Aerodynamic Design of Axial Flow Compressors & Fans

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Lecture 13

Stage Configurations and Parameters (Contd.)

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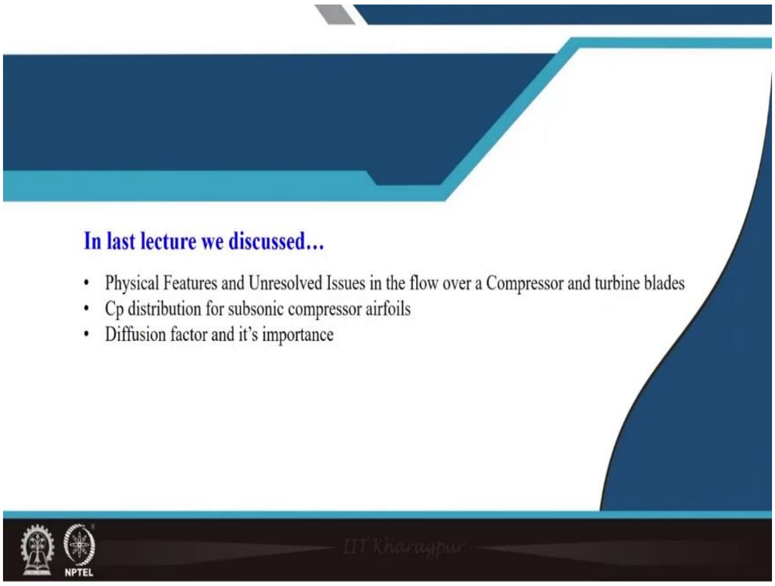

Hello, and welcome to lecture-13. In last lecture, we were discussing about the physical features and unresolved issues in the flow over compressor and turbine blades. And we have realized the flow over suction surface of both airfoils, let it be compressor, let it be say for turbine, for both the cases, you will be having many difficulties and challenges. And, these days people they are exploring the possibility to resolve those issues. Now, in sense of understanding what we say, lifting force, we have correlated our lifting force with the C_p distribution for say particular compressor airfoil.

So, we have discussed, what will be the C_p distribution for C4 airfoil, for double circular arc airfoil and NACA 65 airfoil. And we have realized the shape of the leading edge, that's what is very important, basically, that's what is handling your flow acceleration, initially happening near the leading edge; and on trailing edge, we will be having the flow that's what is getting diffused both on my pressure surface, as well as on my suction surface. Then we have introduced a new parameter, that's what is called diffusion factor, that diffusion factor it was included by NACA or say NASA in say 50s and 60s. Based on say their experimental results on cascade, they people, they have put with a number, that's what is called diffusion factor.

So, how my flow that will be having on my suction surface, that's what will be deciding the diffusion factor. And we have correlated this diffusion factor with flow angles and one more parameter we have introduced, that's what is our solidarity of the blade. And that solidity we have defined as say chord to pitch ratio, where pitch, that is nothing but it is 2 π R divided by number of blades.

We have discussed about say high aspect ratio blade, we have discussed about the low aspect ratio blade, and we realized by changing the number of blades, basically, we are changing the diffusing passage between two blade. This passage that's what will be responsible for rising of our pressure. So, many times in order to check with the design, people they are considering diffusion factor as one of the calculating parameters.

Many times, people they are using diffusion factor as a parameter and based on that assume number, they are calculating the number of blades, which are required for both stator as well as for rotor. We will be discussing on this aspect in detail when we will be discussing, say how to decide the number of blades. So, let us move ahead with the next.

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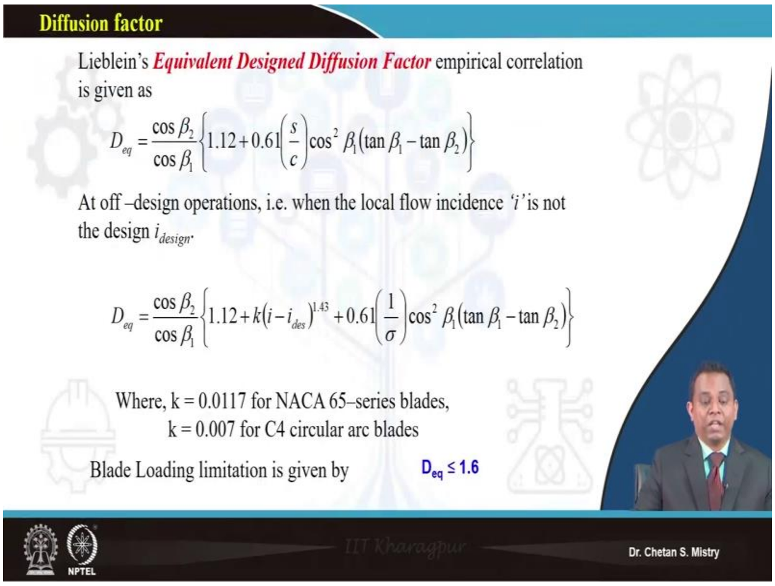

