Aerodynamic Design of Axial Flow Compressors & Fans
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Lecture – 27
Cascade Aerodynamics (Contd.)

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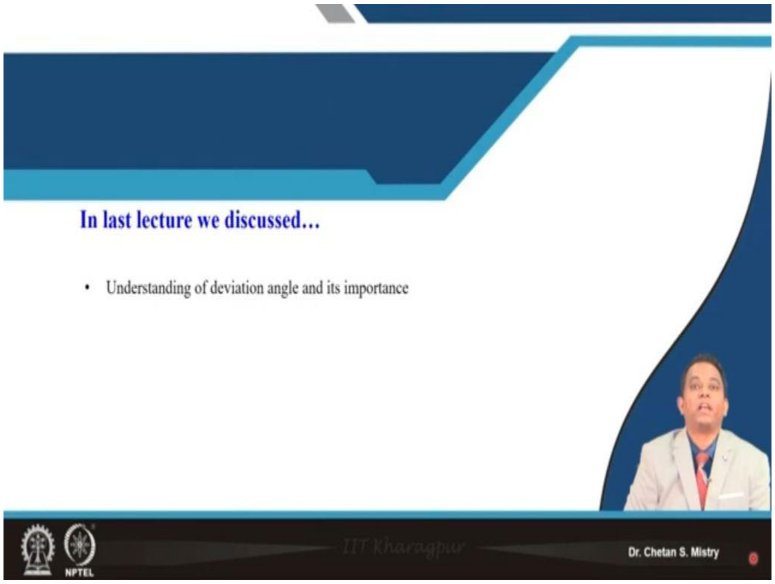

Hello, and welcome to lecture-27. We are discussing about the cascade aerodynamics. In last lecture, we started discussing about say deviation angle and its importance. So, we realized in line to what we have discussed about the incidence angle, deviation angle is also equally important. And we realized the incidence angle that can be 0, but deviation angle can never be 0; because that’s what is a property of our airfoil. And that’s what will be giving or going to give us the deviation angle inherently for particular kind of airfoil for our axial flow compressor.

And based on Carter's correlation, we have discussed the deviation angle, that’s what is depending on ‘m’ parameter, it is depending on what is my camber angle, it is also depending on what is my solidity. And at the same time, we were started discussing about how do we calculate this deviation angle as per our requirement.

And as we have seen, like based on this fundamental correlation, we can do our calculation for the deviation. But, at the same time with the enhancement and improvement of computational technology, people they started visualizing what is happening near the trailing edge, based on say flow visualization, based on say contour plots, based on C_p distribution; and accordingly, they are modifying the angle at the exit, okay.

Now, when I say they are changing the angle at the exit; so, as we have discussed for incidence angle what we are doing is inherently or by default, we are giving some incidence angle at the design stage only. So, accordingly our blades they have been made and we have defined that as a blade angle. Similarly, for deviation also need to be considered. So, when we are doing our design, that time by default this deviation angle we need to incorporate in our design stage. And based on that my blade metal angle, that's what will be decided with at the exit.

So, now when I say my blade it is made, that blade is made with the blade angle at the entry; or metal blade angle at the entry, and metal blade angle at the exit, okay. So, do not get confused in sense of what we say as a deviation angle, this deviation angle we are taking care at the initial stage only during our design, okay. We will be discussing all these in detail when we will be discussing the design for say low speed compressor. We will be discussing these for high speed compressor; we also will be discussing that for say contra rotating configuration.

Equally we will be discussing for industrial fan design. But, at this moment we can understand we need to take care of change of incidence angle and change of deviation angle during the design stage only. Now, let us move to say next configuration.

