Aerodynamic Design of Axial Flow Compressors & Fans
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Lecture - 12
Stage Configuration and Parameters (Contd.)

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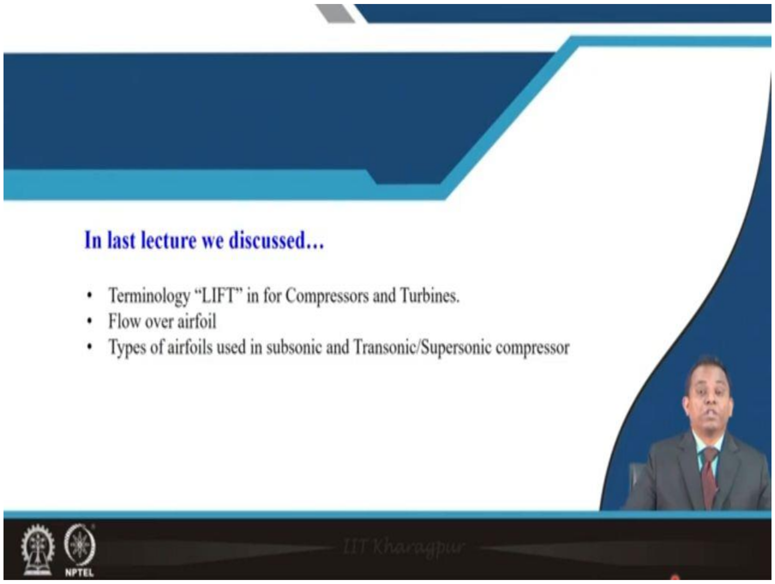

Hello, and welcome to lectur-12. In last session, we were discussing about the terminology called lift, that's what is application to your compressor and turbine airfoils. And we have realized this is what is a main driving for our compressors and turbines. So, we were discussing about the lifting force how we are utilizing the lifting force and how we will be having the rotation of our wheel or rotation of our rotor. Mainly for compressor as we have discussed, my rotation will be from suction side to the pressure side, and for turbine we will be having a rotation from pressure side to the suction side. And that's what will be giving us the benefit in sense of using our lifting force.

Then, we have discussed about the flow over airfoil. We have realized how the flow that's what will be moving from leading edge to the maximum thickness, and then after from maximum thickness towards the trailing edge. So, initially we have discussed we will be having our flow to be laminar flow. After maximum thickness up to some distance we will be having the flow transition that's what is happening, and towards the trailing edge we will see our flow to be more turbulent. So, those who are having the background of fluid mechanics or having the background of aerodynamics, just go through these terminologies called laminar flow, transition flow and your turbulent flow, okay.

Then, we were started discussing about different kinds of airfoils which we are using for our axial flow compressors and fans. So, if you recall, we were discussing about the C4 airfoil, we were discussing about NACA 65 airfoil. We have discussed about say computationally made say control diffusion airfoil, we have discussed about double circular arc airfoil, we have discussed about multiple circular arc airfoil, we have discussed S-type of airfoil. And as I told, lot of work, lot of research work, lot of development activities that's what is going on for development of such airfoils, application to fans, application to compressor for aero engines as well as for land-based power plants, okay.

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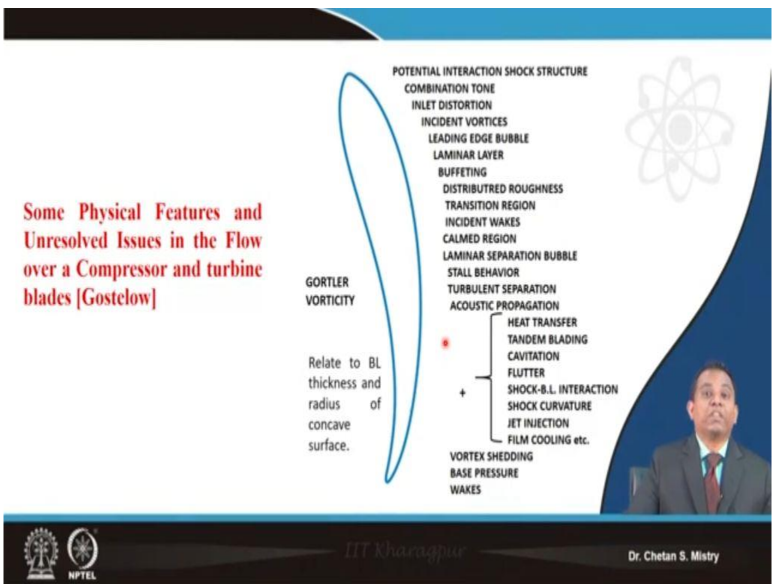

