram, it will be better, that at the outlet of the compressor, from here, the delivery, we want a, we want air at relatively much low velocity but at high-pressure, why? This is because the practical use of these compressors are with the engine or with their plants, gasturbine plants, turbojet, turboprop, turbofan engines, where this air is used in a combustion chamber to burn the fuel.

And when the fuel is burned, a high-temperature is generated, or high-temperature, the air is heated to high temperature by the energy generated because of the burning. So to make the burning more efficiently, what is required that a high-pressure air at high-temperature and high-pressure air but at very small velocity, as low as possible. Sometimes it is unavoidable, for different reasons, that you will know afterwards, if you read the jet engines or the gas turbines in more details.

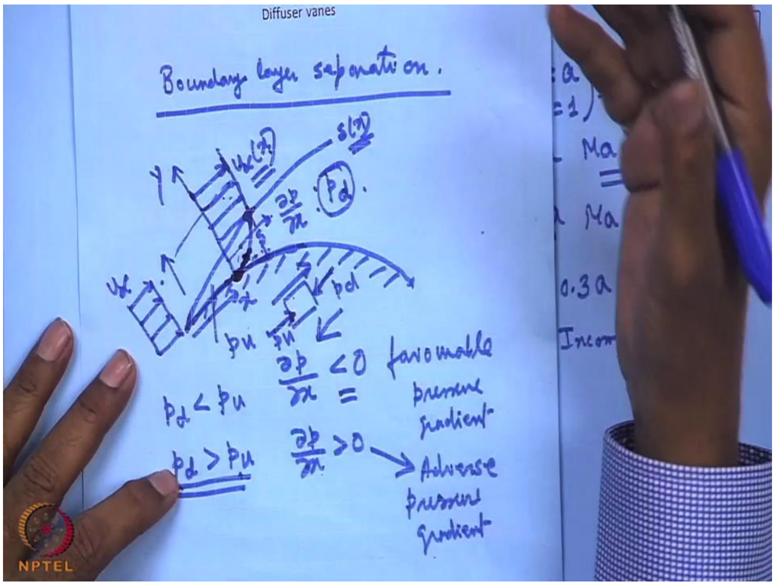
But as far as it should be avoidable, because I velocity the combustion chamber for burning fuel causes several problems like combustion instability, combustion cannot be made so efficient. So to make the combustion more efficient, it is required that a relatively low velocity but high-pressure air, okay, so for that we want that the total energy of the air at the outlet should be mostly in the form of static pressure or you can tell stagnation or the total temperature at the outlet which is the index of the work given to the fluid, should come in the form of only the static temperature or the static pressure, not in the form of kinetic energy.

Kinetic energy will be there as required for to maintain the flow. So therefore what happens, the excess, that means the kinetic energy which is there, which is undesirable is then converted to pressure energy or to convert it to higher static pressure in the diffuser, the similar thing which is then in the case of centrifugal pump. So this diffuser is like this, there are 1st of all, there is a vane less space, 1st of all there is no vane, so it is a vane less space where the diffusion takes place partly and after that the number of vanes which make the final diffuser.

Now why the number of vanes are made, to divide the airstream in several channels, to make an effective control of the flow and at the same time we can get the diffusion, that means a rise in static pressure at the cost of the kinetic energy in a short length as short as possible. So because of this, the vanes, number of vanes are there to direct the flow in different channels. Now I will come to the way less space afterwards, let us 1st discussed these vanes. So the vanes clear the passage, so each and every batch is, this is the width of the passage, has a diverging width, the width diverges, which depends upon the shape of the vanes.

So vanes are curved, so depending upon the curvature, the widths are made so that the cross-section area normal to the flow increases, because of which the velocity decreases in pressure increases. The depth, which is perpendicular to this plane of the figure, the depth of the diffuser is usually constant in the direction of the flow. This means, that means it has a constant depth, this is perpendicular to the plane of the figure.