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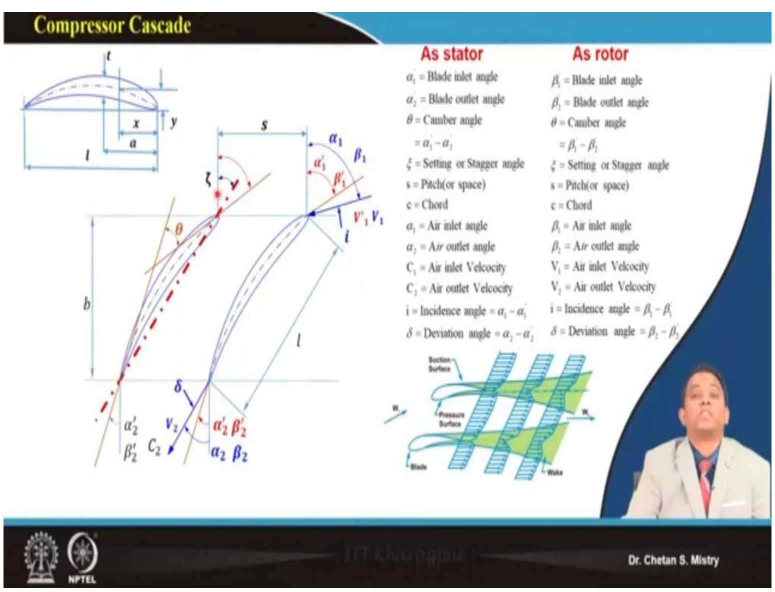

So, here if you look at, one by one we started discussing, so at the entry we have discussed about the incidence angle, at the exit we have discussed about our deviation angle. Now there is one more angle if we consider, this angle that's what we are defining as a stagger angle. So today we will be discussing what all will be the use of this stagger angle.

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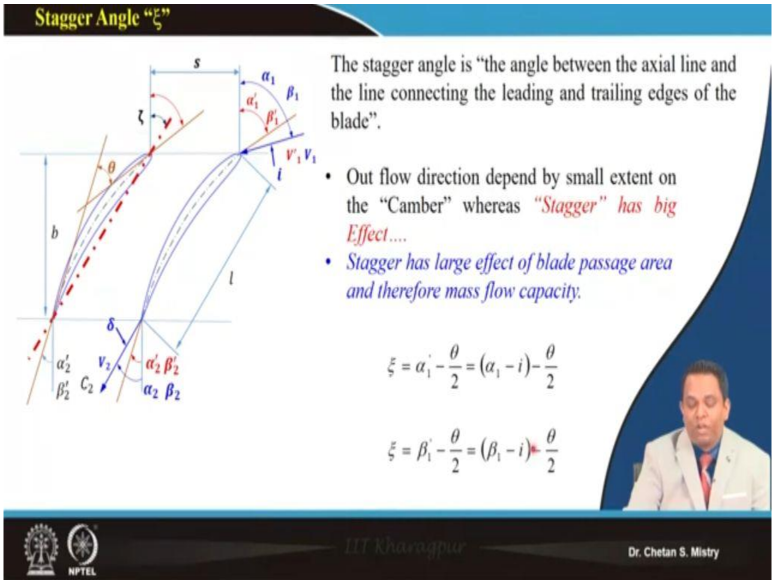

So, stagger angle if we consider, this is what is the angle that's what has been measured with the axial line; and line that's what is joining my leading edge and trailing edge. So, here if you look at, this angle what we are measuring, that's what is defined as a stagger angle, okay. So, outflow condition, that's what is mainly been depend we have seen on our say camber angle, you know; but at the same time, this stagger angle, that's what is having more impact. So, you need to realize along with what we are discussing our incidence angle, deviation angle, our camber angle; this stagger angle is also equally important. Now, this say this stagger angle, that's what it is basically talking about it has large effect on flow passage area, or blade passage area.

And that's what is taking care of your mass flow rate handling capacity, or people used to say swallowing capacity of my compressor, okay. So, if we say my stagger angle, that stagger angle it is given by α_1' (You can say this is my original angle or the blade angle now) $-\frac{\theta}{2}$. So, that's what has been taken care; you can realize; here, this is what is say negative incidence angle; it may be positive incidence angle. So here it says positive incidence. So, that is why $\alpha - i$, if I will be having negative incidence, it will be $\alpha_1 - (-i)$.

Do not get confused here, $-\frac{\theta}{2}$. There are lot of discussion, that's what is going on in order to consider this $\frac{\theta}{2}$ or $\frac{\theta}{3}$. But, conventionally for our understanding for initial stage of our calculation, we are calculating our stagger angle based on this equation, okay. So, this is what will give us idea what is happening in sense of our say stagger angle. Suppose, if we are considering for the blade of rotor, then this equation that will be changed in place of α_1; and we will be having β_1. And in line to that we will be having $(\beta_1 - i) - \left(\frac{\theta}{2}\right)$.

