Introduction to Fluid Machines and Compressible Flow
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Lecture - 22
Centrifugal Compressor Part II

Good morning, and welcome you all to this session of the course. In the last class we were discussing the work required or work done to the fluid and the pressure rise. Let us again continue little bit.

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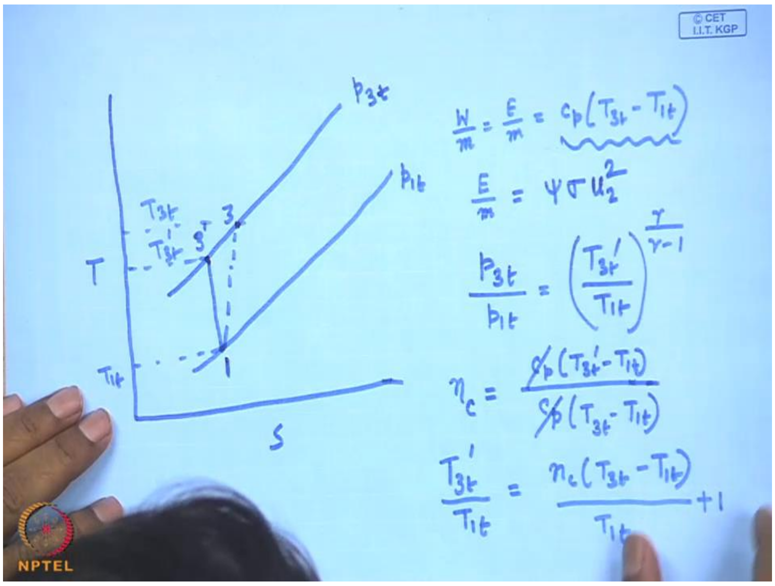

In the earlier discussion, we were trying to express the compression process thermodynamically in T-S plane by showing two pressure lines, constant pressure line. One is the total pressure at the inlet to the compressor, another is the total pressure 3 at the outlet to the compressor, no, it is 3 at the outlet to the compressor, which includes the diffuser 2. That means, if you see this figure you see, that this is the inlet to the compressor, that is impeller and this is the outlet, final pressure rise. If we just, so this p 3 t and p 1 t, I want to find out the total pressure rise in the compressor.

So, now in this case if the entire process is isentropic, then we can show the process in the T-S diagram as I already told, that this is one and this is the T 1 t, this is the T 1 t and this is the T 3 t, this is the T 3 dash t, rather this is T 3 dash t, T 3 t dash, T 3 t dash. This is the actually process, we just state 3. Let this be 3 dash, this is an ideal process. And the actual process, as I told, which incurs the internal reversibility due to fluid friction and internal heat transfer due to temperature gradient and we land up to the actual point 3, which tilts right this way to increase the efficiency. This was well-known.

Now, the work per unit mass, as we found, or energy per unit mass from the steady flow energy equation is C p. This is T 3 t, this is, this is T 3 t is C p T 3 t minus T 1 t. And at the same time we found from the momentum-momentum theorem, which is known as Euler's equation, that E by m equals to psi, the power input factor, into sigma, the slip factor, into the u 2, the peripheral speed at the outlet square at the outlet of the impeller square, ok. So, this is the energy.

Now, now you see, if we want to relate the pressure rise in this process, then the pressure rise can be written. So, pressure rise can be related through the isentropic process, by the isentropic process relation is like this, p 3 t. That means, this pressure, this pressure and this pressure same, the same pressure line divided by p 1 t is T 3 t dash, that means, it is through the isentropic process, that is, the end of the isentropic process T 1 t to the power gamma by gamma minus 1.

Now if we have to relate this T 3 dash to T 3 t, we have to take care of the isentropic efficiency of the compressor. As I told you earlier, the isentropic efficiency is defined as the ideal work done in absence of any friction or internally irreversibility in the process to the actual work done to the fluid or actual work input within consideration of the friction. In this case, the actual work input is more than that in the ideal case. So, therefore if we write, that the ideal work done from the steady flow energy equation will be this, this is found from the isentropic case. And similarly, by application of the steady flow energy equation it is like this. This is the actual work input.

And since air is an ideal gas with constant C p, c p cancels out, this become this eta c, ok. Then, we can write the T 3 from this. We can write T 3 t dash divided by T 1 t is equal to what? Eta c into this, eta c into T 3 t minus T 1 t. This is divided by T 1 t plus 1. Am I correct? Because this divided by T 1 t is this by T 1 t eta c into T 3 t minus T 1 t divided by T 1 t, ok, plus 1. So, this is the, so now if it is, ok.