So, Lieblein, he has given Equivalent Design Diffusion Factor. So, according to him, he has proposed the empirical correlation, this empirical correlation, that's what is showing it is a function of β_1 an β_2 as well as it is a function of my s by c ratio. And according to him, if we consider we are having off design condition, that is what he said like it is a local change of incidence angle, still we have not introduced this parameter; but still let me know and let me tell you say, when we say of design condition, that means my compressor it has been designed for particular mass flow rate and for particular speed. The change of your speed, that means your peripheral speed for velocity triangle, that will be changing.

And if that's what is your case, my flow will not incident at the angle for what it is been designed. That's what is called off design condition. In line to that we will be having say or mass flow rate, that's what is changing from design condition towards the low mass flow rate side, even for the high mass flow rate side, under that condition also in my velocity triangle, the parameter called axial velocity, that's what is going to change and that will be changing my blade angles or blade incidence angles.

$$D_{eq} = \frac{\cos\beta_2}{\cos\beta_1}\left\{1.12 + 0.61\left(\frac{s}{c}\right)\cos^2\beta_1\left(\tan\beta_1 - \tan\beta_2\right)\right\}$$

So, according to him, he says like we can calculate equivalent diffusion factor, that's what is nothing but my incidence angle at that particular incident minus design angle and this is what is a formula for that.

$$D_{eq} = \frac{\cos\beta_2}{\cos\beta_1}\left\{1.12 + +k(i - i_{des})^{1.43} + 0.61\left(\frac{1}{\sigma}\right)\cos^2\beta_1\left(\tan\beta_1 - \tan\beta_2\right)\right\}$$

$$where, k = 0.0117\ for\ NACA\ 65 - series\ blades$$

$$k = 0.007\ for\ C4\ circular\ arc\ blades$$

He has introduced a parameter called 'k' parameter, according to him this 'k; will be 0.0117 for NACA 65 aerofoil and 0.007 for C4 circular arc blades, okay.

And blade loading limitation, that's what is we are calculating based on these Lieblein's equivalent factor, he said that it needs to be less than 1.6. So, many times during the design incidents, people they are taking this parameter also into the consideration, but mostly, most preferably, people they are going with the diffusion factor, what we have discussed in the last session.

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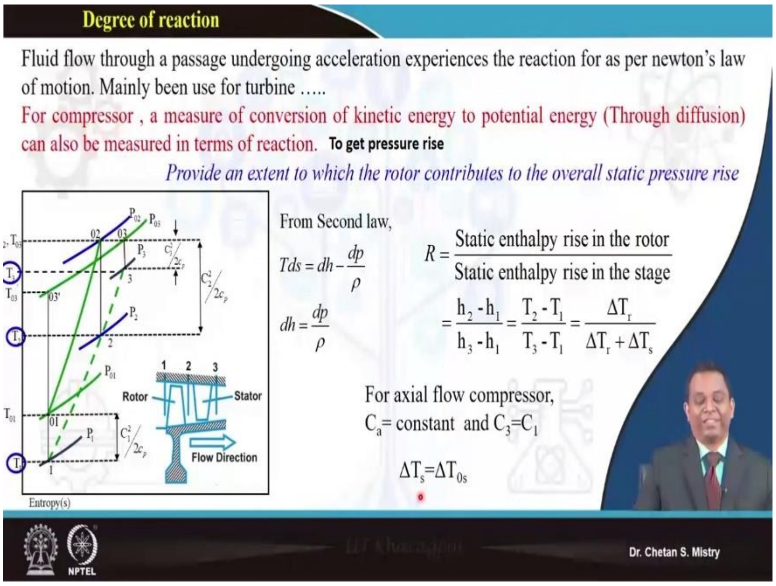

Now, let me introduce a new parameter that's what is called say degree of reaction. So, fluid that's what is flowing through the passage it will experience the acceleration and because of this acceleration, it will be having say reaction force that's what will be acting; that is based on our Newton's second law of motion. This logic of degree of reaction that was applicable for say turbines. So, initially before gas turbines, people they have designed the steam turbines, and based on that concept, people they have started designing the gas turbines.