Now, let us move ahead. Here this is what is one of the feature that's what was given by Gostelow. He did, he has reported a whole lot of work related to cascade study and his data, that's what is available in open literature, as on today people they are using. According to him, some of the physical features and unresolved issues in the flow over compressor and turbine blades that's what he has listed here. And if you recall, I was telling you, we are more interested what is happening on our suction surface. And here if you look at, this is what it says potential interaction shock structure, combination tone, inlet distortion, incident for vortices.

You can see when we are discussing or we discussed about say transonic compressor or transonic airfoils, we will be having formation of shock near the leading edge. And as we have discussed this leading edge, this leading edge that need to be a sharp leading edge, okay. If it is a sharp leading edge, then only we will be holding our shock on the surface of my blade. Next, if you look at, that's what is say the noise issue that's what we are defining in sense of say combination of tone. So, when my wheel is rotating or my rotor it is rotating, it will be cutting the air and that's what will be giving the generation of noise.

So, majority of contribution of noise that's what is coming from the rotation of my wheel. We are having inlet distortion, you can realize this distortion is nothing but it is a disturbance. This disturbance may be we can say in sense of pressure, in sense of velocity, in sense of total pressure, say in sense of total temperature, or maybe because of atmospheric change, or say because of your cyclone; all those things that's what will give my flow at the entry to be disturbed, or it is different from what it is been designed.

So, that is very challenging aspect. These days universities and industries they are working on development of this kind of fans and airfoil which are called distortion free fans or say distortion free compressors, okay. Then, we are having say leading edge bubble, laminar layer, we will be having buffeting, we will be having say roughness. You can understand when we are flying, so, along with your air, there maybe possibly that dust particle also will get sucked from say atmosphere. And that will be sticking on the surface of my blade. And you can understand we are looking for our surface of this suction surface that to be a perfect surface.

Other than this suction surface if I will be having sticking of air say particle, dust particle on this surface, that will change my flow physics on the suction surface, and that's what will give off-design performance. Means for what we have designed, that compressor will not work according to our expectation. And that is the reason people they are doing, after a few flying hours, they are doing compressor washing, okay. Then we are having say distributed roughness, transition region, incident wake, calmed region, laminar separation bubble, stall behavior, turbulent separation, acoustic propagation.

Along with that we are having say heat transfer, we are having tandem blading, we are having cavitation. Suppose say, I am using this kind of airfoil for say my axial flow pump, there I am having problem, that is what we can say it is a cavitation problem. We are having flutter, it is your aero mechanical problem. Shock boundary layer interaction, shock curvature, jet impingement, film cooling, vortex shedding, so many.

So, you can understand all these aspects that’s what need to be considered when we are making airfoil. And that airfoil which is application to your compressor, which is working under adverse pressure gradient. So, just look at the challenges what we need to face, when we say we are using our airfoil for making of blade, it is not that easy in that sense.

Even on my pressure surface, I will be having boundary layer thickness and radius of say concave surface. That’s what will be giving you Gortler vorticity on that surface, okay. So, just realize what we mean to say is, you know, your airfoil what we will be using for axial flow fan or say axial flow compressor, it is having so many difficulties. As on so many issues people they are still resolving, okay.