(Refer Slide Time: 5:29)



Now before going to explain this, I will tell another criteria, what should be the curvature of the vanes so that the diffusion process, that is the deceleration of the fluid, is efficient without losses. So that is more important in a diffuser. So therefore we must tell something about boundary layer separation, boundary layer separation. Now let me tell you something about boundary layer separation. Okay, now let me tell you something about boundary layer separation.

Now we will see that when a fluid flows, come to the basic principle of fluid mechanics which probably you have learnt in fluid mechanics, again it is a recapitulation of the earlier things that when a fluid flows from one point to another point or an average from one section to another section, what is a gradient which makes the flow possible? It is the energy gradient. That means fluid flows from a higher energy to a lower energy.

So therefore when the fluid flows from a point or section to another point or section downstream when the pressure increases, then the fluid flows against an adverse pressure gradient because, why because the fluid element faces a higher pressure at the downstream, that means the direction in which it is flowing. But still the fluid flows because of the energy gradient. Energy at upstream is always higher than that at the downstream. But what happens you see, when the fluid flows past the body, let us consider this as a recapitulation.

Let us consider the fluid, not understand this, let us understand an external fluid, the fluid fluid is flowing past the curved surface for example. Now let a fluid enter with a uniform velocity, let us recapitulate what is boundary layer flow. Now you know that when the fluid flows past the solid surface, at this solid surface, the relative velocity of the fluid with respect to the solid surface the velocity of the fluid relative to the solid is 0. This is purely because of the interaction between solid and the fluid.

This is pure interaction between the solid and the fluid, I am not going into details of it, this can be broadly conceived as a consequence of the addition between the fluid and the solid and their interfacial process by which the fluid is not allowed to slip over the solid. That means its velocity relative to solid is 0. That means the surface is at rest, the fluid velocity will be 0. And what happens, the fluid just above, in the near vicinity of the solid is being retarded to a very low velocity because this happens to the momentum transport in the cross direction.

Because of this momentum transport from fluid to fluid, because of the molecular transport, it is at the molecular level, the fluid velocity from 0, if we consider the solid at rest, ultimately attends the free stream velocity. Ultimately attends the free stream velocity, it attempts actually asymptotically at any section but if we consider some 99 percent of free stream velocity as the free stream velocity itself, then we can call this as the boundary layer thickness at that section and this grows like this.

That means there is a boundary layer within which the fluid velocity changes from 0 to almost the free stream velocity. So this retardation of the fluid from its free stream velocity takes place within the boundary layer because of the momentum transport. The fluid is retarded within a layer very close to the solid surface, this is known as boundary layer or the shear layer which is a function of X. Now this X as a distance x, I denote the face velocity as U infinity X which is me not be same as the U infinity at the entrance.

This is because of what, if the surface imposes a pressure gradient, that means surface due to its curvature may impose a pressure gradient in the potential zone, that is the zone above the boundary layer by the flow velocity in the transverse direction, for example Y is uniform. And this is known as boundary layer region. So therefore this boundary layer is impressed with the pressure gradient which is imposed by the curvature of the surface, that is Dell P Delta X.

Now when the pressure at the downstream, let some typical downstream section pressure is D and some typical upstream section pressure is U. When search of the downstream is less than PU, by mathematical term, we tell that Dell P Dell X is less than 0, because in the increasing direction of X, the direction of flow. That means fluid is flowing with a negative pressure gradient, then what happens, if you consider a fluid element, since this pressure is low, and this pressure is high, the upstream pressure, so fluid experiences then it is pressure force in the direction of flow.