So, now, this degree of reaction parameter, that's what is equally applicable here, even for say compressor. So, it says for compressor, the measure of conversion of your kinetic energy into potential energy through the diffusion can also be measured by using the reaction parameter, that's what is called, we are getting, what we say in sense of our pressure rise.

So, this is what will be giving you idea like what will be the contribution of your pressure rise both by rotor as well as by stator, okay. So, from our second law, we can say,

$$Tds = dh - \frac{dp}{\rho}$$

$$dh = \frac{dp}{\rho}$$

If we consider our compression process to be isentropic process, we can say my enthalpy and pressure they both are in relation.

So here, if you recall, we have discussed our T-S diagram, okay. On that T-S diagram, my station 1, that's what is representing my entry condition; my station 2, that's what is representing my exit condition of rotor and station 3, that's what is my exit condition from the stator. So, you can say for stage, my entry condition is one and by exit condition, that's what is at station 3, okay. So, let me put this parameter say degree of reaction; this degree of reaction we can write down in sense of say,

$$R = \frac{Static\ enthalpy\ rise\ in\ the\ rotor}{Static\ enthalpy\ rise\ in\ the\ stage}$$

$$= \frac{h_2 - h_1}{h_3 - h_1} = \frac{T_2 - T_1}{T_3 - T_1} = \frac{\Delta T_r}{\Delta T_r + \Delta T_s}$$

So, if I am writing that we can write down say my enthalpy rise in the rotor, that's what is $\frac{h_2-h_1}{h_3-h_1}$. So, that we can represent in sense of temperature we can say $\frac{T_2-T_1}{T_3-T_1}$. It is nothing but my $\frac{\Delta T_r}{\Delta T_r+\Delta T_s}$. For axial flow compressor, we are assuming our axial velocity to be constant. And as I told this earlier, we are having our entry absolute velocity and exit absolute velocity that's what is coming to be same. So, for that purpose, we can say my $\Delta T_{stage} = \Delta T_{0s}$.

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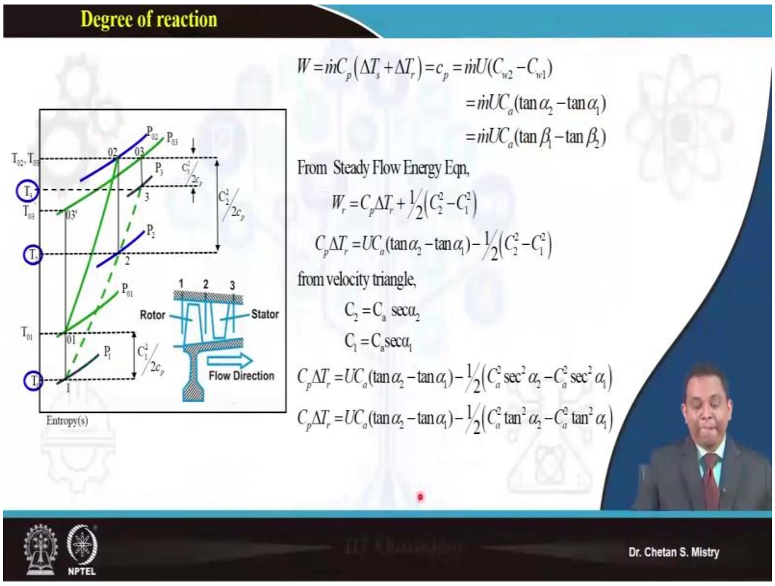