Now, if we, if we, this I will use if we, now ok, please wait. This, if now we use this expression here, then we can write, that p 3 t by p 1 t equals to what? T 3 dash by T 3 is this that means, 1 plus eta c into T 3 t minus T 1 t divided by T 1 t to the power gamma by gamma minus 1. Again, I can substitute this temperature difference, T 3 t minus T 1 t, the difference in this stagnation temperature at the end of the compression that means, end of the compressor after the compression in the diffuser 2 and the inlet stagnation or total temperatures is this difference in terms of the work per unit mass. We can write 1 plus eta c into, this will come sigma psi sigma power input factor u 2 square. So, this is E by m. Now, we are replacing this thing divided by c p T 1 T sigma

Student: not visible

Professor: Not visible, oh, yes, I am sorry, I am sorry, that it is not visible. Now, it is visible? So, this we can now write, to the power gamma by gamma minus 1. So, here you see, that the pressure ratio, which is an important parameter for the compressor, is expressed in terms of the peripheral speed of the impeller at it stream. Now, here what happens is, that sigma is usually not a variable one. It lies between, as I told earlier, some value point, around 0.9 eta c is the compressor isentropic efficiency. This value is almost fixed to something like 0.85. Now, for a given inlet total temperature, therefore we see, this pressure ratio is proportional to the impeller speed in this fashion. So, this is a very important relation of the pressure ratio to impeller speed.

Now, I will come to a very important thing of the centrifugal compressor, not centrifugal, centrifugal or axial compressor. Now, as I told earlier, since the compressor handles fluid, which are compressible in nature, they are gas, they are not liquid, there bulk modular elasticity is little less. So, therefore depending upon the flow velocity, the density changes and if the change of density is appreciable, flow is compressible.

And in compressible flow first consideration is, that the change in density with pressure. There are other considerations depending upon the flow region, which takes place in compressible flow, which I will discuss afterwards and I will be telling you about the compressible flow, that depending upon the flow regions, especially when the flow velocity is very high some typical features, which is typical, which are typical to compressible flow, take place. If the flow velocity is very high and close to the acoustic velocity or the velocity of sound relative to the fluid at that state, then different physical pictures are observed.

So, therefore in a compressible flow, one of the very important criteria to specify the flow is the ratio of the flow velocity to that of the sound velocity relative to that flow at the state of the fluid, and that dimensionless number is known as Mach number.

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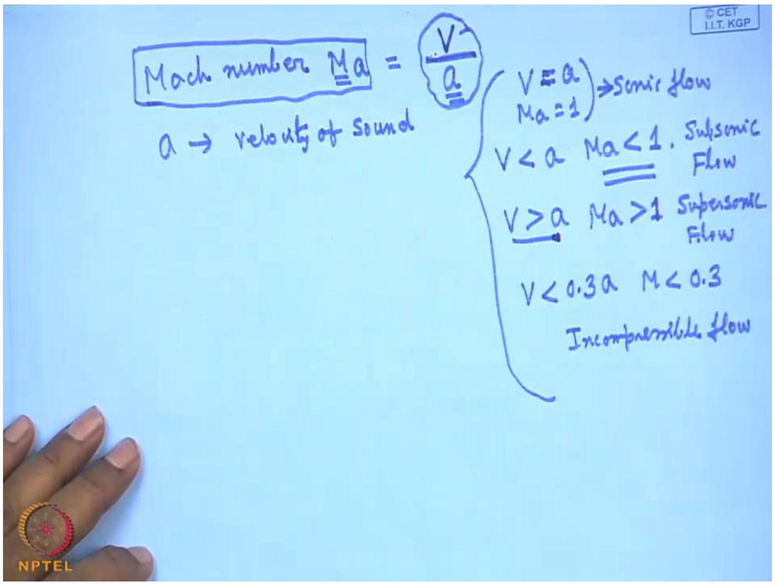

So, therefore I write you a Mach number consideration and this is for all machines or all device that handles compressible flow or the flow of compressible fluids Mach number, that is, Ma, which is defined as the ratio of the flow velocity divided by the velocity of sound or acoustic velocity. This is velocity of sound, acoustic velocity a is the velocity of sound or acoustic velocity, velocity of sound or acoustic velocity relative to the fluid flow at that state of the fluid. So, it very much depends upon the state of the fluid, state means for example, density and temperature of the fluid. So, this is a very important criteria.