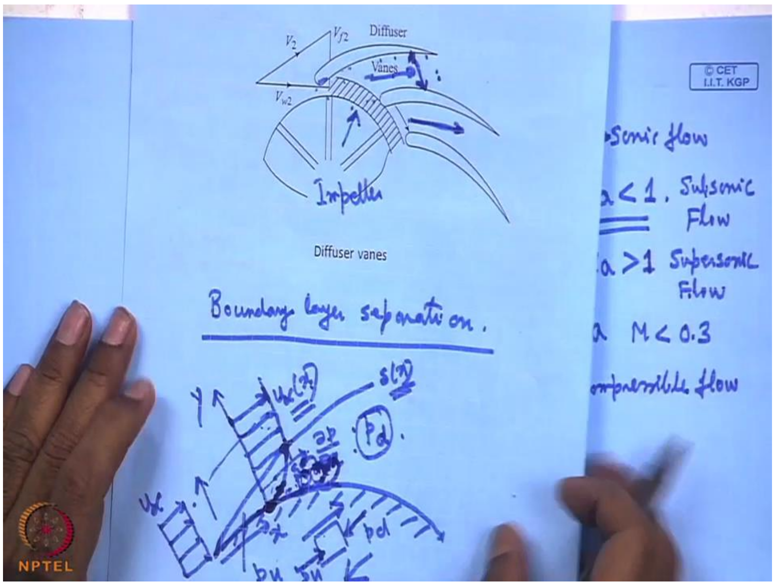
That is why this is known as in fluid mechanical term as favourable pressure gradient, favourable pressure gradient. But when due to this curvature, the pressure gradient becomes other way, that means the downstream pressure at any typical downstream location is greater than PU, then by mathematics, Dell P Dell X is greater than 0. So a negative pressure gradient me favourable pressure gradient and this is known as adverse pressure gradient. In this case PD is more than PU.

So therefore the fluid is facing a force, net pressure force in the direction opposite to the flow, that means it opposite the flow. This creates an adverse effect, so that is known as adverse pressure gradient. So when this type of adverse pressure gradient takes place, in case of diffusion which we are discussing now, when the pressure is increased, this is the static pressure, so downstream pressure is higher than the upstream pressure. This case prevails. So fluid faces an adverse pressure gradient.

But still the fluid flows because the energy gradient pushes it, energy gradient makes it possible to flow. But what happens, for the fluid particles very close to the wall, the kinetic energy is totally consume, the kinetic energy is destroyed because kinetic energy is ultimately coming to 0, fluid is retarded because of this momentum transport, okay. This is being manifested by the property fluid viscosity.

So therefore for the liquid, fluid particles close to the surface, kinetic energy falls appreciably so that they cannot surmount the adverse pressure U. That means the total energy becomes insufficient at the upstream to flow, that means the energy gradient is reversed. Okay, so that means the fluid with low kinetic energy near the solid cannot surmount the adverse pressure U and then what happens. At some point it happens where the gradient of energy opposes this, it becomes reversed and the fluid flows in the opposite direction.

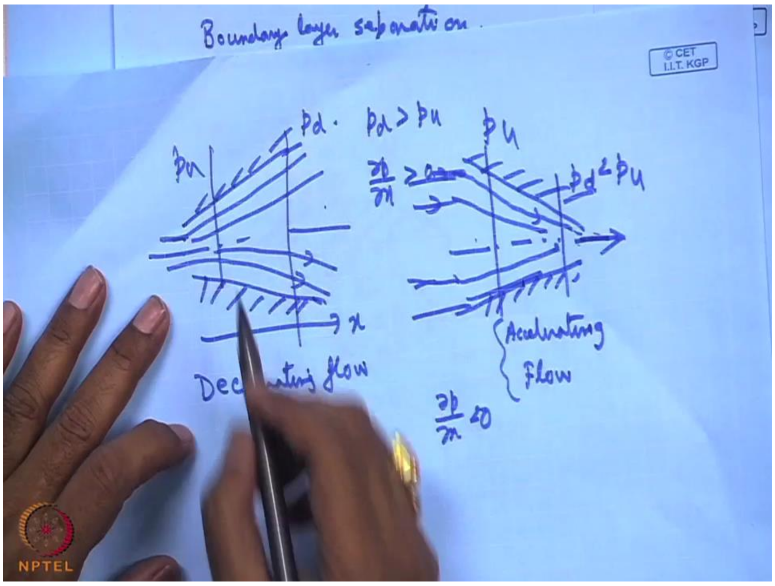
(Refer Slide Time: 12:28)



This is known as flow reversal. If you draw the, here the velocity after the flow reversal, after the flow reversal, here the flow reverses, if you draw the velocity profile, you will see the velocity profile is like this. You understand, so this part, the fluid flows in the opposite direction. This is known as boundary layer separation and this creates a large number of eddies, recirculatory flows. And by virtue of which, the total mechanical energy of the fluid is being curtailed, is being reduced and what happens, energy totally conserved.

