Introduction to Airbreathing Propulsion
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Lecture – 42
Centrifugal Compressor (Contd.,)

Okay so let us continue the discussion of the different blade arrangement in centrifugal compressor. So what we have looked at so far in the different equation system and then when you have different kind of rotor blade configuration.

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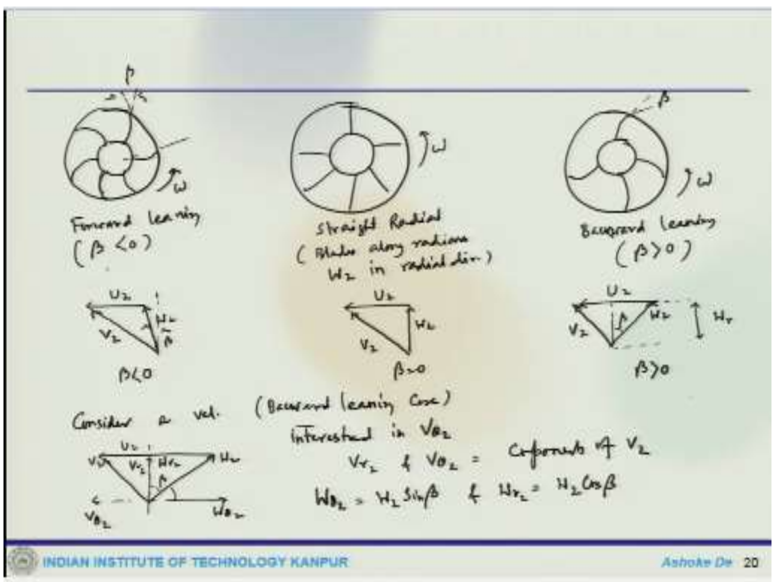

So this is where we have actually stopped the discussion in the last lecture where we have different kind of arrangement forward-leaning, straight or backward-leaning. So this obviously provides you a different kind of velocity triangle for the flow field. Let us consider this one of the case of the backward-leaning. And if we draw the triangle again, so let us say this is what it goes and this is what it swirls back.

So this is my U_2, this is V_2, this is W_2, okay. And there you have this, this direction it would be $W_{\theta 2}$ so this is my β this direction it is $V_{\theta 2}$ and so this direction there would be my V_{r2} and at the same time W_{r2} okay. Now we have considered a backward-leaning case and what we are interested in $V_{\theta 2}$ okay so we are interested in $V_{\theta 2}$. So V_{r2} and $V_{\theta 2}$ are the essentially these are the V_{r2} and $V_{\theta 2}$ these are the radial and theta components of V_2. Now from the diagram what one can write

$$W_{\theta 2} = W_2 \sin \beta$$

And

$$W_{r2} = W_2 \cos \beta$$

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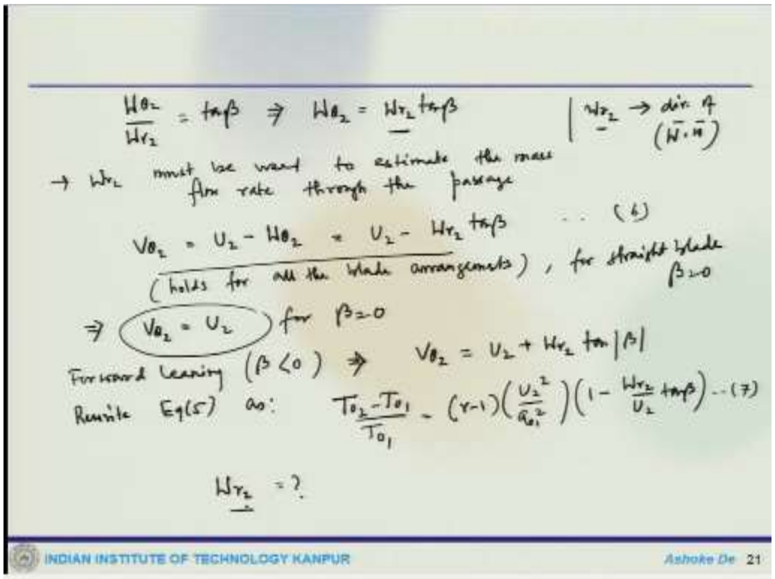

