Fluid Machines.

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Lecture-32.
Basic Principles and Energy Transfer in Centrifugal Compressor Part III.

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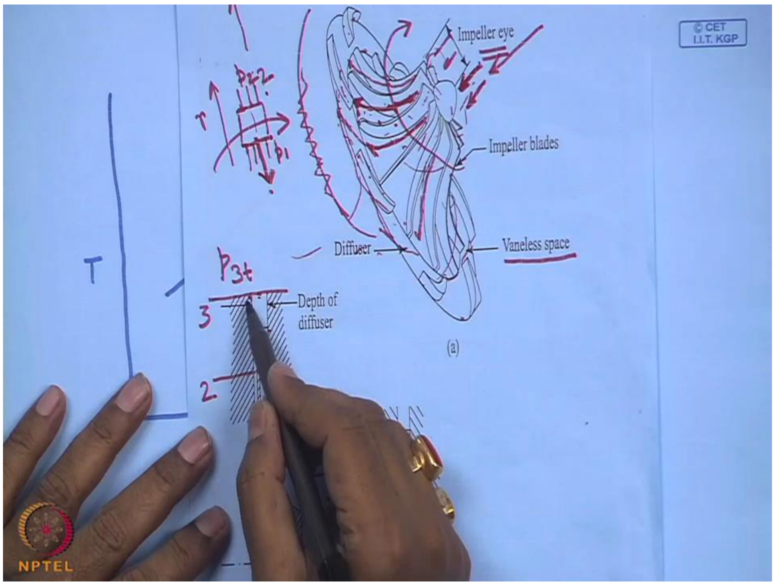