So because of this creation of local recirculatory flow in the form of eddies which takes place because of the flow reversal, the boundary layer is detached and all boundary layer assumptions fall there. So what happens, from the practical point of view that part of the mechanical energy, that means the static pressure is being converted into intermolecular energy. Which from the viewpoint of mechanical energy is a loss and that is why people tell that this is the separation loss.

(Refer Slide Time: 13:36)



Now when we give a diverging passage, therefore now if you consider a diverging passage. Therefore now if you consider a diverging passage, the same thing, now with, this was with the external surface, now you consider a diverging passage. Now one thing, if the pressure is favourable, then the fluid particle does not have any flow reversal, it always flows. So therefore this flow reversal all boundary layer separation takes place whenever the pressure gradient is adverse.

This is clear because in favourable pressure gradient, even if the kinetic energy becomes low, the pressure force itself, this is the favourable pressure gradient, this is that, this case, that that is always a pressure force in the direction, the pressure force will help it to push in the direction of the flow. That will never happen with a favourable pressure gradient. It is a very important thing to remember.

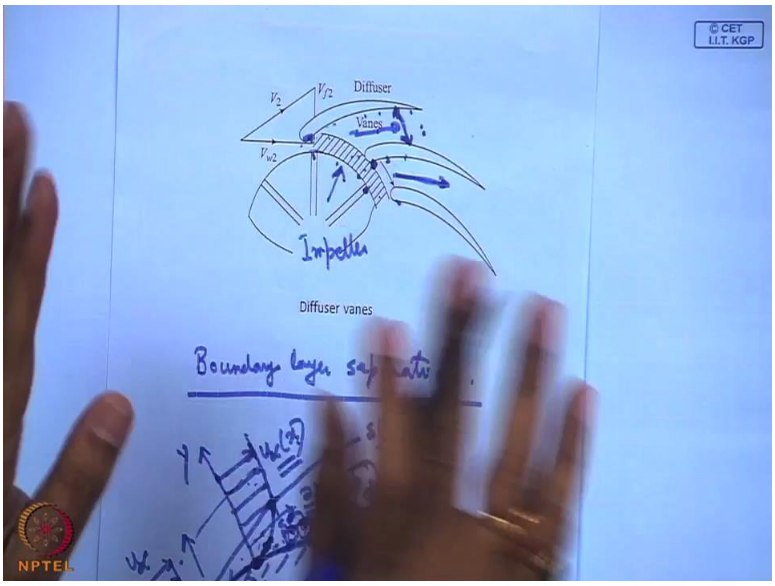
Now when the fluid flows in the diverging Channel for example the streamline maybe like this, so here what happens, the fluid flows, that any typical section PD and PU, so PD is greater than PU, so here Dell P Dell X is if this is X, Dell P Dell X is greater than 0, that means this is an adverse pressure gradient, here the separation will take place. Whereas this is the decelerating flow. Decelerating means, decelerating, that means its flow velocity is reduced and pressure is increased.

In an accelerating flow, if you consider the flow through a converging duct, that is a nozzle, in case of, this is the nozzle flow, this is a streamline. So therefore this is the streamline from a far distance, this is parallel. So in a nozzle flow, this is accelerating, accelerating flow.

Accelerating flow, that is nozzle. Where in subsonic flow, that I will again discuss afterwards, a converging passage acts as a nozzle for accelerating flow and a diverging passage acts as a decelerating flow.