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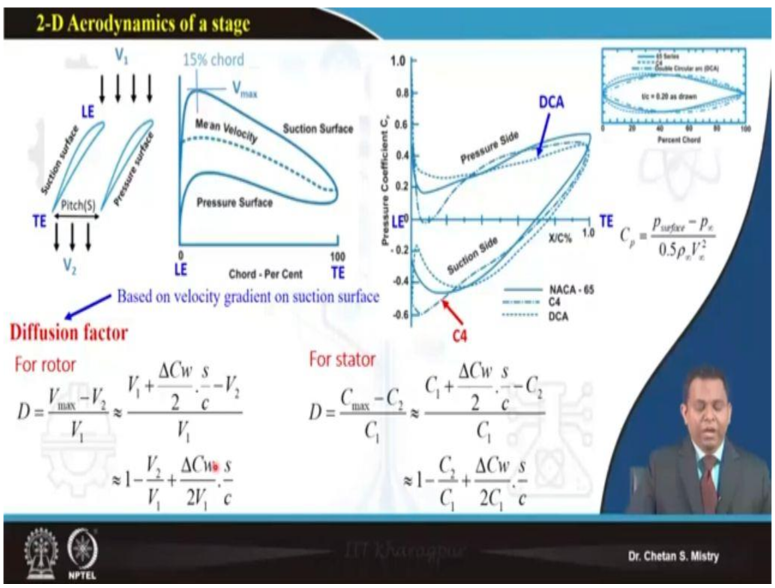

Now, with this background, let us try to move ahead, let us try to understand how this is what will be helping us for say design of our compressors and fans. So, here if you look at, this is what we say, we have arranged our two airfoils at particular section, say at the midsection. If I am arranging in this way, that’s what is called linear cascade. We will be discussing what is the meaning of that, at this moment, just realize I have arranged these two airfoils as per my section at particular station.

This region as we have discussed, it is called my leading edge and trailing edge, we are having inlet area, outlet area. Suppose, if I consider my entry velocity is V_1, I will be having my exit velocity, say V_2, okay. The distance between these two airfoils or two blades, people they are defining that as a pitch, okay. If I will be measuring my distance from leading edge to the trailing edge, that's what is defined as a chord. And if I will be measuring my distance vertically, that's what is called axial chord. We will discuss again when we will be discussing about the aerodynamics of these blades, okay.

Now, here if you look at, this is what is a plot from NASA SP 36. So, you can see here, what it says? As we have discussed somewhere here, I will be having my stagnation point, we will be having our acceleration of flow, that's what is happening on my suction surface. So, you can say, this is what is representing my acceleration of flow. You can see a whole lot of acceleration, that's what is happening on my suction surface, okay. You can say around 10 to 15 percent of chord, you will be having maximum velocity, so here I am writing that as say, V_{max}, okay. Now, what is happening when we are moving downside?

As we have discussed this is what is your diffusing passage, and for diffusing passage, we will be having our flow that's what will be getting decelerated. So, here if you look at, from this 15 percent chord to downside, my velocity that's what is decreasing, that will lead up to say my trailing edge, okay. In line to that, let us see what is happening on our pressure surface. So, here if you look at, for pressure surface, we will be having initial acceleration, you can see; in this particular region, we will be having the acceleration of my flow, and then after it will be having the deceleration of flow on my pressure surface, okay.

So, too much of acceleration, that's what is happening on my suction surface. We will be having small acceleration that's what is happening on my pressure surface, okay. And this together if we will be joining that's what is representing what is happening with my velocity on the surface of my airfoil. Now, here if you look at, this is what is representing my pressure coefficient versus my chord, okay. This is what is representing my leading edge and this station that's what is representing my trailing edge, okay. And we have seen in last lecture, we are having say subsonic airfoils, we can say it is a C4 airfoil we are having, NACA 65 we are having or 65 series, and we are having double circular arc.