Now, what we learn from our basic fundamental equation for the specific work, we can write down our work it is $\dot{m}C_p(\Delta T_s + \Delta T_r)$; that's what we can represent in sense of $\dot{m}U(C_{w2} - C_{w1})$ So, this $(C_{w2} - C_{w1})$, that's what we can represent in sense of our flow angles, that is α_1 as well as in sense of α_2 and β_1 and β_2. Now, if I consider this as a control volume, and if I will be applying, say my steady flow energy equation for this particular stage, we can write down, for work done, it is

$$W_r = C_p \Delta T_r + \frac{1}{2}(C_2^2 - C_1^2)$$

And this work done for my rotor I can write down it is $C_p \Delta T_r$, that's what is we are writing in terms of my aerodynamic work and thermodynamic work to be same. And this is what is representing my velocity component,

$$C_p \Delta T_r = UC_a(\tan \alpha_2 - \tan \alpha_1) - \frac{1}{2}(C_2^2 - C_1^2)$$

If that's what is your case, and if you are using our velocity triangle, we can write down my $C_p \Delta T_r$ in sense of angle tan angle, so this is what is representing my tan θ.

$$C_2 = C_a \sec \alpha_2$$
$$C_1 = C_a \sec \alpha_1$$
$$C_p \Delta T_r = UC_a(\tan \alpha_2 - \tan \alpha_1) - \frac{1}{2}(C_a^2 \sec^2 \alpha_2 - C_a^2 \sec^2 \alpha_1)$$
$$C_p \Delta T_r = UC_a(\tan \alpha_2 - \tan \alpha_1) - \frac{1}{2}(C_a^2 \tan^2 \alpha_2 - C_a^2 \tan^2 \alpha_1)$$

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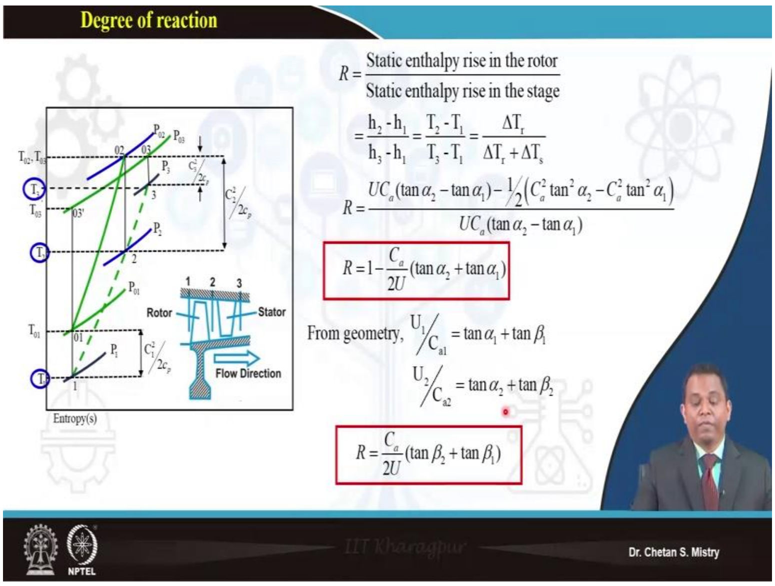

Now, if I will be putting that together in, in the formula for my static enthalpy rise for rotor divided by stating enthalpy rise in the stage, we can write down this equation in sense of UC_a α_1 and α_2.

$$R = \frac{Static\ enthalpy\ rise\ in\ the\ rotor}{Static\ enthalpy\ rise\ in\ the\ stage}$$

$$= \frac{h_2 - h_1}{h_3 - h_1} = \frac{T_2 - T_1}{T_3 - T_1} = \frac{\Delta T_r}{\Delta T_r + \Delta T_s}$$

$$R = \frac{UC_a(\tan\alpha_2 - \tan\alpha_1) - \frac{1}{2}(C_a^2\tan^2\alpha_2 - C_a^2\tan^2\alpha_1)}{UC_a(\tan\alpha_2 - \tan\alpha_1)}$$

On simplification, my degree of reaction that's what is coming,

$$R = 1 - \frac{C_a}{2U}(\tan\alpha_2 + \tan\alpha_1)$$

Now, what we learn from our velocity triangle, we can write down by,

$$From\ geometry,$$

$$\frac{U_1}{C_{a1}} = \tan\alpha_1 + \tan\beta_1$$

$$\frac{U_2}{C_{a2}} = \tan\alpha_2 + \tan\beta_2$$

this is what we have discussed why we are writing U_1 and U_2.

So, if I am simplifying this equation, I can write down my degree of reaction, that's what is given by

$$R = \frac{C_a}{2U}(\tan\beta_2 + \tan\beta_1)$$

So, this formula, that's what is defined as a degree of reaction, we can write down this degree of reaction both in relative blade angle, we can write down that in sense of absolute flow angle also.

