Introduction to Airbreathing Propulsion
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Lecture – 44
Centrifugal Compressor (Contd.,)

Okay so let us continue the discussion on this centrifugal compressor what we were talking about is the slip and what that happens because of this rotating frame of reference you have these blades are already exposed to the rotation and thus highly dynamic loading obviously one issue is to tackle with the material. Because these materials are what kind of blade you have depending on that with the radial centrifugal, I mean the backward leaning or the forward leaning you have all these centrifugal stresses which are developed.

So that is one aspect of it now apart from that material perspective you have another issue is that the flow dynamics. So these blades when they are exposed to this rotating frame of reference there are lot of things happen and one important thing is that now apart from other forces whatever you talk about the stress and all these you have Coriolis forces and that happens because of this rotation and these blades are rotating along the I mean across frame of reference and you have Coriolis forces and because of that you have different level of pressure gradient and across the blade profile and we will see all these details and each leads to slip.

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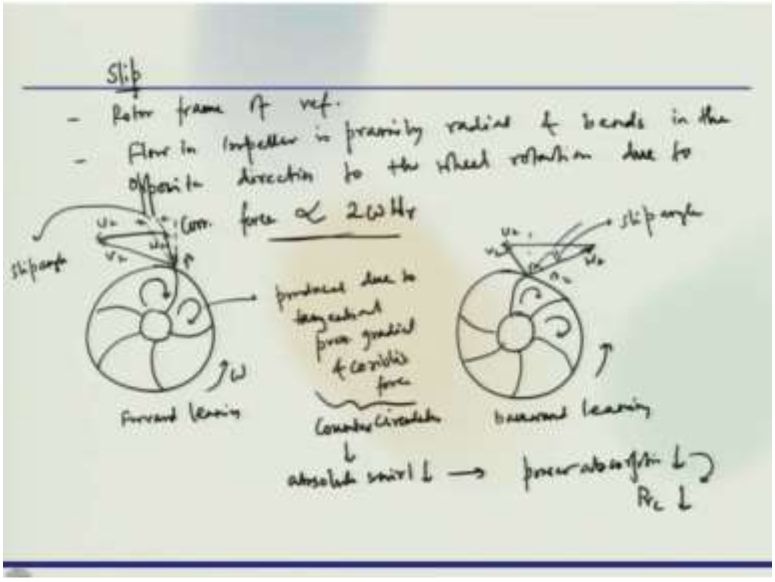

So this is what we were started talking about the slip and so just to give you we have these Coriolis and impellers are bit opposite direction to the wheel of rotation. So you have this now there is a counter circulation which is produced inside this blade passages and that because you have this tangential pressure gradient these are the curved blades or whether even if you have a radial blade you have tangential pressure gradient and we will see that in next few minutes.

And one existence of the thing is the tangential pressure gradient and second is the Coriolis force because of this you get this counter circulation. Now once you have this counter circulation this actually reduces the absolute swirl the rotation. So that means the effective speed goes down which lead to the reduction in the pause absorption overall pressure ratio actually get heat so this is known as this is known as slip in centrifugal compressor okay and the slip factor.

One can define that let us say epsilon which would be the

$$\epsilon = \frac{V_{\theta 2}}{U_2}$$

or one can write this is absolute swirl to exit full speed so that the ratio which is known as the slip factor. Now we can look at the radial blade what happens.