And here if you look at, this is what is representing the actual shape of your airfoils, okay. So, if we compare in that sense, we are looking at say, if you look at my C4 airfoil, that's what is this dotted line. It says, I will be having larger leading edge and that will be having maximum thickness up to some station. It says, this is the station where I will be having my maximum thickness. If we look at the next, that's what is say NACA 65, that's what will be having, you know, my leading-edge shape that's what is different. And my suction surface and pressure surface say initial stage up to maximum thickness, I will be having that to be lower thickness compared to my C4 airfoil.

And if you look at for DCA - double circular arc, you can see, the leading edge is almost say, you know, it is a sharp edge kind of configuration. It will be having small radius at the leading edge, it will be having small radius at the trailing edge. So, this is what is representing my DCA airfoil. Now, if we will be measuring what is happening on my suction surface and what is happening on my pressure surface? That is what we will be representing in sense of the term, that's what is called, say… pressure coefficient.

So, this pressure coefficient is nothing but

$$C_p = \frac{p_{surface} - p_\infty}{0.5\rho_\infty V_\infty^2}$$

So, those who are having the background of aerodynamics, they maybe knowing this is what is representing my pressure coefficient. Now, this pressure coefficient in your experimentation for aerodynamics lab, you might have measured this pressure distribution, and then after based on that, you might have calculated your lifting force, okay. Now, let me tell you, we are also in line to that only. Only difference is what we are understanding for airfoil in aerodynamics, it is for wing, and here we are talking about airfoil at particular station, okay.

Now, have look at what is happening in sense of your pressure coefficient. So, first let us look at say what is happening on my C4 airfoil. So, here, this is what is representing my suction surface. So, what is our observation? I will be having whole lot of acceleration that's what will be happening on my say suction surface. So, when I say acceleration, that is happening, my C_P value that's what will be decreasing. So, you can see this is what is representing my say acceleration of flow on C4 airfoil. Then after, it will be having say deceleration of flow, that's what is moving downside towards the trailing edge.

So, you can see, this is what is representing the acceleration of my flow for C4 airfoil. If we look at on pressure surface, again on pressure surface we will be having the acceleration of flow, that's what is happening on say pressure surface. So, here if you look at, this is what is representing the acceleration of flow near the leading edge, okay. And then after, slowly I will be having the pressure rise and that's what will be merging near my trailing edge. So, you can say, this is what is representing my C_P distribution. Let me tell you, area under this curve, that's what is defined as a lifting force when we are saying aerodynamics.

If we are using this concept for our compressor airfoil, basically area under this curve, that's what is representing my pressure rising capacity of that particular airfoil, okay. So, when you are doing your design, after doing design, maybe you will be going with say your computational study. In computational study, it is preferred that you understand what is happening with your C_P distribution on your suction surface and pressure surface at particular station. And just look at how you are managing your flow on suction surface, how you are managing your flow on the pressure surface.

You can understand if I will be managing my flow nicely on my pressure and suction surface, that's what will be giving me very good C_P distribution, that means it will be giving me what pressure rise I am expecting, okay. So, many times people when they are doing their computational study, they need to do post processing in sense of understanding what is happening at particular station, they are using this C_P as one of the parameter. Let me go to the next. This is what is representing for say 65, so, this is what is for NACA 65. Here also I will be having my acceleration of flow that's what is happening, but in compared to your C4, my acceleration is slightly lower on the suction surface.

Same way, this acceleration, that's what is happening slightly lower on my say pressure surface also. And here if you look at, this is what is representing my distribution of C_P for NACA 65, okay. And as we have discussed for double circular arc, I will be having acceleration, and that acceleration will be moving towards the downside here, okay. So, if you compare for my C4, that's what will be around say may be 10 to 15 percent of chord. For NACA 65, it will be from 15 to 20 percent. And here if you look at, for double circular arc, it will be around say 40 percent of chord, 30 percent of chord. You will be having say, you know, acceleration of flow and then after you will be having smooth deceleration of the flow.

If you look at carefully and if you are comparing all together, you will see my pressure distribution on the pressure surface for double circular arc that's what is roughly constant, okay. So, this is what will give us idea what is happening in sense of my C_P distribution. And now we realize, what is the use of my lifting force, when we are talking for application of say your compressors as well as fans. Now, you know, you will be going aggressive, we are always discussing we want to increase the pressure rising capacity of particular stage.