So, this is what is giving us idea how do we calculate our stagger angle. So, let us try to look at what all is a meaning.

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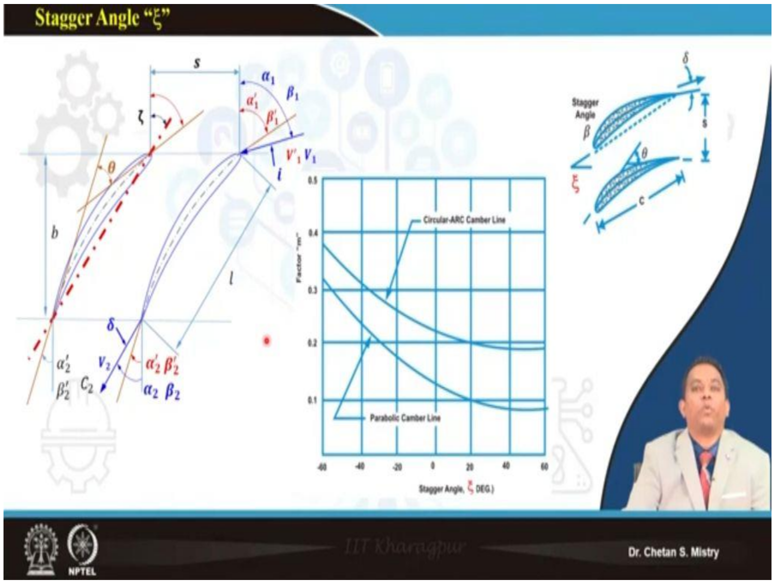

Now, as we were discussing earlier, this is what is a line that's what is representing my camber line. So, we have defined the camber line, that's what is dividing my airfoil in two equal halves, okay. We can have different kinds of camber lines. So, one it says circular arc camber line, we can have parabolic arc camber line. Here in this case, if you look at, this is what is representing the change of my stagger angle and my 'm' parameter. Remember this 'm' parameter, that's what we are using for the calculation of our deviation angle, okay. So, based on my selection of which kind of blade and based on my 'm' parameter, that's what we can go with this change of say stagger angle, okay.

It says we will be having the variation of this stagger angle to be on higher side, when we are considering say circular arc camber line, okay.

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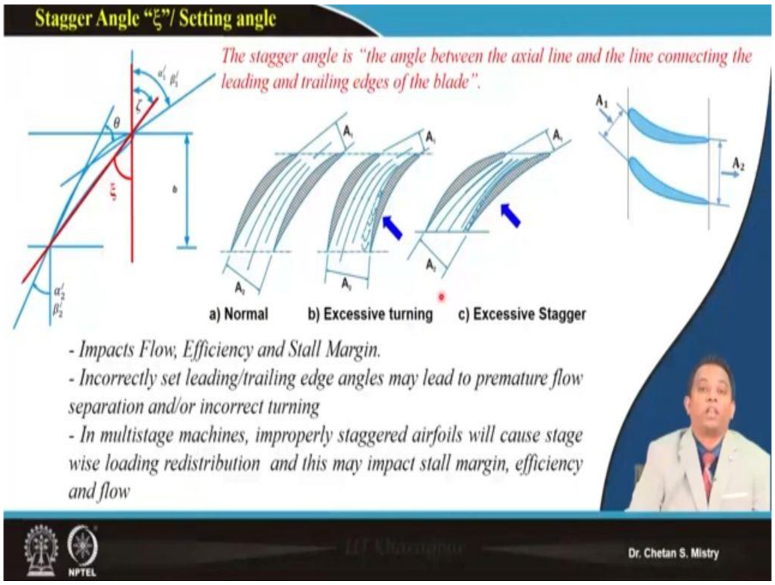

Now, let us try to look at what we need to realize in sense of stagger. People they used to say stagger angle as setting angle also, okay. So, here if you look at if you recall, this is what we have discussed earlier also. Now, if you try to recall we have discussed about our flow passage area as a defusing passage area. That's what will be having entry area and at the exit, we will be having exit area. So, within the blade passage, we are considering our passage area as a diffusing passage area. So, what we are doing? Say, this is what is my normal operating condition. This is what is absolutely working fine, where we are having our flow; that's what is following our suction surface and the pressure surface.