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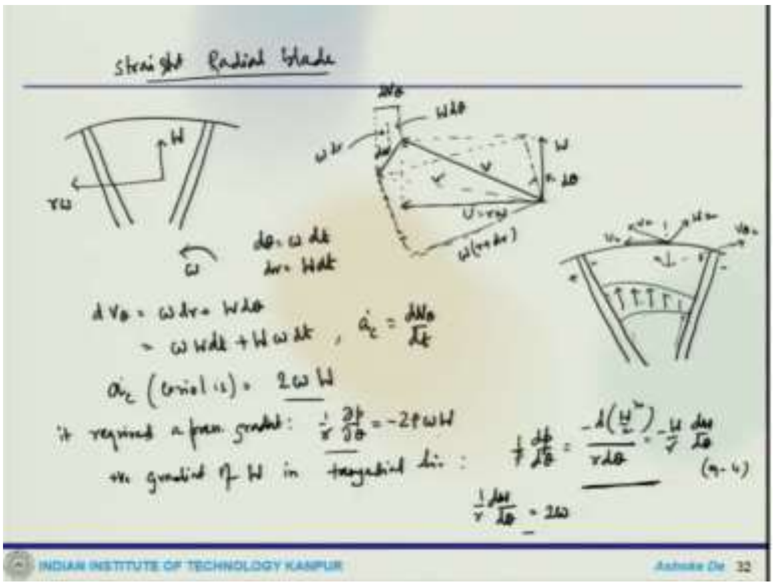

I mean that is a simple one we can take an straight radial blade we can see what happens so let us draw a simple schematic. So, this is the blade so you have rotation in this direction so what you have this side is the W this is our ω okay. So if I draw the velocity triangle how it looks like so it starts goes there comes there and so this is my sort of let us so this component is essentially my $U = r\omega$ and this component would be dv okay this component is v' this component is v and then I can have obviously this one.

So, this one is dV_θ okay and we can have so let us say this comes here this is what

$$dV_\theta = \omega dr + W d\theta$$

so that is the one which goes back there okay. So, one can it slightly it has to be rectangle so this is what you can have that is fine and there would be two more thing within this this side this is called this dr and this side is $Wd\theta$ so that is what you have.

Now what is $d\theta = \omega dt$, $dr = Wdt$ now what we can write is that the

$$dV_\theta = \omega dr + W d\theta$$

So, this is the total which we are writing there are two components so that one can write

$$dV_\theta = \omega W dt + W\omega dt$$

So, this is

$$\dot{a}_c = \frac{dV_\theta}{dt} = 2\omega W$$

Now this one requires and pressure gradient okay now the radial pressure gradient if you look at so that it requires a pressure gradient. So, this would be

$$\frac{1}{r}\frac{\partial p}{\partial \theta} = -2\rho\omega W$$

now this $\frac{\partial p}{\partial \theta}$ which is the tangential pressure gradient now the existence of this tangential pressure gradient which means there would be a positive gradient of W in tangential direction. So, which one can see it would be written

$$\frac{1}{r}\frac{\partial p}{\partial \theta} = \frac{-d\left(\frac{W^2}{2}\right)}{rd\theta} = -\frac{W}{r}\frac{dW}{d\theta}$$

So, this from equation 4 one can write obviously there are certain small assumption which are associated there the assuming that all streamlines have the same stagnation pressure in the rotating frame of reference. So, this is one assumption which is there that to get these things now what it will give me

$$\frac{1}{r}\frac{dW}{d\theta} = 2\omega$$

So if I look at these things now as the Coriolis forces this is the outlet of the impeller, impeller can have I can just read all these things and let us say this is two different side of it pressure suction pressure suction side and this is where you will have v theta 2 this is where you have W_2 this is where you have v_2 and this direction it would be u_2.

So, these are the component that you will have so what happens once these Coriolis forces the disappeared towards the outlet of the impeller that means this is the outlet side a fluid particle in the middle is unable to continue in a purely radial direction. So that actually causes a slip now that is one part of it that means since these Coriolis forces they are going to disappear towards the outlet of this impeller the fluid particle which actually stays in middle they are unable to continue so that causes the slip which you have already looked at it now $\frac{\partial p}{\partial \theta}$ so that also relieved towards the tip so when you go towards the tip that also relieved.