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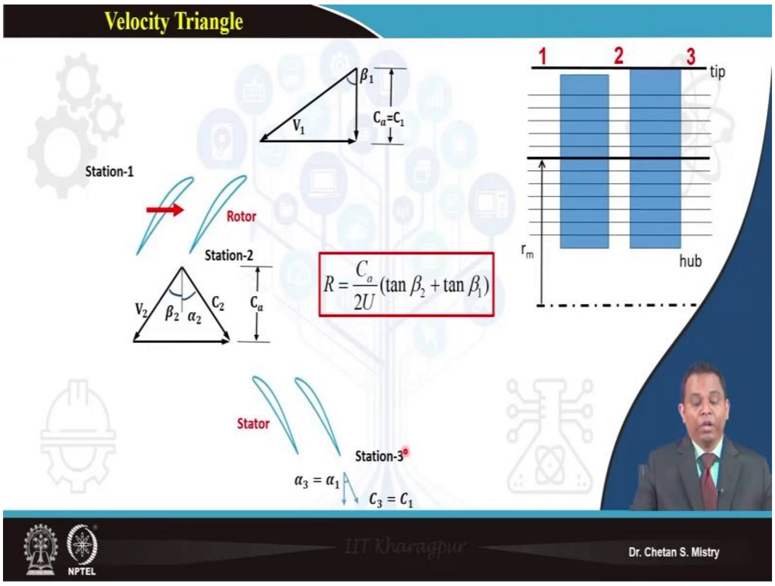

Now, if this is what is your case, what we learn? Say, this is what is my basic velocity triangle at the midsection you can say. Now, for this velocity triangle, we already have discussed how we are plotting our velocity triangle, let me put this velocity triangle at the tip region. So, if I will be putting at the tip region; you can say, this is what is my U_{tip}, I will be having my relative velocity component that's what is V_1' and my angle that's what is β_1', at the entry.

Same way, if I am considering at the exit of my rotor, I will be having my outlet relative velocity as V_2', and I will be having my angle as β_2'. So, this is what is representing how my flow angle and my relative velocity, that's what is going to change near my tip region, okay. Now, if I will be talking about the hub region, I will be having this kind of configuration at the entry; I will be having this as my velocity triangle at the exit.

Now, just remember, my degree of reaction that's what we are writing in sense of

$$R = \frac{C_a}{2U}(\tan\beta_2 + \tan\beta_1)$$

Now, at all stations, if you are looking at, hub, at mid-section even at the tip section, my β_1 and β_2 they are going to change. If I consider I am having my axial velocity to be constant, this parameter will remain same and this U it is nothing but my peripheral speed at particular location.

So, you can understand, like with change of my radius, my degree of reaction also is changing. So, you can say my degree of reaction that's what is varying from this mid-section, it is varying towards the shroud, it is also varying towards your say hub region. So, we are having this kind of diffusion or this kind of degree of reaction variation along the span.

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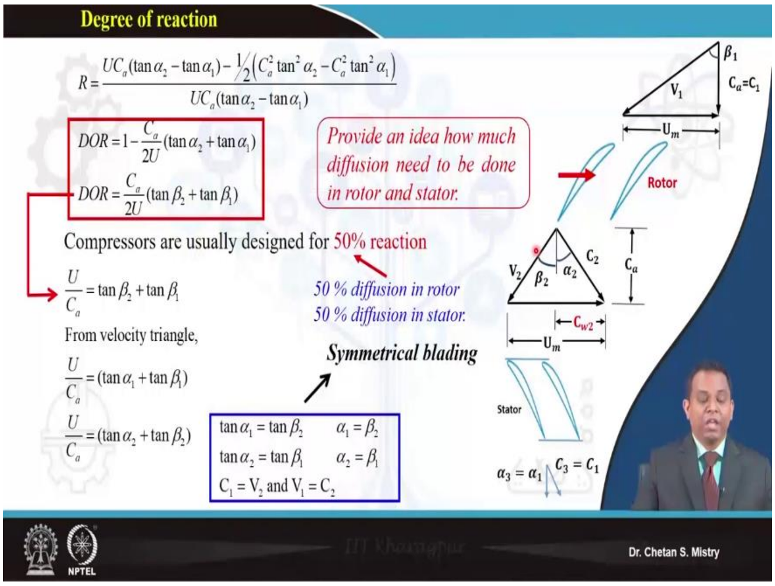