Now, going a little greedy, if I will be giving excessive turning to this blade, it will be giving the flow separation that's what will be happening from my suction surface. Basically, what we are doing is we are trying to increase the outlet area here; and that's what we have defined as say excessive turning. And we have realized when we are having our $\Delta\beta$ to be large, that's what will lead to my camber angle to be large. And that's what is giving the flow separation to be happened on the suction surface. That's what is giving more chances for the flow to get separate from the suction surface.

Now, here if you look at, the same configuration what we have done? We have just changed the stagger angle or the setting angle; such that, you know, we will be having our inlet area and outlet area, that's what is different. So, when we are going this kind of configuration by giving say excessive stagger angle, then also we will be having the chances for the flow to get separated from the suction surface. So, this stagger angle, that's what is very important, when we are talking in sense of what is happening on the blade surface, okay. Now, here at this moment we are discussing everything in sense of subsonic airfoils.

When we will be discussing about the transonic airfoils, we will realize this stagger angle, that's what is the main driving parameter for use of those transonic airfoils; because that's what is managing the flow between two blades, okay. So, when we will be discussing about the transonic airfoil, that time we will be touching this point again. What it says? Like this stagger angle, that's what is having impact on flow efficiency and stall margin. So, if you consider the flow that means what amount of flow, that's what is flowing through my blades or from my rotor; that's what has been set or adjusted by this stagger angle, okay.

So, we say the swallowing capacity of our compressor that's what is being driven by this stagger angle. Second, that's what is in sense of efficiency. If we consider, say when we are having this stagger to be excessive, we have say the flow separation, that's what is happening from the suction surface. That's what will lead to increase the losses; that means this is what is decreasing our efficiency. So, in order to improve the efficiency, we need to be very careful in selection of this stagger angle. Next, that's what is my stall margin; so, same is a situation. So, you know, these days people they are going a little greedy, they are looking for the stall margins to be larger.

And when we are looking for the stall margin to be larger, that's what will be managed by setting our stagger angles, okay. It says incorrectly set leading or trailing edge angle may lead to premature separation and or incorrect turning; yes, this is what we have discussed, okay. For multistage configuration, improperly staggered airfoil that will cause the stage wise loading; that's what will be getting redistributed, okay. And that may lead to impact on stall margin, efficiency and flow. So, this is what we can say it is very important parameter.

Let me point out here, suppose we are talking about say industrial fans. In industrial fans, my blades, that's what is remain same; they people they are having special kind of arrangement. What it says, the change of say…you know, setting angle or they are changing the pitch; they are doing the pitching. Basically, pitching is nothing but that's what is setting of the stagger angle. So, if we recall, when we are using our wind tunnels in order to have particular velocity at test section; mainly we are changing or we are setting our blade angles. Not blade angles, that's what is we are changing our say this stagger angle or setting angle, okay.

Now, recent developments in aero-engines, there also people they are started talking about variable pitch fans. Not much detail that's what is available in open literature, but companies they are working on those kinds of configurations. If you recall, we were discussing about the incorporation of inlet guide vanes. So, if you consider, my inlet guide vane blades are same. But, what we are doing? We are changing our angle for inlet guide vanes. When we say we are changing the angle of inlet guide vanes, remember one thing what we are doing is we are changing our stagger; and that's what was managing our mass flow rate.

And that's what is helping us to avoid the situation as and when we are looking for high mass flow rate, we will be setting our angle accordingly. When we are setting our angles or mass flow rate requirement is lower, we will be setting our angle accordingly. So, this stagger angle, that's what we can say, this is what we can arrange, okay. For that it is one.

Secondly, when we are doing our design, that time we are incorporating this stagger angle; so, do not get confused with setting angle and stagger angle that has similar meaning. But during design calculation also, we need to set our angles; and that's what we say is a stagger angle. And that stagger angle, that's what we are calculating based on what is my inflow angle α_1 or β_1, and what is my say incidence angle and what will be my camber angle, okay.