So I can write

$$\frac{W_{\theta 2}}{W_{r2}} = \tan \beta$$

which in this ends

$$W_{\theta 2} = W_{r2} \tan \beta$$

Now we are interested in this component W_{r2} because this component of the velocity in the; velocity in the normal direction of the outlet area. So this is the normal component in the outlet area. So this is the direction essentially if you look at W_{r2} this provides the direction of $\bar{W} \cdot \bar{n}$ And since this is along the normal direction W_{r2} is the normal component.

So, this W_{r2} must be used to estimate the mass flow rate through the passage, so that is quite important observation here because which component to consider when we are supposed to find out the mass flow rate along this. Now once you will look back to the velocity triangle what we can write that

$$V_{\theta 2} = U_2 - W_{\theta 2}$$

so just to look back in this triangle so this is what we are writing.

So we can expand this, this should be

$$V_{\theta 2} = U_2 - W_{r2} \tan \beta$$

let us say equation 6. Now this equation what we have just obtained this actually holds for all the blade arrangements though we have derived it through the velocity triangle of backward-leaning system but if you look at the other thing also so this holds good, only exception is that for straight blade $\beta = 0$, okay. So that is what it is going to happen.

So finally what we obtain here

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

Now this is what you get for $\beta = 0$. Now for forward-leaning where $\beta < 0$ you get

$$V_{\theta 2} = U_2 - W_{r2} \tan |\beta|$$

Now we can rewrite equation 5 as

$$\frac{T_{02} - T_{01}}{T_{01}} = (\gamma - 1) \frac{U_2^2}{a_{01}^2} \left(1 - \frac{W_{r2}}{U_2} \tan \beta\right)$$

So that is our; so here still the question remains. What about W_{r2} or what is W_{r2}, how do we estimate that? So that could be quite straightforward to estimate when we talk about that radial component.

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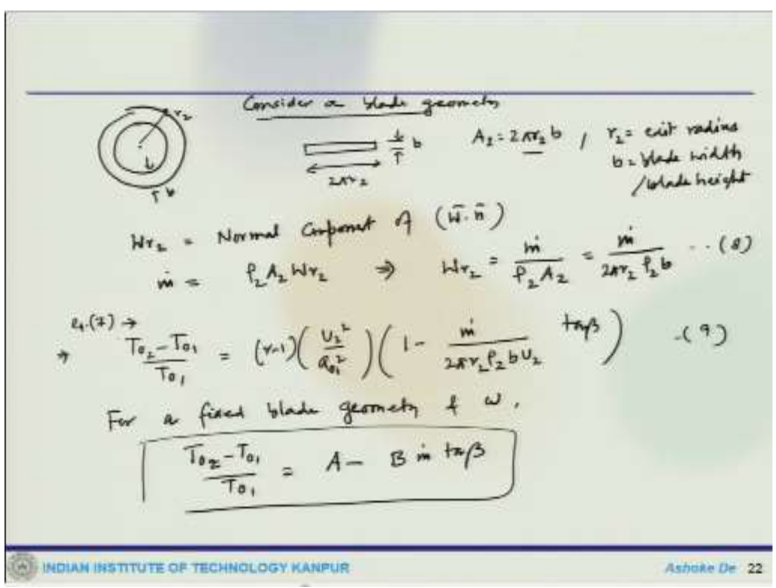

Let us say we consider an blade like this, okay. So let us say this is b, this is r_2, so consider; this is consider a blade geometry like this so essentially this is what the; this distance would be $2\pi r_2$ and this would be b, so

$$A_2 = 2\pi r_2 b$$

So the; here r_2 is the exit radius and b is the blade width. So one can also say this is; one can say this is also blade height whatever they prefer to do that.