So that I am not telling, this will be discussed afterwards in detail. That in a converging press it when the flow is accelerated, which we usually known as nozzle, Dell P Dell X is less than 0. That means a downstream pressure is always less than upstream pressure. So therefore always there is a force in the direction of the flow to push it. So therefore a diverging passage anywhere where you have the diffusion process, that the pressure is increasing the direction of flow, you have to be very careful of the boundary layer separation.

(Refer Slide Time: 16:04)



Now the separation is very sensitive with the angle of everything. If the angle of diverging is more, what happens that the rate of pressure increase, that is the adverse pressure gradient is more so that the separation occurs early. So therefore angle of divergence, the angle of divergence is very important in a diffuser duct, diverging is very important and that should be less than equal to 10 degree, 10 to 11 degree. So angle of divergence should not be made more than 10 degree. So it is restricted for design of any diverging passage.

So therefore here also, the diverging passage, divergence angle should be restricted at each and every point. Okay. Now I come to the vane less space. Now the divergence angle at the inlet to the diffuser vanes should also match with the direction of the velocity. And since the diffuser vanes are static vanes, so direction of the velocity means, the velocity, fluid velocity which comes out of the impeller, that direction should match the direction here, otherwise what will happen, otherwise there will be incident loss, loss had the incident.

However, here we cannot say so because the velocity with which, the direction of the absolute velocity with which the fluid comes out of the impeller is not same to that at which it will enter because there is a vane less space. So therefore we have to know when the fluid flows, the nature of the fluid flow or the flow field in this vane less space. Now the 1st question is that Sir why I will give a vane less space?

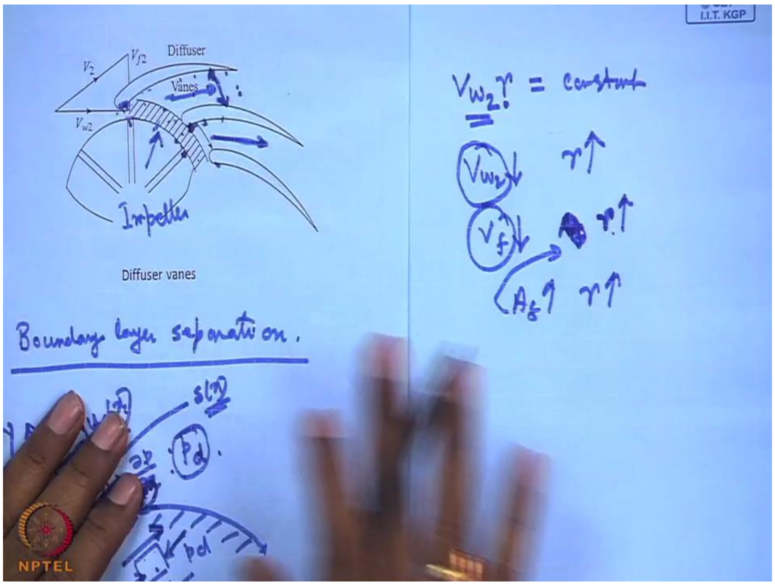
Why not, the diffuser vane should be given or should be provided right at the outlet of the impeller tip so that the fluid which will come out of the impeller will go to the diffuser? But it is not done. Always a vane less space is provided, this is because of few reasons. 1st one is that the Mach number of flow is reduced before it enters to the diffuser vane and Mach number has to be reduced means that the velocity of flow has to be reduced.

So therefore it is required that before the fluid enters or impinges or slides or whatever way you tell, the diffuser vanes, its velocity should be reduced. Therefore some space should be given which will act as a diffuser to reduce the velocity. And number 2 reason is that if we do not give that space, what happens, there will be an excessive circumferential variation of static pressure.

If you give all the, if you provide all the diffuser vanes very close to the impeller tip, then there will be an excessive variation of the circumferential stress which is radially propagated upstream inward to the impeller and creates a vibration and impeller blades may fail due to this vibrational fatigue. And this vibration is a function of the relative velocity of the fluid and the number of impeller vanes and it is more dangerous if this frequency or this vibration coincides with the natural frequency of the impeller.