And when the flow velocity equals to the sound velocity, then Mach number equals to 1 and we call the flow as sonic flow. This flow is called as sonic flow. When the flow velocity is less than a, Mach number is less than 1, the flow is known as subsonic flow, subsonic flow. This is, this will be the discussed afterwards, just an introduction I am giving you so that you can understand things. When this is greater than a, that is, Mach number greater than 1, this known as, the broad, the classification supersonic flow.

And there is a regime in the subsonic flow. When v is less than roughly 0.3 a or Mach number is less than 0.3, then the flow may be treated as incompressible flow, incompressible flow. You understand incompressible flow? That means, the density does not change with the pressure or the change in density with the pressure is negligible, ok. Relative change in density is negligible. So, these are the regimes of flow.

Now, what happens if the flow is supersonic? At any state depending upon its velocity, then some features are observed, which causes extra losses of energy and in compressor, which causes extra looses of static pressure, ok, which is undesirable. So, therefore for compressor design one has to be very careful, that Mach number of flow should not exceed necessarily or usually at any point of flow in the compressor over the sonic level, so that other complicated features of compressible flow will come into. So, this is known as Mach number considerations.

So, therefore at each and every section of the compressor the Mach number has to be considered and here the Mach number, if you see the definition, that the definition, the velocity of flow, it is the velocity relative to the moving solid surface. When there is a flow velocity pass the solid surface, it is the velocity relative to the solid surface and in a turbo machine the solid surface are also moving, solid surface has also the velocity. So, therefore the relative velocity of the fluid has to be considered in defining the Mach number, which has to follow this criteria of being less than 1 to make the flow subsonic to avoid excess losses.

So, one of the important section is the inlet to the impeller. Actually, the Mach number velocity of flow will be high at the outlet of the impeller where it gains kinetic energy from the impeller where the energy is being imparted to the fluid. So, to restrict that Mach number, which is maximum at the outlet t, we have to check the Mach number at the inlet of the impeller too. So, therefore the inlet design has to be made in such a way, that Mach number is relatively low.

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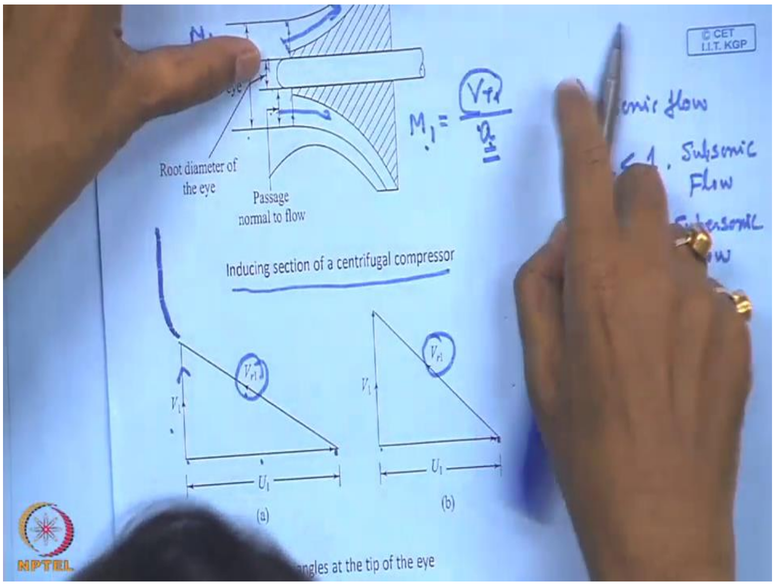

Now, you see an inlet section of the impeller, that is, the inlet part. This is known as the inducing section of a centrifugal compressor. You see, this is the eye, this is the root of the eye and this is the tip of the eye. So, this is the tip diameter of the eye and this is the root diameter of the eye and this is the passage of the flow, normal flow. That means, it is the cross-sectional area of the flow velocity. The flow turns like this, try to understand very well, like this. So, therefore the design of the tip should be such, that the Mach number should be low.

Now, how do you define Mach number, just I told you in a, at this moment, that Mach number at entry to the fluid here if you define, it has to be defined based on the relative velocity, that means, v r 1 divided by a. Now, a depends upon the fluid state here, but v r 1 depends upon how the fluid is being allowed to enter to the impeller eye.

Now, as you remember, the impeller is like this. The impeller design, again I show you, the impeller blade is like this. At the eye the design is like this, so this is a velocity triangle. You see, that this is the relative velocity, which angle matches at the angle of impeller blade at the inlet. Now, these two are specific or typical velocity diagram. This diagram is for a very large impeller diameter where the peripheral speed is more than u 1, ok.