Now m dot; so W_{r2} is; W_{r2} is the normal component of $(\bar{W} \cdot \bar{n})$. So one can write

$$\dot{m} = \rho_2 A_2 W_{r2}$$

which will get you

$$\frac{\dot{m}}{\rho_2 A_2} = W_{r2} = \frac{\dot{m}}{\rho_2 2\pi r_2 b}$$

So again I will rewrite the equation of the equation 7. So equation 7 becomes

$$\frac{T_{02} - T_{01}}{T_{01}} = (\gamma - 1)\frac{U_2^2}{a_{01}^2}\left(1 - \frac{\dot{m}}{\rho_2 2\pi r_2 b U_2}\tan\beta\right)$$

so that is our equation 9.

So if you have a fixed blade geometry so for a fixed blade geometry and the rotational speed, this temperature rise will become some sort of an

$$\frac{T_{02} - T_{01}}{T_{01}} = A - B\dot{m}\tan\beta$$

so this is one of the functional form what can have for a fixed blade geometry and rotational speed. So once you change that, so the geometry and all these things will also change. Now if you look at these particular equations the temperature rise, so we can see for different blade configuration how it varies.

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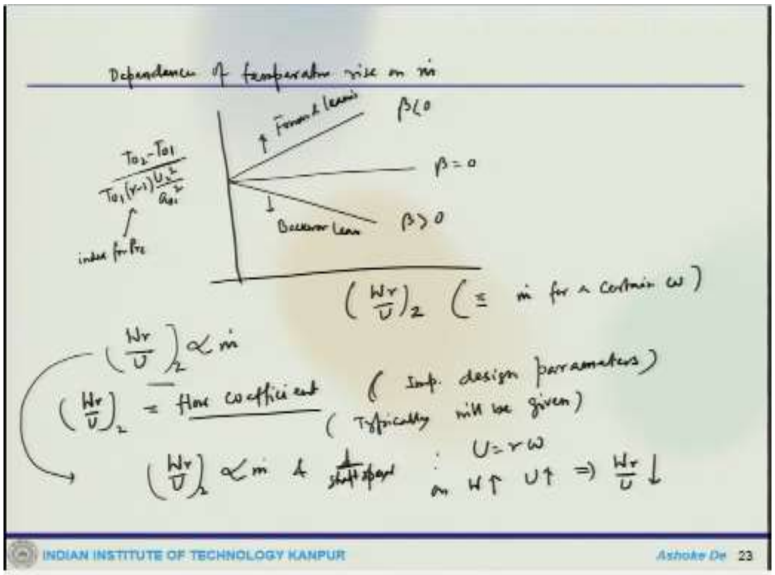

So one can look at the dependence of temperature rise on $\dot{m}$, so we can draw some curve here like this, so this side it would be

$$\frac{T_{02}-T_{01}}{T_{01}(\gamma-1)\frac{U_2^2}{a_{01}^2}}$$

So this actually index for P_{rc}. So what we can see this will vary like this. This is for straight blade $\beta = 0$, this is $\beta < 0$ so that means forward-leaning, this is $\beta > 0$, this is backward-leaning so they go in this way.

And this side is my $\left(\frac{W_r}{U}\right)_2$, so this is equivalent to $\dot{m}$ for a certain rotational speed. So this essentially what one can say $\left(\frac{W_r}{U}\right)_2$, is proportional to $\dot{m}$ something like that, so this is how the temperature rise would be dependent on the mass flow rate for different kind of blade arrangement. Now this guy $\left(\frac{W_r}{U}\right)_2$ is called the flow coefficient. So this is one of the very, very important design parameter.

So this flow coefficient becomes quite and typically for design if you; this would be typically given for considering or if you would like to get the design done. Now as we said if this guy if you look at it this is directly proportional to m dot and universally proportional to shaft speed. So $\left(\frac{W_r}{U}\right)_2$ directly proportional to $\dot{m}$ and inversely proportional to the shaft speed which is U. Now what happens, so again $U = r\omega$ as W increases U also increases so as a result $\frac{W_r}{U}$ decreases. Now one can make certain note here.