And to avoid this usually the impeller vanes are not multiples of the diffuser vanes, this is one of the reasons. So therefore because of reduction of Mach number and the velocity and that circumferential variation of the static pressure, there is a vane less space. Now vane less space is a space which having an increase in cross-sectional area and in the vane less space if you want to know the principle, the flow field, then we can write like this.

(Refer Slide Time: 19:50)

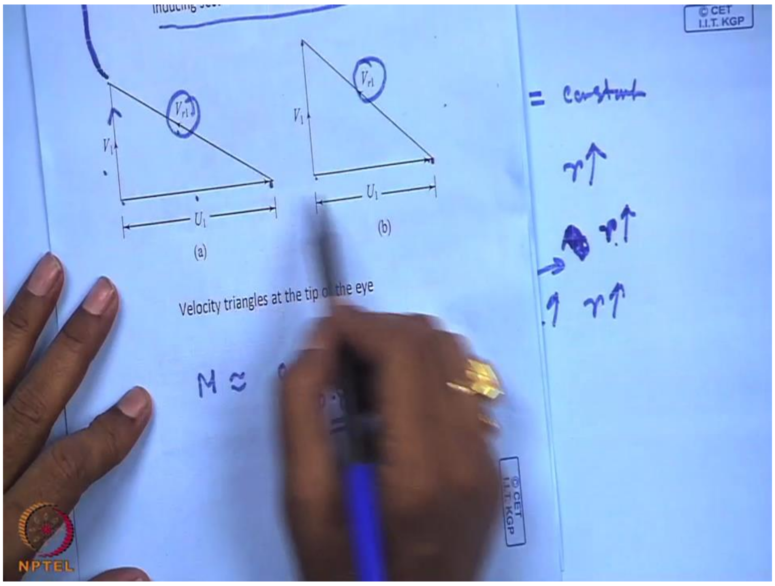


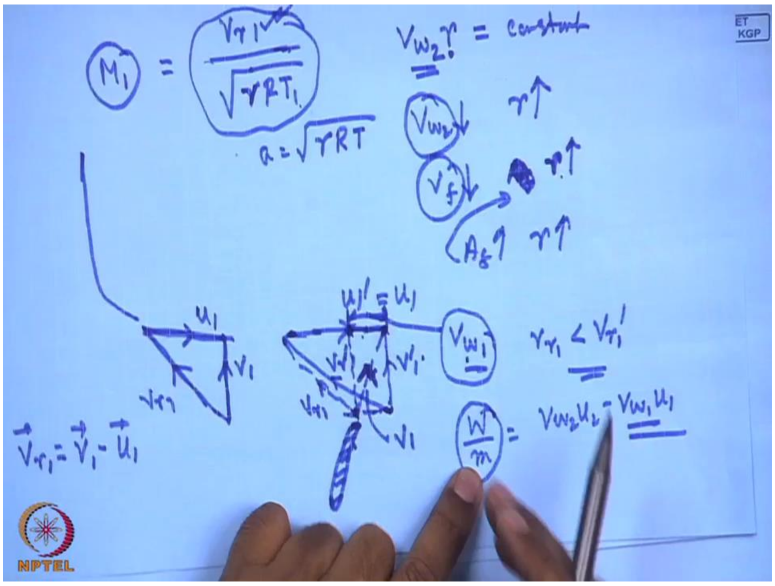
Since there is no and energy transfer, the VW2, that is the tangential component of velocity at the tip of the impeller into the angular momentum comes out, that is the constant. That means VW2 decreases with increase in R, it is inversely proportional to R. So therefore with the increase in R, the VW2 decreases, there is a decrease in VW2 with the increase in R. Okay.

Now another thing is that if you consider the flow velocity V F, this also decreases, this is because with the radius for a constant depth, that means the depth is constant in the perpendicular to the plane of the figure, the flow area, flow area with the, sorry, with the increase in R, the flow area increases, so I write simply the increase in R. Because with the increase in R, flow area increases, that means AS increases with increasing R, so because of that space takes place.