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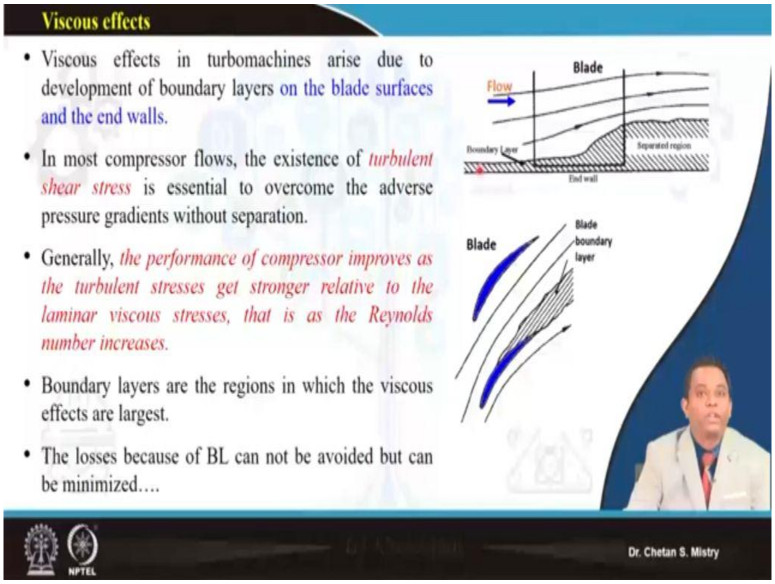

Now, having all this idea, let us try to learn something different. Say, you know, like aerodynamics, as this course define, its aerodynamic design of axial flow compressors and fans. So, your understanding of basic aerodynamics, that's what is very important. Let us talk about the viscous effect. It says the viscous effect in turbo machinery is arise because of development of growth of your boundary layer on the blade surface. If you look at this is my blade surface and even near the endwall region, okay. So, most of the compressor flow that's what we say it is a turbulence shear stress, okay; and that's what is helping in order to adhere my flow on the blade surface, even under adverse pressure gradient.

So, mean dominating flow that's what is say turbulence shear stress. If we consider laminar viscous effect, that's what is not dominating. So now, the configuration is what is happening on my blade surface, that's what is very important. And we know the effect of this viscous or say viscous effect, that's what we are defining in sense of Reynolds number. That's what is say my inertia force by viscous force and that Reynolds number, that's what we are calculating based on the chord of my blade. This is in recent literature, people they are defining this Reynolds number based on the height of my blade. That's what is having some different philosophy.

But, we can understand what is happening on my blade surface, that's what is very important. So, if we try to understand we want or we are looking for our flow to be more turbulent on our surfaces; let it be suction surface, let it be my pressure surface, we are looking for our flow to be turbulent, okay. So, boundary layers are the region where we are having this viscous effect to be maximum. We cannot say reduce that part or we can say we cannot avoid the formation of boundary layer; but we can try to minimize that part, okay.

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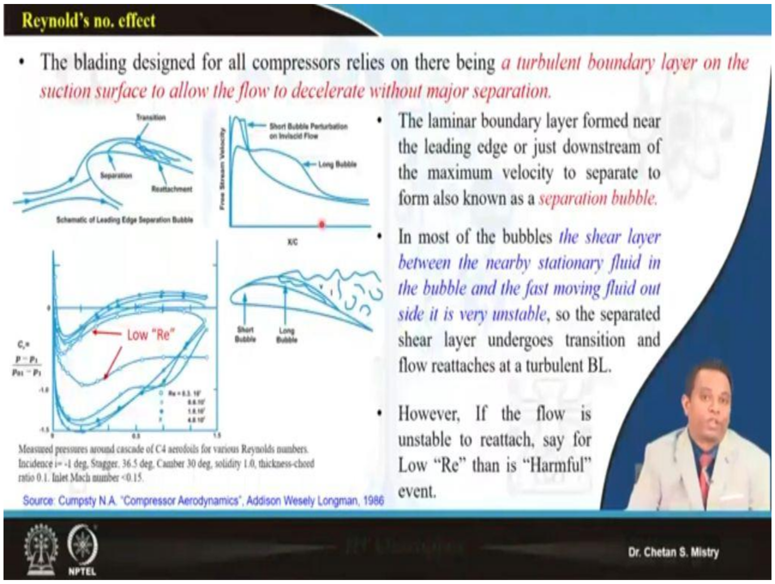