And because of the large diameter, the frontal area becomes large for which the flow velocity or the absolute velocity is less, which gives rise to higher relative velocities. And we have to be very careful here. The Mach number will be more, but at the same time the mass flow, it can accommodate more mass flow, ok. But if you now reduce the velocity, this is the typical diagram of a small eye tip diameter there, what you will get? We get a u 1 like this relatively lower than this, but the flow velocity is high, so that v r 1 may be reduced, but it is very difficult to conclude which one is greater or lower. That depends upon the relative values of u 1 and the value of v 1. However, this v r 1 is our prime important such that v r 1 by a, that is, the ratio of Mach number should be low. And we try to design the impeller in such a way, that the Mach number lies between 0.7 to 0.9, usually 0.8, so that we avoid losses.

What happens I tell you in little brief, which will be discussed in more detail when I will teach you the compressible flow. What happens if the flow is supersonic, that means, in a compressible flow if the flow velocity is more than the acoustic velocity, local acoustic velocity, then what happens? If under certain boundary conditions or in the disturbance of the flow, flow has to adjust and accordingly decelerate. Then, the supersonic flow suffers a sudden deceleration through a sudden discontinuity and that discontinuity is known as shock. So, therefore a shock takes place.

A supersonic flow cannot adjust itself to have a gradual and smooth transition in the form of deceleration from supersonic to subsonic. It cannot happen. And in compressible flow, when the flow is supersonic due to the circumstances or the boundary conditions imposed on the flow, flow has to decelerate and this is adjusted by a sudden deceleration or a sudden discontinuity in the flow. And this discontinuity is a really mathematical discontinuity, which takes place within almost infinitesimal region whose length is in the terms of molecular diameter and that is how discontinuity in the flow is known as shock in general. And that shock, what matters to the practical case is, that due to that shock there is an abrupt loss in the total energy. This is total irreversible process.

So, what matters is, that because you can ask me, Sir, when the deceleration takes place, when the fluid come to some subsonic stage what happens, that pressure increases? Yes, static pressure may increase, but if you consider the total mechanical energy, there is a huge loss in the total mechanical energy. Some of the pressure part, that is, pressured energy, you can call loosely, and the kinetic energy, there is a loss.

So, therefore in design of any compressible flow machines or compressible flow device, one has to be very careful. First of all, it is better to avoid the supersonic state of flow and, or supersonic state of flow is unavoidable, one has to be very careful, so that supersonic flow should be decelerated in a way, that shock does not take place.

Here, again I am telling you, which I will explain afterward. It is not, that always shock will take place. It depends upon certain boundary condition imposed on it, so that shock has to take place. But it may occur, that flow may be made in such conditions with design backed pressures and many other things, that I will discuss afterwards as shock may be avoided. But in practice it may not be done because a supersonic flow, when it comes, for example, when an aircraft moves with supersonic velocity, as you know, that when aircraft moves with a supersonic velocity, that is, velocity more than the sound velocity at the state of the fluid there at high altitude, then what happens relative to the aircraft? The fluid moves with supersonic velocity.

So, for upstream, the fluid approaches the supersonic velocity. When it approaches the nose of the aircraft, then what happens? The fluid has to decelerate, fluid has to decelerate when it tries to strike the nose and flow past the nose and that deceleration is causing the shock. And oblique shock occurs at the nose of the aircraft. So, these are the things probably, you know, today these are popular things. So, therefore I must say, that this Mach number consideration is very important consideration. And therefore, the impeller eye design has to be made, so that Mach number at inlet that is based on the relative velocity at the inlet, should be low.

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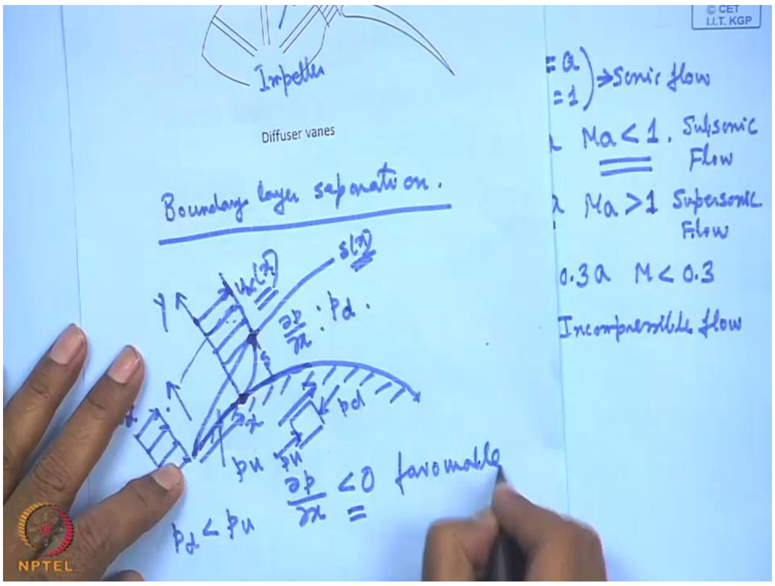