That means both the tangential velocity component and the flow velocity, okay. Both decreases as a whole the absolute velocity decreases. So a diffusion takes place. So therefore the Mach number is reduced number residues but at the same time this vane less space has to be designed in such a way that should be in conjunction with the inlet angle of the vane so that finally the fluid velocity direction should match the diffuser vane. This is okay, this is almost all about the design of the diffuser.

(Refer Slide Time: 21:42)





Now I will come to another thing which I forgot to tell you earlier in this connection regarding this inlet mark number here, okay, please wait, I will just show you here, yes, here is, I just forgot to tell you that this inlet thing which I have shown you. Sometime what happens is that reduce the Mach number at the inlet, it is not required here, I told that reduction of Mach number at the inlet, I go back to the earlier discussion that if this is the vane at the impeller tip, this is the impeller vane, so we know that this is the typical diagram, this is the typical diagram at the inlet.

This also I just forgot to tell you, you must know that this is U, this is VR1, this is B1, this already we discuss, the impeller vane. Here VR1 relative velocity, that is V1, this is U1 - U1.

Now here what happens, to reduce this Mach number, we already discussed earlier that A, now let A is gamma R T1, how, this is because that this acoustic velocity which will be again told you afterwards in compressible flow classes that for a ideal gas, the acoustic speed of sound velocity can be expressed as root over gamma, that is gamma is the ratio of specific speed, R is the characteristic gas constant and the temperature T1.

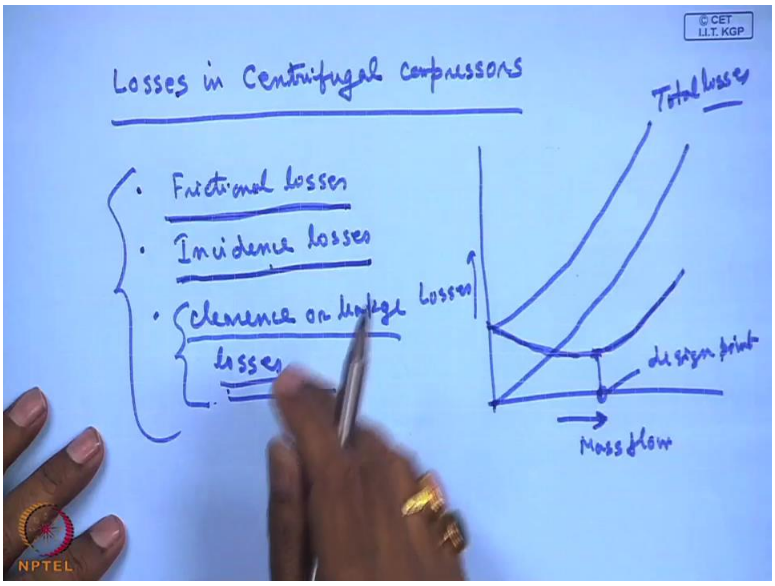
So therefore this is a question of Mach number. Now the VR is sometimes reduced by what do you know, by giving a deflector. And the thing is like this, for the same, I again draw this diagram for the same velocity, radial, flow velocity and the same, so this is the ideal one, this is the ideal one V1, U1 and VR1. So the dotted one is like this, this will be my final V1. So what happens, there is certain amount of pre-whirling is giving, that means, what is that, I will tell you, that is like this, a deflector of this type is given which deflect the flow in this way.

Sorry, sorry, sorry this will be this. So this will be my, let this dash now, the ideal one, this is V1 and therefore this is VR1. So for the same U1 dash, is U1. So U1 remains same, flow velocity remains same, V1 dash remains same, so that flow velocity is this component but the fluid velocity is having some angle. That means this portion is the now this portion is now, if you understand well, I am happy, that is the inlet tangential component. That means instead of having a axial entry, which is perpendicular to the direction of tangent, we give an oblique entry by use of a deflector which gives some amount of whirling of tangential component at inlet.