Now, let us move towards the next. If I am writing my degree of reaction in this formula, it says, $DOR = 1 - \frac{C_a}{2U}(\tan\alpha_2 + \tan\alpha_1)$ and this is what is in sense of β_1 plus β_2. Now, let me assume my degree of reaction to be say 50%. When I say my degree of reaction, that's what is 50%, so I can write down this degree of reaction as 0.5. And if I try to simplify this equation, I will be coming up with the kind of configuration where it says my $\tan\alpha_1$ and $\tan\beta_1$ they both are same, it means my α_1 and β_2 are same.

In other sense, it says my α_2 and β_1 that's what it is same. So, it says my α_1 and β_2 are same, α_2 and β_1 that's what is same. Or in other sense, if you are putting in sense of velocity term, it says my absolute velocity at the entry of my rotor, and my relative velocity at the exit of my rotor; same way, my entry velocity, relative velocity at the entry of my rotor, V_1, and my exit absolute velocity, they both will be coming same.

$$\tan\alpha_1 = \tan\beta_2 \qquad \alpha_1 = \beta_2$$
$$\tan\alpha_2 = \tan\beta_1 \qquad \alpha_2 = \beta_1$$
$$C_1 = V_2 \; and \; V_1 = C_2$$

So, we will try to understand what is the physical meaning of that? If we say, we are having this α_1 and β_2 that's what it is same and α_2 and β_1, that's what is same.

So, in your velocity triangle, you can say you will be having change of all these angles. If this is what is the kind of configuration, we can say, that's what is called symmetrical blading; we will see what we mean by symmetrical blading. It says when I write say my degree of reaction, that's what is 50%, so it implicates like 50% of my diffusion that's what is happening in my rotor, and remaining 50% that's what is happening in my stator, okay. And this is what is giving us idea how good the diffusion that's what is happening within my passage.

Now, let me tell you, say… when I have started with the discussion for the construction of axial flow compressor, that time we were discussing, say purpose of my rotor, that's what is to have, you know, conversion of my kinetic energy into potential energy, or we can say that is what we will be giving rise of my pressure and purpose of stator it was to guide the flow. But, looking to this, you just realize, we are having stator they are also doing the diffusion work.

So, now the thing is, it is not only to guide the flow, there are many designs where people they are doing diffusion both in rotor as well as for stator, okay. So, we need to understand one part here, like how we are dividing our diffusion work that's what will be giving us what will be my degree of reaction, okay.

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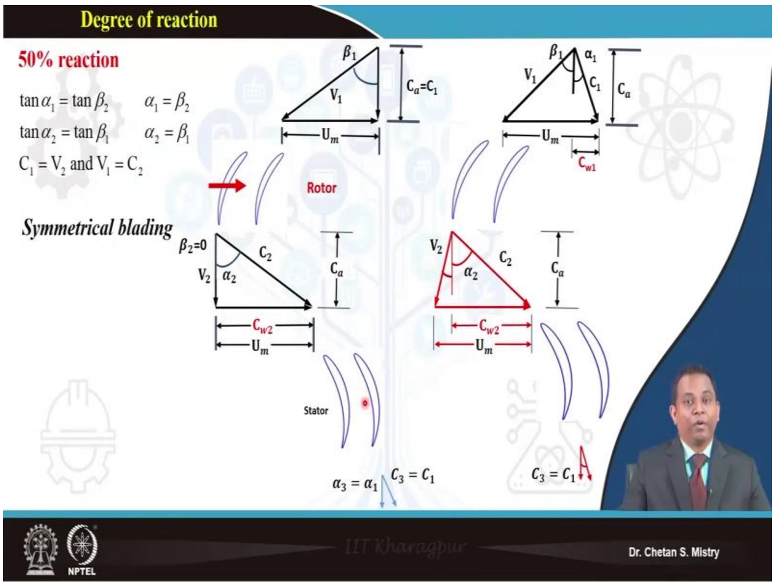

Now, here, if I will be putting my symmetrical kind of configuration, so suppose if I consider my flow, that's what is entering with some absolute velocity at rotor, okay. So, you know, like here, if I will be writing, I will be having my, you know, angle, that's what is α_1. And based on your velocity understanding, I will be writing my flow which is entering inside my rotor with my relative velocity V_1, okay. And that's what will be coming out from my rotor at some angle, we say that's what they say my angle β_2.