Now, next is this diffuser. Now, I come to the next part, that is, the second component, diffuser. Now, what is diffuser? That is same as that of your centrifugal pump diffuser. Now, we know, that impeller and diffuser are the two important parts. This is impeller, impeller, this is impeller. Now, what 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 increase in, 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, 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 engines or with the plants, gas turbine plants, turbojet, turbo power, turbofan engines, where this air is used in a combustion chamber to burn the fuel. And when the fuel is burned, high temperature is generated or high temperature, the air is heated to a high temperature, why? The energy generated because of the burning. So, to make the burning more efficiently what is required is, that a high pressure air, at high temperature and high pressure air, but at very small velocity, as low as possible. Sometime it is unavoidable for different reasons that you will know afterward if you read the jet engines or the gas turbines in more detail. But as far as it should be avoidable, because the high velocity in the combustion chamber for burning fuel causes several problems, like combustion instabilities. 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, ok. 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 the stagnation of 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 this 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 x rays, that means, the kinetic energy, which is there, which is undesirable is then converted to pressure energy or to converted to higher static pressure in the diffuser. The similar thing, which is done in the case of centrifugal pump. So, this diffuser is like this. There are, first of all there is a vaneless space, first of all there are no vane, so it is a vaneless space where the diffusion takes place partly and after that there are number of vanes, which makes the final diffuser.

Now, why the number of vanes are made to divide the air stream 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 flowing different channels.

Now, I will come to the vaneless space afterwards, let us first discuss these vanes. So, these vanes create the passage, so each and every passage, this is the width of the passage, has a diverging width, the diverges, which depends upon the shape of the vane. So, vanes are curved. So, depending upon the curvature the widths are made, so that the cross-sectional area normal to the flow increases because of which the velocity decreases and pressure increases the depth, which is perpendicular to this plane of the figure, that 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.

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 loses. 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, ok. Now, let me tell you something about boundary layer separation.

Now, you see, that when a fluid flows, come to the basic principal of fluid mechanics, so you probably learned in fluid mechanics, again it is a recapitulation of the earlier things, that when a fluid flows from one point to another point or in an average from one section to other section, what is the gradient, which make the flow possible? It is the energy gradient; that means, fluid flow from a higher energy to a lower energy. So, therefore when the fluid flows from a point or a section to another point or section downstream where the pressure increases, then the fluid flows against an adverse pressure gradient, why? Because fluid element faces a higher pressure at the downstream, that means, the direction in which it is flowing. But still, the fluid flow because of the energy gradient energy at upstream is always higher than that at the down upstream.

But what happens, you see, that when the fluid flows past a body, let us consider this a recapitulation, let us consider the fluid. Now, to understand this let us consider an external fluid. A fluid is flowing past at curved surface, for example, now let a fluid enter with uniform velocity. Let us recapitulate what is boundary layer flow. Now, you know, that when the fluid flows past a solid surface, at this solid surface, the relative velocity of the fluid with respect to the solid surface or the velocity of the fluid relative to the solid surface 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 there interfacial process by which the fluid is not allowed to slip over this solid. That means, its velocity relative to solid is 0. That means, its velocity relative to solid 0. That means, that surface is at rest, the fluid velocity will be 0. And what happens, the fluid just above it in near vicinity of the solid is being retarded to everything, 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 attains the free stream velocity, ultimately attains the free stream velocity. It attains actually asymptotically at any section. But if we consider some 99 percent of the 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 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 the function of it.

Now, this takes at a distance, a i denote the free stream velocity at as u infinity a, which may not be the same at 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 improve pressure gradient in the potential zone, that is, the zone above the boundary layer where 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 a pressure gradient, which is imposed by the curvature of the surface, that is, del p del 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 pressure of the downstream is less than p u, by mathematical term we tell, that dell p dell x is less than 0 because this is in the increasing direction of a, the direction of a flow. That means, the fluid is flowing with a negative pressure gradient there.