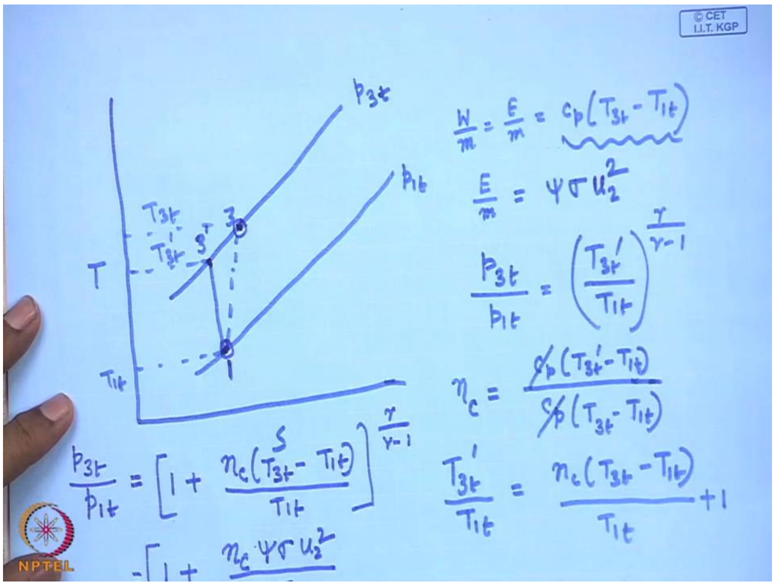

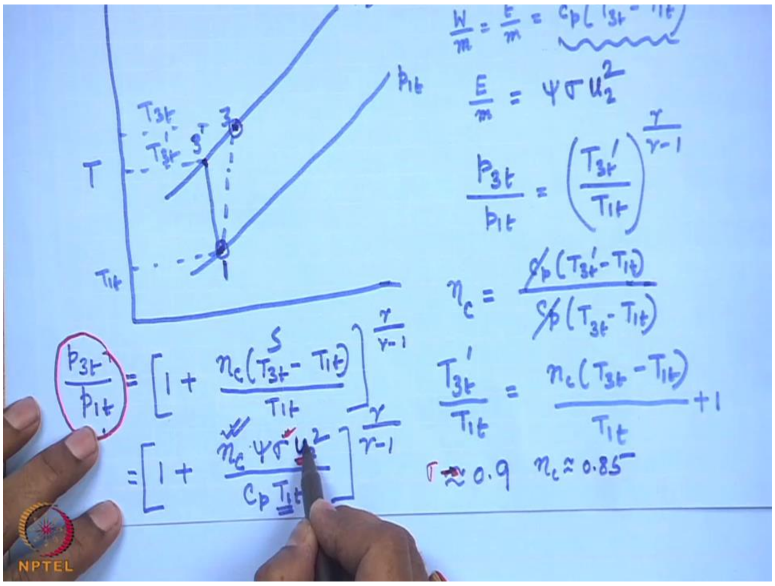

Good morning and welcome you all to this session of the course. In the last class we were discussing the work required or work done to the fluid and the pressure rise. Let us again continue little bit the earlier discussion. We were trying to express the compression process thermodynamically in TS plane by showing 2 pressure lines, constant pressure lines, 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 the impeller, and this is the outlet. The final pressure rise, if we just show this P3 T and P1T, 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 TS diagram as I have already told that this is 1 and this is the T1 T, this is the T1 T and this is the T3 T, this is the T3 dash T, rather this is T3 dash, T3 T dash, T3 T dash, T3T dash. This is the actually the process, we just state 3.

Let this be 3 dash, this is ideal process and the actual process as I told which incurs the internal irreversibility due to fluid friction and internal heat transfer due to temperature gradient and we will end up to the actual point 3 which is heels write 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 CP. This is T3 T, this is, this is T3 T is CP T3 T - T1 T.

And at the same time, we found from the moment of 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 U2, the peripheral speed at the outlet square, at the outlet of the impeller square. Okay. 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.

P3 T, that means this pressure, this pressure and this pressure is same, the same pressure line divided by P1 T is T3 T dash, that means it is through the isentropic process, that is the end of the isotopic process, T1 T to the power gamma by gamma -1. Now if we have to relate this T3 dash to T3 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 internal irreversibility in the process to the actual work done to the fluid or actual work input with in 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 constant CP, CP cancels out, this becomes this, Eta C. Okay, then we can write the T3 from this, from this we can write T3 T dash divided by T1 T is equal to what?

Eta C into this, Eta C into T3 T - T1 T, this is divided by T1 T +1. Am I correct? Because this divided by T1 T is this by T1 T Eta C into T3 T - T1 T divided by T1 T, okay +1. So this is… Now if, it is okay, now if we, if we, if we now, okay, please wait. This, if now we use this expression here, then we can write that P3 T by P1 T equals to what? T3 dash by T3 is this, that means 1+ Eta C into T3 T - T1 T divided by T1 T to the power gamma by gamma -1.

Again I can substitute this temperature difference T3 T - T1 T, the difference in the stagnation temperature at the end of the compression, that means the end of the compressor, after the compression in the diffuser 2 and the inlet stagnation of total temperature, this difference is in terms of the work per unit mass, we can write 1+ Eta C into this will come, Sigma Psi, Sigma power input factor U2 square.

So this is E by M. Now we are replacing this thing divided by CP T1 T. Sigma not visible, oh yes, I am sorry that it is not visible, now it is visible. So this we can now write to the power, gamma by gamma -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 its tip. 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 compressor isentropic efficiency, this value is almost fixed to something like 0.85.

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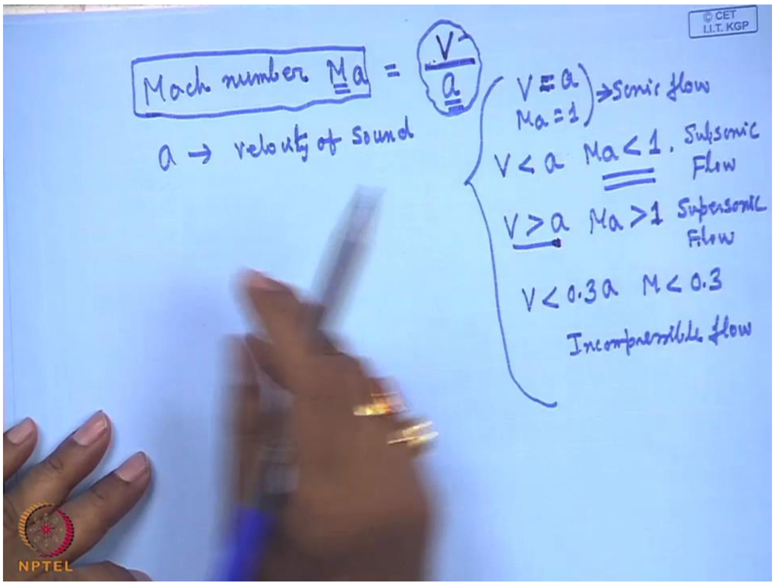

Now for a given inlet total temperature, therefore we see this pressure ratio is proportional to the impeller speed in this fashion. So this is a very important relation of the pressure ratio to impeller speed. Now I will come to a very important thing of the centrifugal compressor. Not centrifugal, centrifugal and axial compressor. Now as I told earlier, since the compressor handles fluid which are compressible in nature, they are gas, they are not liquid, their bulk modulus of 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 1st consideration is that the change in density with pressure. There are other considerations depending upon the flow regime which takes place in the compressible flow which I will discuss afterwards when I will be telling you about the compressible flow. That depending upon the flow regime, especially when the flow velocity is very high, some physical features which is, typical, which are typical to compressible flow takes 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 is dimensionless number is known as Mach number.