Now, if we look at here. So, Reynolds number as we have discussed, that's what is correlating our viscous effect and inertial effects. So, here in this case, if you look at, this is what is representing the C_p distribution for C4 airfoil, under different entry Reynolds number. So, here if you look at, say…we are having say… this Reynolds number in engine; that's what is in the range of $10^5\ to\ 10^6$, okay. If you configure here, say when we are having this to be lower Reynolds number, we can say that's what has direct impact on the C_p distribution. So, when we are having our Reynolds number to be higher, our C_p distribution is going higher.

That means, this is what is working as per our expectation. What is the meaning of that? When my blade is subjected to lower Reynolds number, there is a deterioration in the performance, okay. So, let us try to understand what is the meaning of that. What we have learned? Say, suppose, this is what we consider as our airfoil; and suppose if we consider my flow that's what is striking here. What we learn? We will be having initial acceleration of the flow that's what will be happening on my suction surface. And there maybe possibility of the formation of separation bubble on my suction surface at the initial stage.

So, here, this is what is forming say kind of bubble; we can say we are having shear layer inside. We will be having shear layer, that's what is moving outside, okay; and that's what will be forming say separation bubble near the leading edge. And because of presence of that, later part we will be having early transition; that's what will be happening. And on later part, we will be having our flow to be turbulent flow. So, here if you look at, this is what is representing two different shape of say laminar separation bubble. So, here if you look at, we can have, say, smaller laminar separation bubble, we can have larger separation bubble, okay.

So, that's what has been extended from 10% to almost say maybe 70% of my chord, okay. Now, when we are having this laminar separation bubble, that's what is say larger on my suction surface; that's what is impacting what is happening on my blade surface, okay. And later on, if you try to look at because of formation of large separation bubble, we will be having flow separation that's what will be happening near my trailing edge, okay. So, this is what is very important; we need to realize this part, okay.

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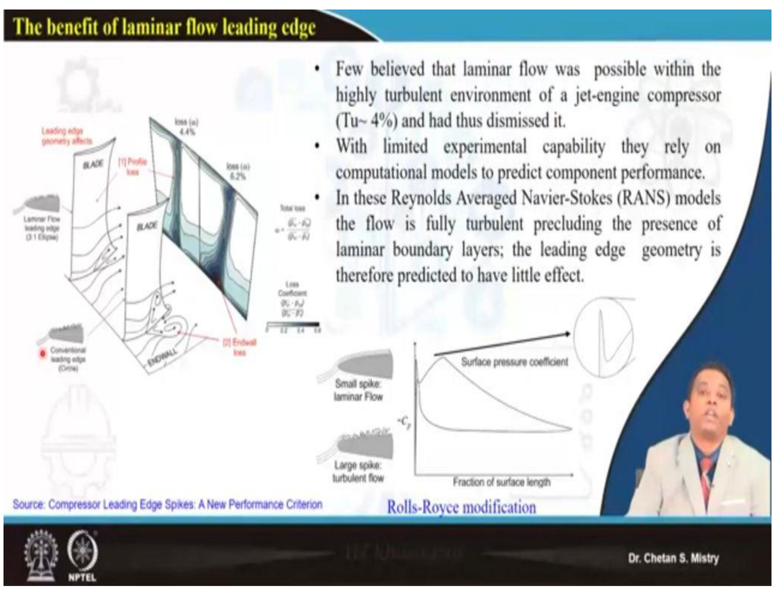