That's what is in order to meet lot of requirements, lot of expectations for future engines. And if you will be going aggressive, then there maybe chances of flow separation, that's what will be happening. And when I say there is a flow separation will be happening, it will not give what C_P distribution we are looking for.

So, when I will be discussing about the cascade, that time we will be discussing these aspects what is happening there. Now, with this data, say Americans mainly for NASA, earlier name as NACA, they people they have come up with some solution, say in sense of, you know, diffusing capacity of particular airfoil or for particular rotor and stator configuration.

What they say? Like if I consider this is what is say my maximum velocity, if I consider I am having my entry velocity is V_1, and my exit velocity is say V_2. Then they say, they have introduced the parameter, that's what is called say diffusion factor. So, what it says? Based on say velocity gradient on the suction surface, they have defined this as say $V_{maximum}$. So, this is what is my V_{max}, here this is what is my V_2. So, here you can say it is a V_2, so, it is

$$D = \frac{V_{max} - V_2}{V_1} \approx \frac{V_1 + \frac{\Delta C_w}{2} \cdot \frac{s}{c} - V_2}{V_1} \approx 1 - \frac{V_2}{V_1} + \frac{\Delta C_w}{2V_1} \cdot \frac{s}{c}$$

Then, slowly they realized, rather using this relation, this is what is depending on aerodynamics of my arrangement. So, this is what is they are saying, say here 's', that's what is representing my pitch. So, you know, how far I have placed my blades or how many blades I have accommodate in particular distance. That's what is called my pitch and what is my chord, okay? Then, they have replaced this with ΔC_w, and they say, my diffusion factor, that's what is a function of say, you know, my relative velocity or velocity at the exit, velocity at the entry. What is my ΔC_w?

That's what is my working capacity, ΔC_w that means $C_{w2} - C_{w1}$. And this is depending on my parameter called pitch and it is also depending on my chord, okay. So, this if I am using V, that means we must realize this is what is in relation with our rotor, okay. For rotor, we are interested in relative velocity, okay. And just recall, for rotor our relative velocity at the entry that will be larger, my relative velocity at the exit is lower, okay. Suppose say, if I am using this concept for the stator.

For stator also we can do the calculation for the diffusion factor, but in that in place of using your say relative velocity component, we need to go with the absolute velocity component. So, this is what is the relation for that, okay. So, based on say understanding what is happening on the surface of airfoil? They have come up with the solution, that's what is saying it is a diffusion factor.

$$D = \frac{C_{max} - C_2}{C_1} \approx \frac{C_1 + \frac{\Delta C_w}{2} \cdot \frac{s}{c} - C_2}{C_1} \approx 1 - \frac{C_2}{C_1} + \frac{\Delta C_w}{2C_1} \cdot \frac{s}{c}$$

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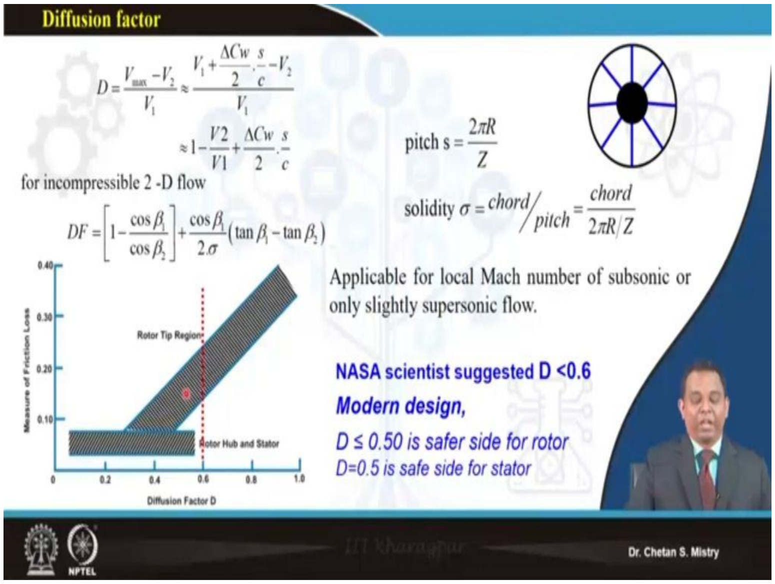