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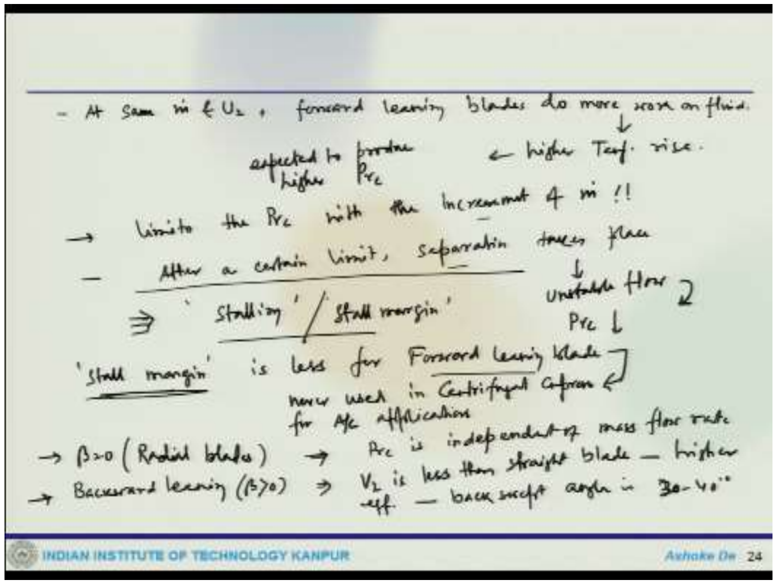

Let us say at same $\dot{m}$ and U_2, forward-leaning blade, so forward leaning blade do more work on fluid, so that means this is higher temperature rise. And also expected to produce, so this is what expected to produce higher pressure rise too. But; or however we will see later m dot causes increase in pressure rise but there is a limit to this rise. So there is a limit to the P_{rc} with the increment of $\dot{m}$.

So that is another important thing to be considered that it is not very indefinite or infinite that if you keep on increasing that the pressure rise is going to be also higher and how. After a certain pressure rise the air starts to separate from the blade. So basically what happens here after a certain; after a certain limit the air starts to separate from the blade so separation takes place so which means there would be an adverse pressure gradient, so which will be giving rise to very unstable flow and drop in pressure rise.

So that situation when it arises that there is an increase in pressure rise and after a certain limit it cannot be done because there would be blades flow separation at the blade, so this will lead to a very unstable, so this lead to the unstable flow and then as a consequence there will be drop in the pressure rise. So when that happens this kind of situation which is known as stall; stalling phenomena or this is known as stalling or stall margin of the blade.

So every compressor blade is designed for a particular stall margin. So this is what will go more into the details later on, we will see how the stall margins are designed or derived based on the flow conditions and the blade geometry. So now here we are talking about different kind of blades for forward-leaning blade this stall margin is always less for forward-leaning blade, okay. So since this is very low or the stall margin is low which indirectly means that you have you have a very limited operation of this kind of blade.

Because if your flow or mass flow rate increases so pressure rise will be higher and then suddenly or very quickly the flow starts separating, so this is what it is dictated by this stall margin. So these kind of blades are never used in centrifugal compressor for aircraft application, so that is; so the consequence is that never used in centrifugal compressor for aircraft application because the stall margin is very less.

So you cannot really afford to have a design or a compressor blade which has a very low or small stall margin. Now at the same time for radial blades where beta is 0, okay, so here one can see Prc is independent of mass flow rate, so that is another thing. And the another the other case when you have backward-leaning blade, backward-leaning case where beta is positive so that is what you have. Here the V_2 is less than straight blade so you have higher efficiency at the same time the back swept angle is around 30 to 40 degree.