But for the same flow velocity, that means to accommodate the same mass flow rate, we have a reduction. That is VR1 is less than VR1 dash. So sometimes a deflector plate is used. But here what we will lose, we gain in terms of reducing the Mach number so that the impeller tip, we may be little sure that Mach number is not supersonic so that shock losses occur there. But we introduce a whirling component, this is known, giving a pre-whirling at the inlet so that the energy per unit mass or the work done per unit mass is now VW2, as you know this is the formula, but here now VW 1 is not 0.

So if it is 0, it is this. So therefore for a given VW 1, small VW1 is generated, so we lose, so that means at the cost of specific work, we give this pre-whirling. That means the work input to the fluid will be less. That means what we lose is the efficiency of the compressor. That means it is requires more energy for a given pressure rise, but the Mach number is reduced. So this was told and okay, then this diffuser is, you know about the diffuser.

(Refer Slide Time: 26:09)



Now I come to the losses in centrifugal compressor. Losses in centrifugal compressors. What are the different losses in centrifugal compressors? Now losses, there are different types of losses on centrifugal compressors. So they are like this, one is the frictional loss, frictional losses. Another is the, frictional losses, another is the incidence loss, incidence losses, another is the clearance or leakage losses, clearance or leakage, leakage losses. Okay. Now one by one, the frictional losses are typically the fiction.

Now the fluid flows through the compressor blade passages, comes in contact of the solid surface and the fluid to fluid layers, that is because of viscosity, skin friction is there, that is purely frictional loss. Apart from that, there is a separate the loss, boundary layer separation or there may be losses due to shock. Now these losses are known totally as frictional losses. Frictional losses mainly comprises the skin friction and the suppression loss.

Suppression loss is very important in compressors because throughout the flow is there with adverse pressure gradient. Means that there is always a deceleration of the flow. So separation loss and the skin friction combines the total pressure losses at the friction, total friction losses. So what is this loss 1st of all? This is loss again, the loss in mechanical energy. Which is mostly manifested in terms of the loss in the or the shortfall in the static pressure of the compressor at the outlet.

So frictional losses is because of the friction, the skin friction and the boundary layer separation because of the decelerating. Incidence losses are losses because of the fact that when the flow velocity while flowing through the vane does not follow the vane angles.

Especially at incidence to the vane, if the flow velocity, the direction of the flow velocity relative to the vane is not following the vane angle at the inlet, there are losses. And this will happen if the compressor does not work at its design condition.

So therefore off design conditions, the incident losses will take place when the flow cannot glide the vane both that at inlet and outlet, that is the relative velocity angle differs from that of the vane angles. Another is the clearance or the leakage losses which take place because of the clearance between the impeller eye shaft and the casing of the compressor. Okay. The impeller eye and the casing, impeller eye tape and the casing, these are typical mechanical thing which we can reduce that by proper sealing. But when the impeller eye tip diameter is very large to accommodate more mass flow rate, the sealing becomes a problem.

So we can reduce that by putting glands, providing glands to reduce the leakage between the, clearance between the shaft and the casing. These are all clearance and leakage loss. But this clearance and leakage losses comparatively very less as compared to frictional loss and incidence loss. Now if you draw a figure of losses versus mass flow, this is mass flow, then you will see, this type of figure, frictional losses are like these, this always increases with the mass flow like this, frictional losses with mass flow.

It is like this, this is 0 when there is no mass flow but incidence losses give the picture like this. This is minimum at the design point, this is the design, design point. And off design point tip, maybe there even at low mass flow and I mass flow, these are off design points wherein both the direction this increases. So if you add these 2, the total losses take place, total losses take this shape, total losses. Okay, so these 3 are the important losses but this is not as important, this is relatively less as compared to the frictional losses and the incidence losses. Okay, I think today I will end here and we will discuss the compressor characteristics in the next class. Thank you.