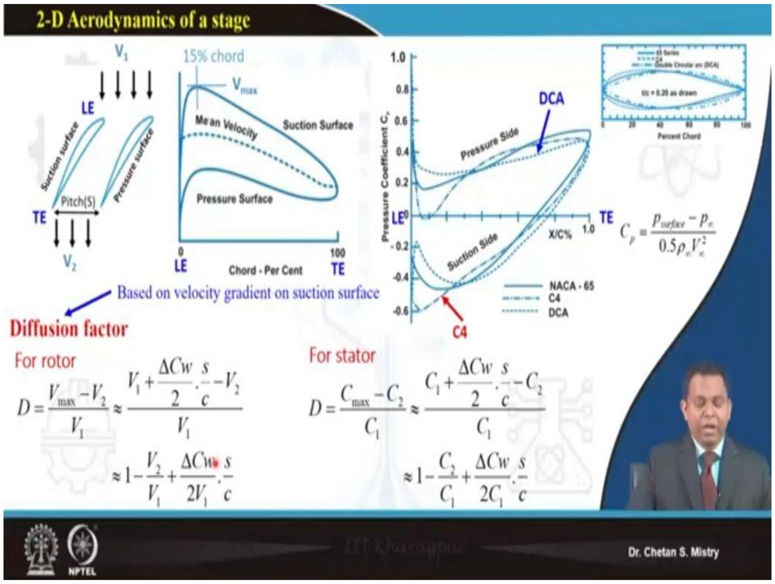

Let us see how exactly we will be using this parameter called diffusion factor. So, this is what we know, my diffusion factor that's what is maximum velocity minus say exit velocity divided by entry velocity.

$$D = \frac{V_{max} - V_2}{V_1} \approx \frac{V_1 + \frac{\Delta C_w}{2} \cdot \frac{s}{c} - V_2}{V_1} \approx 1 - \frac{V_2}{V_1} + \frac{\Delta C_w}{2V_1} \cdot \frac{s}{c}$$

If I will be replacing my velocity components, say a relative velocity component, and my relative velocity component at the entry and exit, I can write down in sense of my β_1 and β_2. So, using your velocity triangle, we will come up with diffusion factor, that is given by

$$DF = \left[1 - \frac{\cos\beta_1}{\cos\beta_2}\right] + \frac{\cos\beta_1}{2 \cdot \sigma}(\tan\beta_1 - \tan\beta_2)$$

Now, here, this σ, that's what is defined as a solidity, okay. So, in sense of understanding now, let me introduce one more parameter that's what is called solidity. This solidity, basically it is defined as say

$$\sigma = \frac{chord}{pitch} = \frac{chord}{2\pi R/z}$$

When I say pitch, I will say this is given by $2\pi R/z$ So, you must realize, suppose say, this is what is say my rotor; so, at all stations, at all radius, at all diameter, I will be having this solidity to be different, okay. What we were discussing in earlier case, this is what is at particular station. Now, you know, like we have realized our blade, it is made up of say number of airfoils, it has number of stations and this is what is having 3-dimensional shape.

So, you can say for all the stations, you will be having different solidities. Same way, at all the stations you are having different β_1, β_2, okay, because my peripheral speed is changing, though my axial velocity is constant. So, you know, I will be having variation of my diffusion factor all the way from hub to shroud or hub to tip, okay.

So, this is what is a compilation of data, that's what was proposed by say NASA. So, in NASA SP 36, they people they have plotted this. And they say, you know, this is what is representing my diffusion factor, and this is what is say my frictional losses. So, basically, they have correlated the separation process or say losses in sense of frictional losses.