So, what happens the accelerates and the boundary layer at the pressure surface is well behaved. So, if I look at this is the pressure side then in this side the boundary layer is well behaved because the del p/del theta the tangential pressure gradient is relieved toward them so from this side to this side this actually is relieved. So flow will so along this side the flow accelerates and the boundary layer is well behaved but at the suction side on the opposite side this side with the suction side.

So, there is an addition of stream wise pressure gradient so which means the along this side the boundary layer is tend to separate and that enhances due to secondary flow of the Coriolis pressure gradient. So, this means the it tends to transport the slow-moving particle towards the surface. So as a result, what will happen is that you get to see a different kind of flow pattern from this side to that side so this is what will happen so if you look at that.

So, this side is your pressure side this is your suction side so this side is well behaved and the pressure gradient is properly behaving so flow remains at the other side actually there is a boundary layer separation. So, the low particles are moving slowly and this is where you get to see this behaviour of the flow pattern inside these passages. So, this what happens when there would be slip when there would be this kind of effect due to Coriolis forces.

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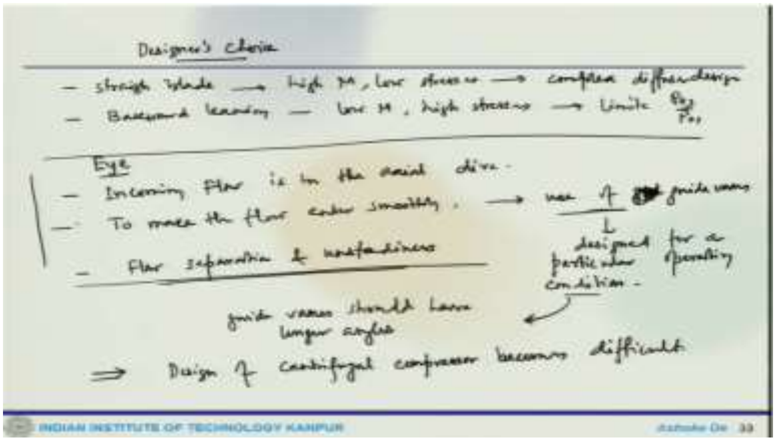

Now we have to make some choices or I would say that it is a designer's choice okay. So, you have straight blade that is which means the high Mach number low stresses but complex diffusion design that is one thing now you have backward leaning then low Mach you have high stresses. So that is you have limited operation of $\frac{p_{03}}{p_{01}}$ but it is also different in manufacturing.

So, you can have your choice what do you want to have and accordingly design things now there are other components of this centrifugal compressor one is the eye here the incoming flow is in the axial direction. Now what happens at the leading edge of the impeller is a tangential component of the velocity due to blade rotation which is obvious hence the relative velocity is at an angle with respect to the axis so what happens to make the flow enter smoothly a series of guide vanes called inducer is used.

So this actually leads the use of guide vanes so that now you can see why these guide vanes are used I mean effectively what you want you want your flow to enter to the impeller very smoothly to do that so you use these guide vanes which actually does that work. So, the other thing is that centrifugal compressor that do not have inducers so if you do not use these guide vanes or inducer as they would be very noisy that is number one.

Now also there could be possibility of flow separation at the inlet and that can lead to unsteadiness. So, once you have flow separation or unsteadiness this can lead to also some sort of an instability inside the impeller blade while doing. So, these are the things to avoid that you have these guide vanes and these guide vanes for some design purposes. So, these are actually designed for a particular operating condition.

So now these are the things that also you need to now once you design and if things actually go of design condition then obviously there will be performance reduction so that is why what you need the guide vanes should have longer angles. So now you see you have different components so and now when you come to the eye and you see all these issues so this means the presence of all these actually make that design of centrifugal compressor is extremely difficult. So that is the bottom-line thing the design of centrifugal compressor becomes difficult you have to take into consideration all these issues which are in place.