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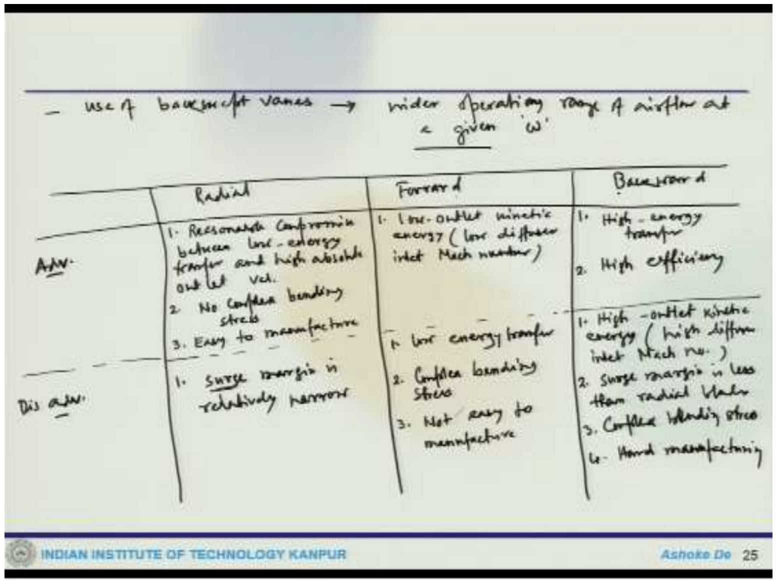

Now this is another advantage the using of this; use of these back swept vanes, what it does that it gives an compression a wider operational or operating range of airflow at a given rotational speed. So this is also very, very important for matching the compressor to is driving turbine. So this is an very important condition. So when you use this kind of back swept vanes it provides you different range of conditions or the mass flow rate and all this.

So I mean you can put things together and have an comparative situation what happens to these different kinds of blades. One could be radial then you have let us say forward and then you have backward, so that is what your type of impeller would be. Now one can list out the advantages first, so this case you have reasonably compromise between low energy transfer and high absolute outlet velocity, so that is one thing.

Second is that you do not have the problem of complex bending stresses, so no complex bending stress. And obviously since it is in straight blade it will be always easy to manufacture or fabricate. So these are the straight or immediate advantages one can have with the radial blades. Now when you go to forward you have low outlet kinetic energy so which on the other hand one can write that in turn is that it is an low diffuser Inlet Mach number, so that is the issue that you have with the forward-leaning.

At the same time when you go for the backward-leaning what you have high energy transfer rate, so this will have high energy transfer also at the same time highly efficient. So you have both the parameters are at the highest side, you have high energy transfer and you have high efficiency of this thing. Now these are the different when you compare each of them separately you can see these are the different kind of advantages and disadvantages you have.

Now the disadvantages if you note down, so here straightway the surge margin is relatively narrow, so this is another term which I am introducing here but I will do more detail discussion when I go into there. So right now this has a very limited operational range. This case you have low energy transfer that is one of the disadvantage. Secondly, since these are curved blade so you have always the bending stress, so you have complex bending stress that is another thing.

Then obviously these are angled curved blades so not easy to manufacture or rather hard manufacturing process, so this is not going to be that very easy. This case, now whatever the advantage you have at the forward case that low outlet kinetic energy, the backward case has that is the one of the disadvantage of the backward case it has an high outlet kinetic energy, so which in the sense mean that high diffuser Inlet Mach number, so that is what has.

This has also the surge margin but is less than radial blades. Obviously, this would be also complex bending stresses, complex bending stress and fourth hard manufacturing. So I mean if you see this particular situation you have three different kind of blades one is radial, forward and backward, but out of that if you look at the advantages backward seems to be the best one where you have a high energy transferred rate and high efficiency, but at the same time you always have certain disadvantage which are associated with this kind of curved blade.

One of the very, very important problem is that obviously when you do this compressor blade design which will we are going to have detailed discussion, the separation, stall margin or surge margin these are the very important characteristics. So what one has to define these margins are because; because of these the blade can become really unstable and the flow separates so there would be not enough pressure rise obviously if you do not have pressure rise which is going to be a problem.

Now the top of that be this forward and backward blades they have complex bending stresses because these blades are curved, so that is another issues that you have associated with these kind of blades and finally I mean the most advantages is the radial blade to manufacture because these are straight so you do not have any angle but other two which are forward or backward you have always a problem in manufacturing because these are curved blade.

So these put together things in a totality that what are the advantage and disadvantage associated with this kind of blade. So what will do that when you have these kind of situations like forward, backward or leaning but out of that lot you can see the backward-leaning has certain edge over the other two. And we will do more detail discussions about this surge margin, stall margin and how one can look at the blade design. So we will stop here and continue the discussion in the following lecture.