So, what they say? Like, for say rotor hub and stator, you know, my frictional losses that's what is remains almost constant, okay. And if I am talking about say diffusion factor, that's what is moving from 0.4 onwards, if you look at carefully, then, near the tip region, my losses that's what will be going to increase, okay. So, my losses that's what is going to increase, okay. So, it says, this logic or this plot what we are saying in sense of diffusion factor that's what is applicable for say subsonic or high subsonic kind of airfoils. As per NASA, this diffusion factor should be less than 0.6.

If you are going more than 0.6, you can understand you are increasing your losses. And when I say you are increasing your losses, you know, your efficiency will go down, okay. So, for most modern design, people they are assuming this diffusion factor in the range of 0.5 or less than 0.5, okay, to be on the safer side. Now, for stator also, the people they are putting this diffusion factor in the range of 0.5. So, now just realize, we are now moving towards what all calculation we need to do for design. So, this is one of the important parameter when you are doing your design of axial flow compressor, okay. So, this is what is defined as my diffusion factor.

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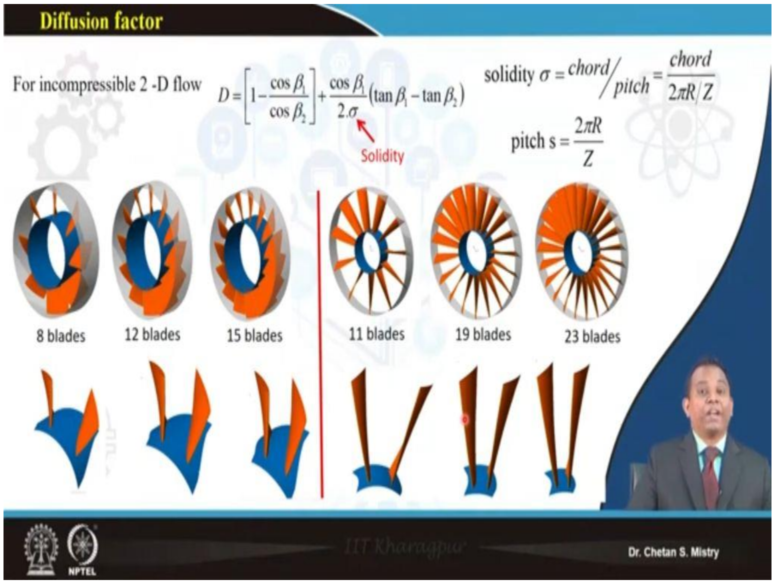

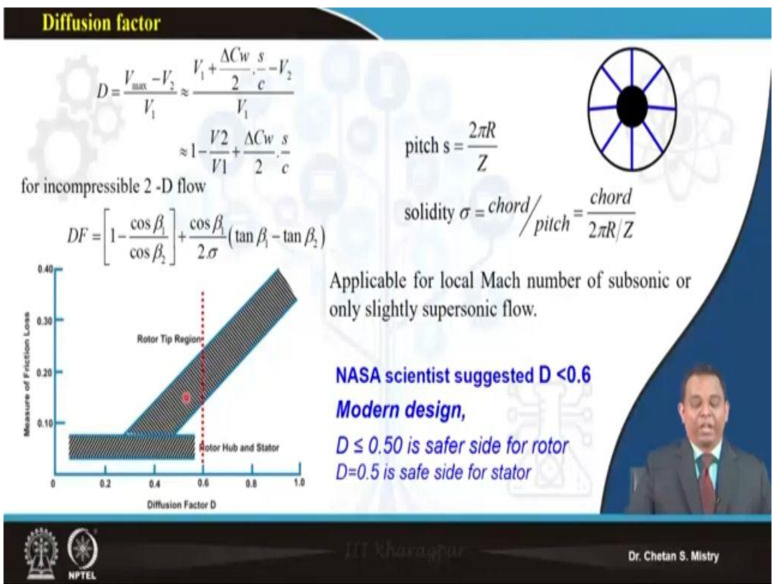

Now, here if you look at, this is what we have discussed in sense of diffusion factor and we have defined this σ as my solidity. So, solidity we have defined as say $2\pi R/Z$, that's what is representing at different radius for particular number of blades. So, Z is nothing but my number of blades, okay. So here, this is what is a presentation for you can say it is a low aspect ratio blade, so it is around say aspect ratio in the range of 1, okay. Aspect ratio in the sense height of the blade to chord of the blade; that ratio is defined as aspect ratio.