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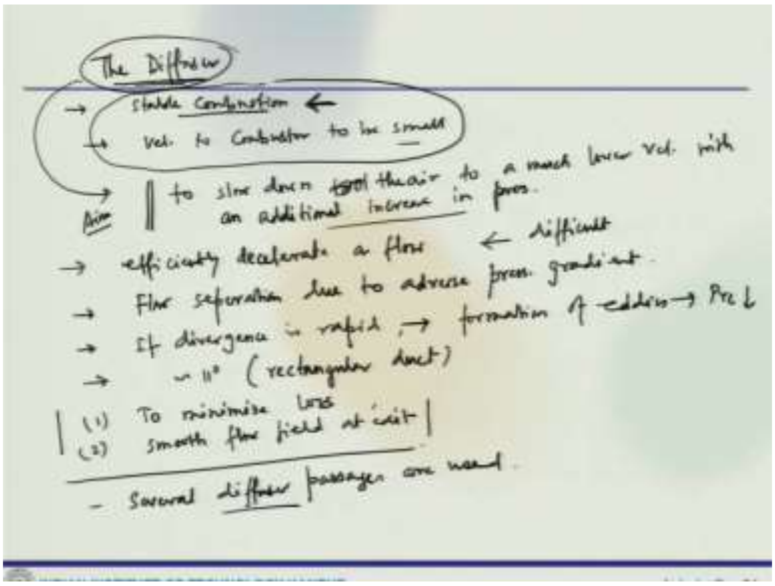

Now we will look at the other component which is the diffuser so what the purpose of this diffuser. Now one has to understand from the gas turbine point of view the flow which comes out of the centrifugal compressor that goes to the combustor and what always want you want stable combustion. So, to have stable combustion the input to the combustion chamber would be also the flow which goes to the combustion chamber that also has to be smooth and without having too much of unsteadiness or instabilities and all these kind of things.

And secondly the combustion not only stable this would happen if exit of the compressor the flow conditions are also quite smooth okay. Third is that the velocity to combustor that also combusted to be small so what goes to the combustion chamber that has to be also small. So, the whole idea about this when it comes out of the exit of the compressor any compressor whether it is a centrifugal compressor or axial compression.

So, your ideas that you slow down this flow field you smooth out the flow field so that goes to the combustion chamber so that is the work which diffuser is does. So that is the purpose of the diffuser to slow down the flow field slow down the air slow down the air to a much lower velocity with an additional increase in pressure. So that is the basic motto of an diffuser so you get some sort of and pressurize so which will add to the overall pressure rise to the across the compressor and also you slow down these things.

So, what it poses once you say that these are my aim or sort of an goal that this poses the challenge that how effectively or efficiently decelerate a flow compared to accelerate it. So, when you try to accelerate that is quite easy or much more easier job other than decelerating a flow more efficiently so this becomes actually bit of difficult. So, it is not that easy so and we have already seen I mean from the area rule of subsonic flow velocity decreases in a diverging and diffusion flow passes is essentially diverging.

Now the pressure if it increases in the direction of the flow that means you are going to have adverse pressure gradient. So, there would be flow separation due to adverse pressure gradient so one has to also keep that in mind if your pressure gradient actually becoming adverse or it is pleases then you will have a flow separation. So, the flow separation would not also help because then you will not get the other thing.

Secondly if you are if divergence is rapid so this may actually result in formation of Eddie's with consequent reduction in the pressure rise. So, the consequence reduction in the pressure rise now I mean there are a lot of experimentation being conducted other study have been conducted or rather the research have been done. So typical the divergence angle would be roughly around 11 degree for a rectangular duct for rectangular that if that is used.

So, the whole point is that the design of the diffuser become important just number one to minimize loss and number two smooth flow field at the exit field at exit and properly slowing down the everything. So that is whole idea so the idea is the single diffuser cannot decelerate the interflow effectively or efficiently over a small distance. Now one may ask why we need a small distance because the several I mean obviously when you talk about the compressor these are going to fit in the engine so obviously the distance and all these are important.