What happens if you consider a fluid element? Since this pressure is low and this pressure is high upstream pressure, so fluid experience is a net pressure force in the direction of the flow. That is why, this is known in fluid mechanical term as favorable pressure gradient, favorable 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 p u, then by mathematics del p del x is greater than 0. So, a negative pressure gradient means, favorable pressure gradient and this is known as adverse special gradient. In this case, p d is more than p u, so therefore the fluid is facing a force, net pressure force in the direction opposite to its flow. That means, it opposes 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, the 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. What, what happens for the fluid particles very close to the wall? The kinetic energy is totally consumed. The kinetic energy is destroyed because kinetic energy is ultimately coming to 0. Fluid is retarded because of this momentum transport, ok, and this is being manifested by the property fluid viscosity.

So, therefore what the liquid fluid particles close to the surface kinetic energy falls appreciably so that they cannot surmount the adverse pressure here, that means, the total energy becomes insufficient at the upstream to flow. That means, the energy gradient is reversed, ok. That means, that fluid with low kinetic energy near the solid cannot surmount the adverse pressure. And then, what happens? At some point it happens where the ((Refer Time: 32:26)) gradient of energy opposes becomes reversed and the fluid flows in the opposite. This is known as flow reversal.

If you draw the, here the velocity after the flow reversal, after the flow reversal here, the flow reversal, 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 flow formed by virtue of which in 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 flowing in the form of eddies, which take place because of the flow reverser, 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 view point of mechanical energy is a loss. And that is why people tell, this is the separation loss now when we give a diverging passage. Therefore, now if you consider a diverging passage, the same thing.

Now, this was with the external surface, now you consider a diverging passage. Now, one thing, if the pressure is favorable, then the fluid particle does not have any flow reversal, they will always flow. So, therefore this flow reversal of boundary layer separation takes place whenever the pressure made in this is adverse. This is clear, because in favorable pressure gradient, even if the kinetic energy becomes low, the pressure force itself. This is the favorable pressure gradient. This is, that this case, that there is always pressure force in that. Direct pressure force will help you to push in the direction of the flow, so it will never happen with the favorable pressure gradient. This is a very important thing to remember.

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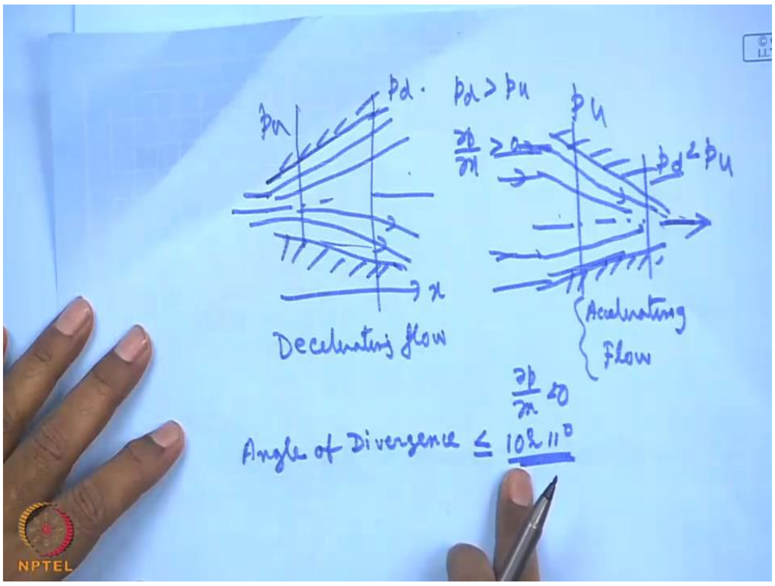

Now, when the fluid flows in a diverging channel, for example, this stream line may be like this. So, here what happens, the fluid flow, that any typical section p d and p u, so p d is greater than p u. So, here del p del x is, if this is x, del p del x is greater than 0, that means, this is an adverse 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 the 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 the stream line. So, therefore this is the stream line, 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, the converging passage acts as a nozzle or accelerating flow and a diverging passage acts as a decelerating flow. So, that I am not telling now, this will be discussed afterwards in the detail, that in a converging passage when the flow is accelerated, which we usually know as nozzle, del 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 increased in the direction of flow, we have to very careful of the boundary less separation. Now, this separation is very sensitive with the angle of divergence. If the angle of divergence is more what happens, that the rate of pressure increase, that the adverse pressure gradient is more, so that the separation occurs early. So, therefore, angel of divergence, the angle of divergence is very important. In a diffuser duct divergence 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 divergent passage, divergence angle should be restricted at each and every point, ok.