Same way, here on right hand side you can see, this is what is high aspect ratio blade, where your height of the blade or span of the blade is larger, and your chord of the blade that's what is smaller, okay. Now, this is what is representing what will happen if I will be changing my number of blades. Suppose, if I consider, this is what is say having 12 number of blades. So, you can say I am making this passage, this particular passage we have realized that's what is your 3-dimensional passage, where your diffusion, that's what will be happening, okay.

Now, if I will be reducing my number of blades. Say suppose, I am reducing that to 8 numbers of blades. What will happen? My passage area at the entry and my passage area at the exit will be changing. And my length, that's what is remain same, because I am not changing my chord. So, this is what will be giving you maybe say formation of your stall or separation of your flow, on from your suction surface, or it may not be giving what pressure rise we are expecting, okay. So, in order to achieve that particular pressure rise, so diffusion factor that's what is giving you idea in sense, you know, like how much maximum pressure you will be achieving, okay.

So, let me increase the number of blades. Suppose, say here, I am increasing my number of blades to say 15 number of blades. What will happen? Again, here if you look at, my passage area that's what is say reducing and that's what may give you what you are looking for in sense of pressure rise, okay. Now, just look at what is happening with my high aspect ratio blades. When I say high aspect ratio blade, I am having my span to be large or my height of the blade is large, and my chord is smaller, okay. So, if this is your case, my defusing passage, you can understand, available, that's what will be smaller length.

So, it is more challenging in that sense. So, if you are looking, here I am having, I am looking for more number of blades. Say, this is what is say original or we can say 19 number of blades. If I will be reducing my number of blades, you can say, my flow area between these two blades that's what is going to increase. That may not give what pressure rise we are expecting from that rotor, okay. Same way, if I will be increasing my number of blades here, I will be having my passage area that's what will be smaller. And if that's what is your case, you may be able to achieve say pressure rise what you are looking for, okay.

But, remember one thing, when I say I am increasing my number of blades, we need to pay somewhere. That's what will be in sense of losses, first thing. Secondly, that's what will lead to increase the number of blades on your rotor as well as stator, and that's what will be increasing your weight of the engine. So, people they are doing the optimization in order to reduce the number of blades, if they are able to reduce one number of blade, that's what will be paying them say in dollars, at the end of the year, it is a huge amount.

And that is where whole development activities as I say it is happening. When I say low aspect ratio blade, it is a more systematic way of doing the diffuser process. When I am talking about say high aspect ratio blade, since my chord available is very short, though you need to manage whole your diffusion within this particular length only, that's what is more challenging in sense of doing design, okay. So, just realize the thing, this diffusion factor what we are introduced, what we have talked about, that's what is very important parameter when we are saying for our design, okay.

And this diffusion factor that's what is the estimation. So, throughout the world, people they are using this diffusion factor as one of the parameter for checking or assessing the performance of that particular design, okay. So, this diffusion factor is suggested it says my diffusion factor that need to be in the range of 0.5. So, many times, people they are assuming this diffusion factor to be 0.5, based on that they are deciding the number of blade. So, that is also one of the design challenge, how you will be deciding the number of blades.

So, people they are using this concept of diffusion factor many times for deciding the number of blades. Or, maybe in order to increase or decrease the diffusion factor they are changing the number of blades. They are changing say chord length, maybe they are changing the aspect ratio of the blade. So, here we are stopping with. Thank you very much! I hope this has given more clarity to you in sense of design. Thank you!