So, I mean there are several diffuser passages are actually used now each passage of this several diffuser is divided by fixed diffuser vanes. So, the leading edge of the vanes are show design in accordance to the direction of the incoming flow that the air in turns is smooth

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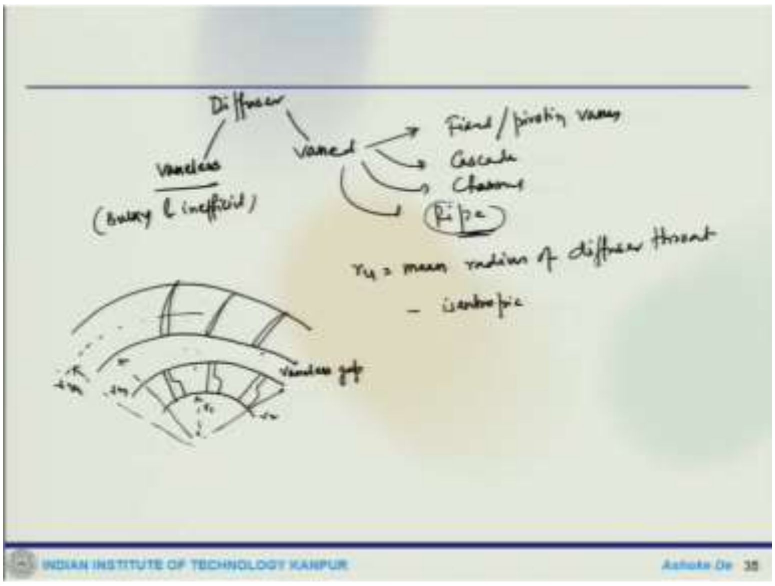

Now we have already seen different kind of diffuser I mean the picture at the beginning. So one can vaneless you can have vaned the thing is that this becomes actually bulky and inefficient and vaned it could be having fixed or pivoting vanes it could be cascade already we have seen this picture it could be channel type or it could be pipe. Now the pipe this was actually I mean I mean just in for an information this was proposed by Pratt & Whitney.

So, this is quite efficient channel or pipe and if you use pipe you can obtain and compressor efficiency of around 85% or so. So the idea is that the flow has to enter smoothly so if I and without having any other extra losses so just getting a picture of it so you can have it one for so these are so I have this okay and I can have these are so this is if I take this one as a centre this is r_1 this goes to r_2 then this goes to r_3 and then finally that goes to r_4.

So r_4 is the mean so that is so this would be the r_4 mean radius of diffusor throat. So now I mean already we have said that the design of the diffuser vane throat are important. So there is a vaneless space between the impeller and the diffuser that we can see this is impeller and this is diffusion so there is a vaneless space between that now since the air is leaving the impeller has to traverse this gap its direction will not be the same as leaving the impeller tip so which is quite obvious.

So, if you see these are my impeller so when it comes out of the impeller it has to go through this vaneless this is my vaneless gap or passage. So, it is not necessarily that this will follow is proper direction as it comes out of the impeller tip. So, to fluid the correct Inlet angle of the diffuser vane the flow is in the vaneless space has to be considered. So, once we want to consider the inlet here this has to be considered and top of that there is no further energy supplied to the air once it leaves the impeller.

So, when it comes out of the impeller in between there is no extra energies provided so the angular momentum must be conserved neglecting any other frictional losses. So, this has to be sort of isentropic okay. So you can see this what happens when it goes into the diffuser and the detail kind of how one goes about the design related issues how that affect all these we can discuss but this is important to know that the flow energy comes out before it goes to the diffuser there is a space which is the vaneless space.

But it may possibly happen that the flow may not retain his direction and all these. So, once we take into account all this calculation, we need to take into this one is a calculation. So, what we will do that will stop here and continue this discussion in the next lecture.