Now, according to our concept for 50 % reaction, what it says? I am having my α_1, that's what is equal to β_2. So, here if you say, this is what is my α_1 that's what is equal to my β_2, okay. Same way, we can say what is my absolute velocity at the entry that is C_1 it is same as my relative velocity at the exit which is V_2, okay. And here, if you look at careful, if you are doing this kind of configuration, my absolute velocity that's what is coming out from my rotor that is going to be large, okay. So, my C_2 that's what will be going to be large.

Now, with this absolute velocity my flow that will be entering inside my stator and we are looking for our exit to be suppose say axial; under that condition, I will be having my diffusion that's what will be happening from C_2 to C_1, okay. So, this is what is representing my velocity triangle when I am having my flow, which is entering at some angle α_1 using my inlet guide vane, okay. When I will be having my $\alpha_1 = \beta_2$ and I will be having my $\beta_1 = \alpha_2$.

Now, let me consider suppose say I am having my flow entry that's what is happening axially. So, you can say this is what is representing my flow entry that's what is say axial entry. If that's what you is your case, according to our understanding for symmetrical blading, my α_1 that's what is coming to be 0, okay, that means my β_2 is coming to be 0.

So, you can say I am having my entry to this rotor it is axial, my exit to this rotor that is also axial, okay. And I will be having say this absolute velocity component that's what is coming to be large and that's what will be passing through this stator passage and that's what is giving me what we say in sense of diffuser. So, according to what we have learned, say degree of reaction to be 50%, maybe you can make your velocity triangle accordingly. Just look at carefully saying like what inlet condition that's what is given whether you having axial in entry or it will be at certain angle, okay.

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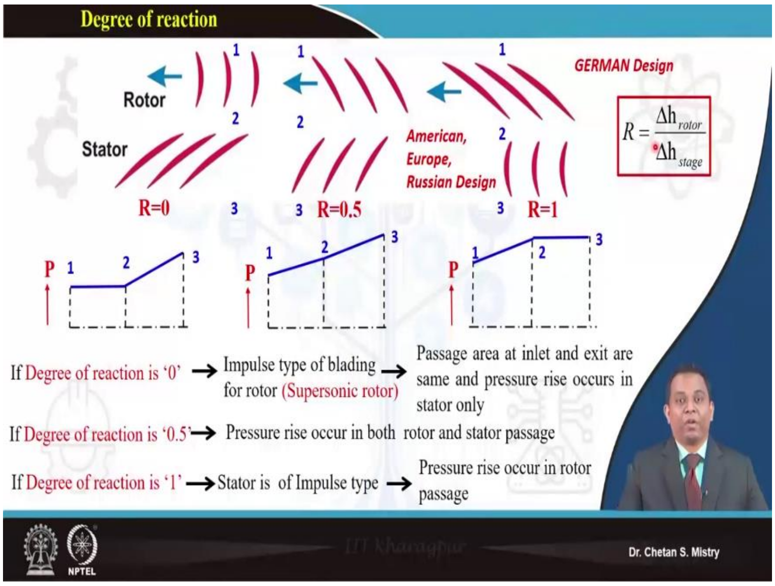

Now, let us move to this particular chart. This is what is a very good representation and very good understanding what we mean by having your degree of reaction, okay. So, very first, that's what is representing my rotor and stator combination we can say as a stage for which my degree of reaction is 0. This is what is representing my degree of reaction to be 0.5.

And this stage, that's what is representing my degree of reaction to be 1 or say 100% reaction, 0.5 I will say 50% reaction and 0 I say 0 % reaction, okay. Now, what we have understood, my degree of reaction, that's what is basically representing what is my enthalpy rise in my rotor, and what will be my enthalpy rise in my stage, okay.

So, here if I consider my degree of reaction to be 0, the meaning is my enthalpy rise in rotor that's what is 0. So, if I am plotting my variation or pressure you can say my entry station is 1, my exit station is say 2 for the rotor, from 1 to 2, I will not be having any rise of pressure. So, that is what say my pressure remains constant, okay.

Now, if you look at carefully it says when I am having my degree of reaction to be 0 under that case, have look at this passage of the rotor, so, here if you look carefully, my entry area and my exit area they both are same, okay, t is not having any change of passage shape. So, this is what is the kind of blading, it is called Impulse kind of bleeding, okay, mostly this kind of rotors are supersonic rotors, they have their special application as and when it will be coming we will discuss.