Now, I come to the vaneless space. Now, the divergence angle at the inlet to the diffuser vane should also match with the direction of the velocity. And since that diffuser vanes are static vane, so direction of the velocity means the velocity, absolute 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 at the incident. However, here we cannot say so because the velocity with v, 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 vaneless space. So, therefore we have to know what the fluid flow, nature of the fluid flow or the flow filled in this vaneless space.

Now, the first question is, that Sir, why I will give a vaneless 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 vaneless space is provided. This is because of two reasons. First 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 the guides, whatever we tell the diffuser vanes, its velocity should be reduced. So, therefore some space should be given, which will act as a diffuser to reduce the velocity.

And number two 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 this circumferential stress, which is radially propagated upstream, you know, what 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 of 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 the circumferential variation of static pressure, there is a vaneless space.

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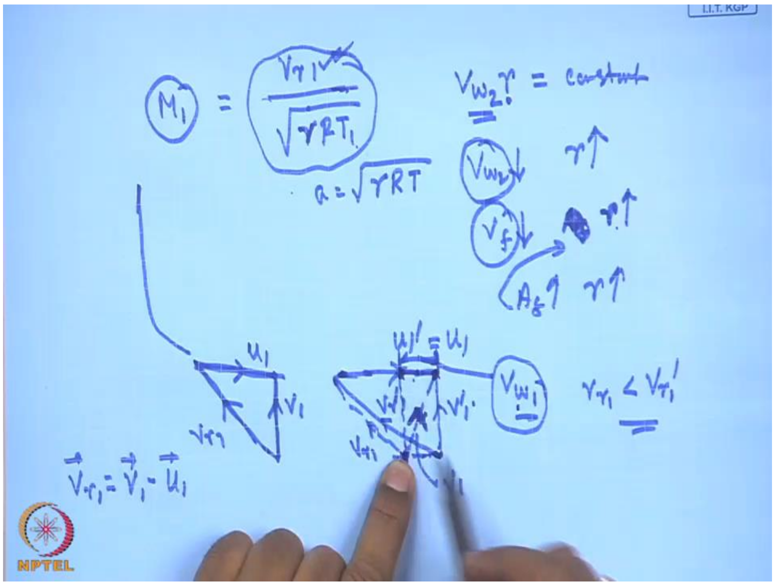

Now, vaneless space is a space, which having an increase in constructional area and in the vaneless space if you want to know the, in principle the flow field, then we can write like this. Since there is no energy transfer, the v w 2, that is, the tangential component of velocity at the tip of the impeller into at the angular momentum comes out, that is constant, that means, v w 2 decreases with increase in r, the inversely proportional to r. So, therefore with the increase in r, the v w 2 decreases. There is a decrease in v w 2 with the increase in r, ok.

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, depth is constant in 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, A f increases with the increase in r. So, because of that this takes place, that means, both the tangential velocity component and the flow velocity, ok, both decreases as a whole, the absolute velocity decreases, so a diffusion take place. So, therefore the Mach number is reduced.

But at the same time, this vaneless space has to be designed in such a way that should be in conjunction with the inlet and the angle of the diffuser vane, so that finally the absolute velocity direction should match the diffuser vane. This is ok, this is almost all about the design of the diffuser. Now, I will come to another thing, which I forgot to tell you earlier in this connection regarding this inlet Mach number here, ok.

Please wait, I just show you here, yes, here I just forgot to tell you that this inlet thing, which I have shown you, this sometime what happens to reduce the Mach number at the inlet. It is not required here. I told the 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 v r 1, this is v 1. This already we discussed impeller vane here, v r 1 is the relative velocity, that is, v 1, it is u 1 minus u 1.

Now, here what happens, to reduce this Mach number we already discussed earlier, that now a is gamma r t 1. How this is, because that this acoustic velocity, which will be again told you afterwards in compressible flow classes, that for an ideal gas the acoustic speed or sound velocity can be expressed as root over gamma, that is, gamma is the ratio of specific heat r, the characteristic gas constant and the temperature T 1. So, therefore this is the expression of Mach number.

Now, the v r 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 flow velocity and the same, so this is the ideal one. This is the ideal one, v 1 u 1 and v r 1. So, the dotted one is like this. This will be final v 1. So, what happens? There is certain amount of prewhirling is given, that means, what is that? I tell you that is like this. A deflector of this type is given, which deflects the flow in this way. Sorry, sorry, sorry, this will be this. So, this will be my dash.