So therefore I write here a Mach number considerations 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 a velocity of sound or 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 equal 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 discuss 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, it is known as, so the broad classification, supersonic flow.

And there is a regime in the subsonic flow where 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. Okay, relative change in density is negligible. So these are the regimes of flow. Now what happens, that if the flow is supersonic at any stage depending upon its velocity, then some features are observed which causes extra losses of energy and in compressor which causes extra losses of static pressure.

Okay, 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 compression, the Mach number has to be considered and here the Mach number, if you see the definition, in the definition, the velocity of flow, it is a velocity relative to the moving solid surface.

When there is a flow velocity past the solid surface, it is the velocity relative to the solid surface and in a Turbo machine, the solid surfaces are also moving, solid surfaces are also in 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.

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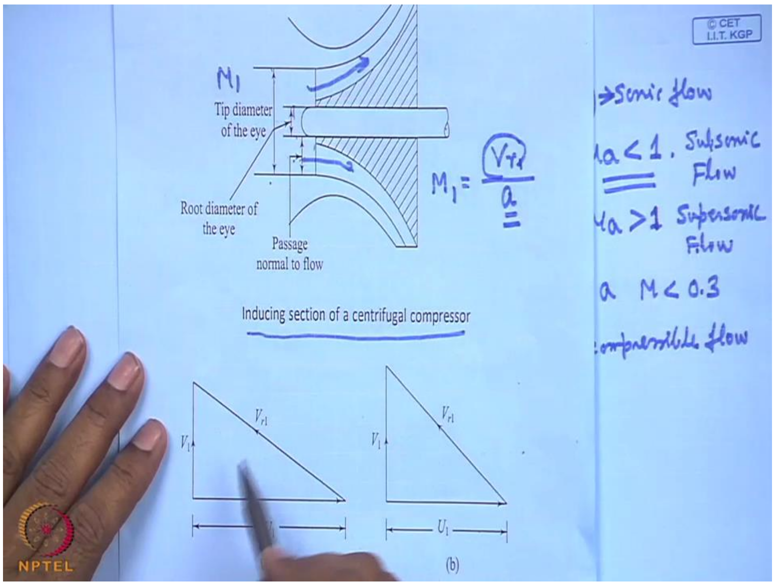

So one of the importance section is the inlet to the impeller, actually the Mach number velocity of flow will be high at the outlet of the impeller where it gains kinetic energy from the impeller where the energy is being imparted to the fluid. So to restrict that Mach number, which is maximum at the outlet tip, we have to check the Mach number at the inlet of the impeller 2, so therefore the inlet design has to be made in such a way that Mach number is relatively low.

Now you see at inlet section of the impeller that is the inlet part, this is known as the inducing section of a centrifugal compressors, you see this is 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 tape should be such that the Mach number should be low. Now do you define Mach number? Just I told you 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 the VR1 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 will show you the impeller blade is like this, at the eye, the design is like this. So this is the relations, velocity triangle you see, that this is the relative velocity which angle, matches at the angle of impeller blade at the inlet. Now these 2 are specific or difficult velocity diagram, this diagram is for a very large impeller diameter where the peripheral speed is more U1, okay 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 a higher relative velocity 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. Okay. But if you now reduce the velocity, this is the typical diagram of a small eye tip diameter. There what we get, we get a U1 like this, this is relatively lower than this but the flow velocity is high, so that VR1 may be reduced. But it is very difficult to conclude which one is better or lower, that depends upon the relative values of U1 and the values of V1. However this VR1 is of, our prime importance, such that VR1 by A, that is the ratio of Mach number should be low.