Now, it says I am having my passage area at the entry and my passage area at the exit of rotor that's what is constant. Now, what happens? From this station 2, my flow will be entering inside my stator and if we go carefully here, this is what is my entry area and this is what is my exit area. So, you can say, my stator that's what is having say defusing passage, so you can say because this is what is making a diffusing passage, I will be having my rise of pressure from station 2 to station 3, okay.

So, this is what it says when I am having my degree of reaction to be zero, then there is no pressure rise that's what is happening in my rotor. The whole diffusion or pressure rising, that's what is happening only in stator, okay. Now, let us move to the next case. It says when I am having my degree of reaction to be 50%, so what we realize, say 50% of my diffusion, that's what is happening in my rotor and 50% diffusion that's what is happening in my stator, okay. If that's what is your case, you can look at carefully, I will be having my rotor passage, entry area and exit area they are different, okay.

Same way if we are looking at what is my entry area at the stator and what is my exit area at the stator they both are different. That means my entry area is lower, my exit area is larger. So, here if you look carefully, what it says? If I am talking about the pressure rise, it says from station 1 to 2, I will be having the rise of pressure and remaining pressure rise that's what is happening from 2 to 3 in my stator, okay.

So, this is what is the physical meaning of what we say 50% reaction. Now, here if you look at this is what is my third case where my degree of reaction, that's what is coming say 100%. So, what is the case, if you look carefully for my rotor, you know, I will be having my passage area that's what is changing from entry to exit, okay. So, you will be having the diffusion that's what is happening only in rotor.

And if we go carefully, here in this case, my stators are of impulse type where I am having my entry area and my exit area to be same, okay. So, this is what is giving us idea how my blade shape, that's what is changing. Let me tell you, when we have started discussing about the degree of reaction that time I told this degree of reaction, that's what is a parameter which is changing from my hub to tip, okay.

So, you can say, maybe near hub you will be having some degree of reaction, maybe at midsection you will be having some degree of reaction, at shroud you will be having different degree of reaction, okay. So, this is what is giving us the passage shape that's what is changing between rotor blades and between my stator blades.

Now, here it is written say most of the German designs, during Second World War when they people they were developing engines, they were preferring to go with say having configuration with the degree of reaction to be 100%, okay. So, most of the German designs for axial flow compressor, what you find, they are having degree of reaction to be 100% means whole the diffusion they are doing only in rotor; stator, that's what is only guiding the flow, it has nothing to do in sense of rising of the pressure.

Now, if you look at for Americans, European or say Russian designs, people they are going with the 50% reaction; they feel, it is to go on the safer side. So, what passage shape, what we are looking at this moment, that's what is very important, okay. And we look at our velocity triangle, you may be realizing, near the hub region, we will be having our degree of reaction that will be coming low, okay. Because my peripheral speed that's what is lower and when I am talking about my degree of reaction near the tip region or my shroud region, where I will be getting my degree of reaction coming to be large, okay. So, my degree of reaction that's what it is varying from say hub to shroud. There are many designs in which people they are assuming degree of reaction to be constant.

So, throughout the span from hub to shroud, they are assuming their degree of reaction to be constant. So, when we will be discussing about the design approach for axial flow compressor we will be discussing different design approaches what people they are adopting these days, okay. And, earlier designs also we will be discussing, and then you will realize in past people they were prefer to go with constant reaction kind of design, say 50% reaction design, most of the compressors, old compressors, they are designed with 50% reaction throughout the span, okay.

So, I am sure, you got the idea, you got the list of what we say, in sense of Lieblein's diffusion factor and we have introduced the terminology that's what is called degree of reaction. And we realize this degree of reaction, that's what is a concept applicable to turbines but here in this case, we are using this equally for our compressor, because compressor is a working device, that's what will be converting your kinetic energy into potential energy or in sense of diffusion. So, working of my compressor, I can make my using this degree of reaction calculation.

So, now you can understand, we are moving more towards the design aspects for axial flow compressors. So, one parameter what we have discussed in last lecture, that's what was say diffusion factor. Today we have introduced the new parameter that's what is called degree of reaction. We will be discussing ahead with more parameters as we go along. Thank you. Thank you very much for your attention! See you in the next class.