Now, the ideal one, this is v 1 and therefore, this is v r 1. So, for the same u 1 dash is u 1. So, u 1 remains same, flow velocity remains same, v 1 dash remain same, so that flow velocity is this component, but the absolute 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 an 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 the inlet.

But for the same flow velocity, that means, to accumulate the same mass flow rate we have a reduction, that is, v r 1 is less then v r 1 dash. So, some time the deflector plate is used, but here what we lose, we gain in terms of reducing the Mach number, so that at the impeller tip we may be little sure, that Mach number is not supersonic, so that shock loses occur there. But we introduced a whirling component. This is known giving a prewhirling at the inlet, so that the energy per unit mass or the work done per unit mass is now v w 2.

As you know, this is the formula, but here now v w 1 is not 0. So, if it is 0, it is this. So, therefore for a given v w 1, small v w 1 is generated, so we lose. So, that means, at the cost of specific work we give this prewhirling, 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 require more energy for given pressure rise, but the Mach number is reduced, so this was told and ok.

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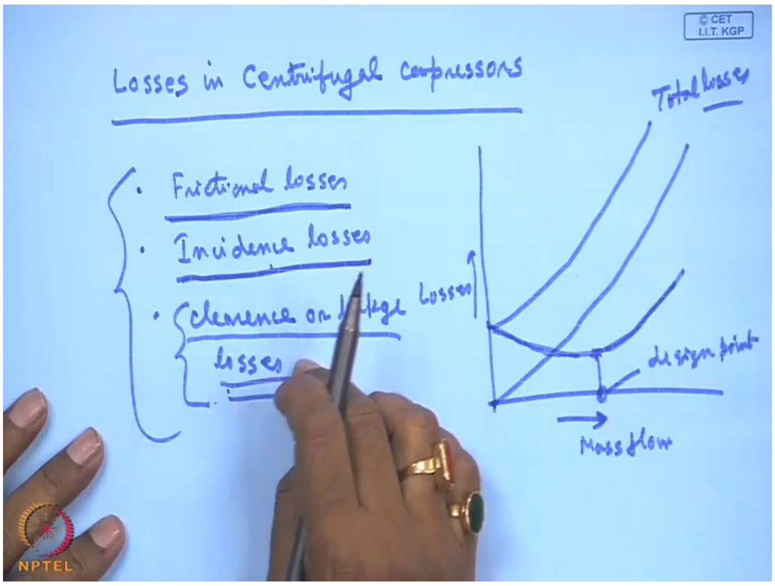

So, then this diffuser is, you know, about the diffuser. Now, I come to the losses in centrifugal compressor, losses in centrifugal compressors. What are the different losses in centrifugal compressors? Now, losses, there are different types of losses in centrifugal compressors, so they are like, this one is the frictional losses, frictional losses, ok. Another is the frictional losses, another is the incident losses, incidence losses, another is the clearance or leakage losses, clearance or leakage, leakage losses, ok.

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

And the separation loss, separation loss is very important in compressor because throughout the flow is they are 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 and the total frictional losses. So, what is this loss? First of all, loss, again the losing mechanical energy, which is mostly manifested in terms of the loss in the, or the short fall in the static pressure of the compressor at the outlet. So, frictional losses is because of the friction, skin friction and the boundary layer separation.

Because of the, decelerating incident losses are losses because of the fragment vane, 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 designed condition.

So, therefore of design conditions the incident losses will take place when the flow cannot glide the vane, both at its inlet and outlet, that is, the relative velocity angle differs from that of the vane angels. Another is the clearance and leakage losses, which take place because of the clearance between the impeller eye shaft and the casing of the compressor, ok, or the impeller eye and the casing impeller eye tip, and the casing impeller eye tip, and the casing. These are typical mechanical things.

We can reduce that by proper sealing, but when the impeller eye tip diameter is very large to accommodate more mass flow rate, this sealing becomes a problem. So, we can reduce that by putting glance, providing glance to reduce the leakage between the clearance, between the shaft and the casing. So, these are all clearance and leakage loss, but this clearance and leakage lose is comparatively very less as compared to frictional lose and incident 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 is like, that it always increases with the mass flow like this. Frictional loses with mass flow, it is like this, this is 0 when there is no mass flow, but incident losses gives a picture like this. This is minimum at the design point, this is the design, design point and of design point take may be there even at low mass flow and high mass flow. These are of design point where in both the directions this increases. So, if you add these two, the total losses take place, total losses take this shape, total losses. So, these three are the important losses, but this is not as important. This is relatively less as compared to the friction losses and the incident losses, ok. I think, today I will end here and we will discuss the compressor characteristic in the next class.

Thank you.