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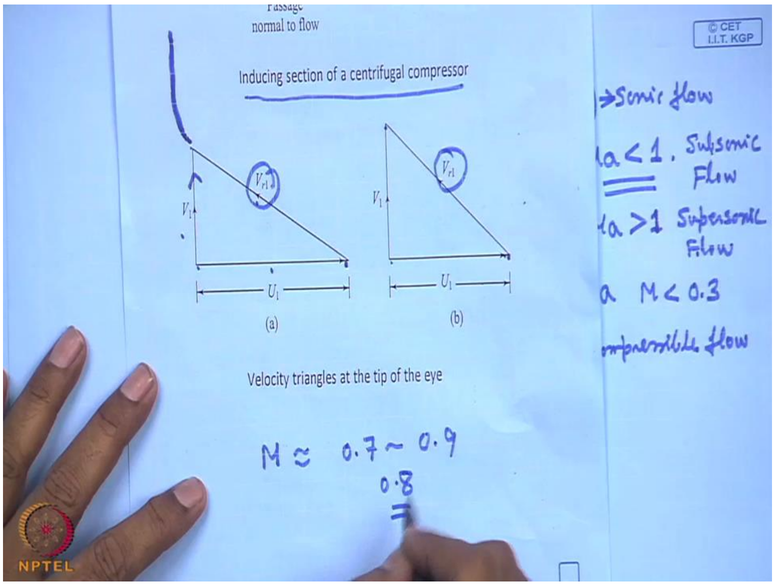

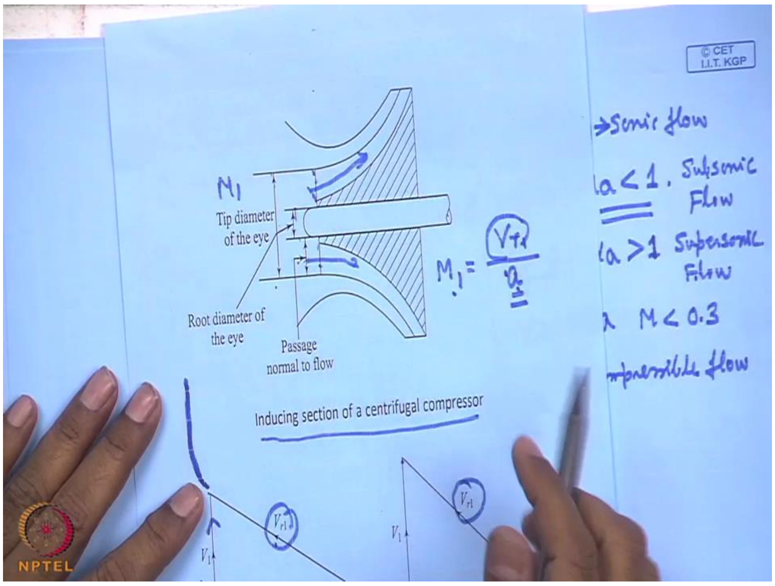

And we try to design the impeller tip in such a way that the Mach number lies between 0.7 to 0.9, usually 0.8, so that we avoid losses. What happens I tell you a little brief, which will be discussed in more detail when I will teach you the compressible flow. What happens if the flow is supersonic, that within a compressible flow, 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 certain deceleration through a certain discontinuity and that that this continuity is known as shock.

So therefore a shock takes place, a supersonic flow cannot it just 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, go to the circumstances, or the boundary conditions imposed on the flow, flow has to decelerate. And this is adjusted by a certain deceleration, certain discontinuity in the flow and this discontinuity is really mathematical discontinuity which takes place within almost infinite small region whose length is in the terms of molecular diameter.

And that sharp discontinuity in the flow is known as shock in general and that shop, what matters to the practical case is that due to that shock, there is an abrupt loss in the total energy. This is the total irreversible process, so what matters is that, because you can ask me Sir when the deceleration takes place, when the fluid comes to subsonic stage, what happens, the pressure increases. Yes, the 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 wasted energy you can call mostly and the kinetic energy, there is a loss.

So therefore in design of any compressible flow machines or compressible flow device, one is to be very careful, 1^{st} of all it is better to avoid the supersonic state of flow and or supersonic state of flow is unavailable, 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 afterwards, it is not that always shop will take place, it depends upon certain boundary conditions imposed on it, so that shock has to take place.

But it may occur that flow may be made in such conditions with design back pressures and many other things that I will discuss afterwards where shock may be avoided. But in practice, it may not be done because the supersonic flow when it comes, for example when an aircraft moves with the supersonic velocity, as you know, that when aircraft moves with supersonic velocity, that is velocity more than the sound velocity at the state of the fluid there, the high altitude.

Then what happens, relative to the aircraft, the fluid moves with supersonic velocity. So far 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 decelerates, but 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 you only 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. Thank you.