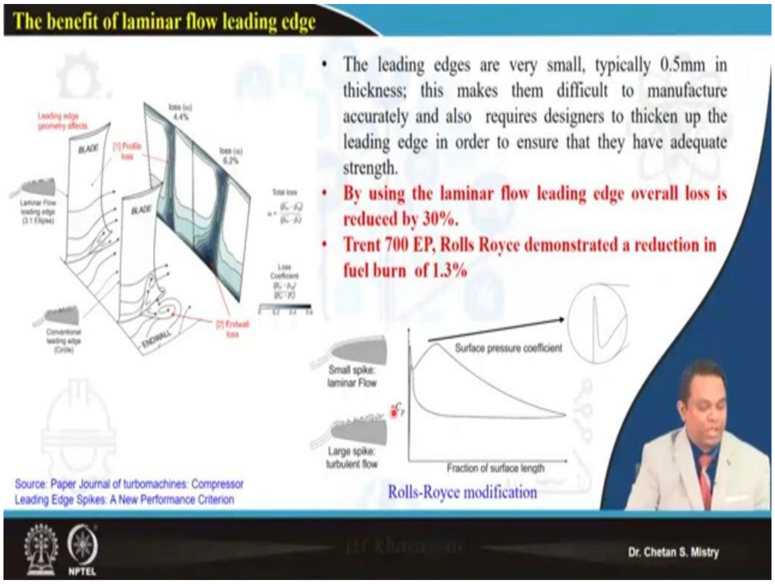

Now, here if we move, this is what is one of the work that's what has been reported by University of Cambridge; and they have worked this for Rolls-Royce. So, here if you look at, these are the blades. Now, we have understood near the hub region or near the endwall region, we will be having the formation of secondary flow in that particular region, that's what is defined as say endwall losses. So, downstream, in the down plane, if you look at this is what is representing the loss; that loss we are defining in sense of total pressure loss, it is $\frac{P_{01}-P_{02}}{\frac{1}{2}\rho V^2}$.

So, near the hub region if we look at, we are having the losses to be very high, okay; it says almost this loss it is 6.2%. Now, in order to minimize these losses, what they have done? So, here if you look at carefully, this is what is original blade that's what is having say conventional leading edge. So, that's what is having circular shape; so, here we are having circular shape, okay. Then, in order to minimize these losses, they have done their computational study; so, these results are computational results. So, they have modified the leading edge that's what is having say elliptical leading edge.

So, this leading edge is elliptical leading edge; that's what it says my flow is behaving nicely near the suction surface. And that's what will lead to reduce or minimize these endwall losses, okay. So, here we are having the losses near the hub region that's what is going to reduce, okay. And that's what it says, it is possible to have reduction in loss from 6.2% to 4.4%. So, if you try to recall, we were discussing about what is the effect of shape of my leading edge. So, here in this case if you look at, this is what is representing my conventional say leading edge; this is what is my modified leading edge.

They defined that as a laminar flow leading edge. Now, you know, like, we need to remember one thing, this computational study when we are doing, we are solving basically say RANS equation. That's what is a truncated form of full Navier-stokes equation, where we are neglecting so many parameters. And that's what is the reason why it may not be possible for us to capture what is happening near the leading edge in sense of laminar flow. We are assuming whole our flow on the blade surface is a turbulent flow, okay. So, it demands for systematic study that's what needs to be carried out on the suction surface what is happening.

Now, that's where, our cascade tunnel, that's what is coming into the picture. So, in order to study this situation, in line to what Reynolds number we are having, what we need to do is we need to select our chord accordingly. We will be discussing this point, because this chord length, that's what is very important for our design configuration also. So, in order to study what is happening on my blade surface, we will be selecting larger say chord cascade. Now, when we are having larger chord cascade, we can capture what all minute details that's what is happening on my suction surface, same way what is happening on my pressure surface.

Now, those data what we have captured using cascade tunnel, which say recent measurement techniques, maybe PIV; they can use maybe by using hot-wire anemometry with flow visualization. We will be having whole lot of data that's what will be available. Now, those data that can be used for validation for the development of new turbulence models, what we are using for our CFD analysis? Now, companies, these engine manufacturing companies, they already have their database with them; and based on that they are taking care of all these things, what is happening on the blade surface, okay.

Now, this concept what we are discussing? It says by using this, they are able to minimize the loss by say almost 30%; that's what is a big number, okay. And the same concept, that's what they have adopted for Trent 700 EP, and they have found by incorporation of this kind of leading edge, they are able to reduce the fuel burn by 1.3%. Now, this small number what you are observing, that's what we can say it is for particular one engine. There are a number of engines they are fitted with aircraft, they are flying globally. Now, if you count per year, the barrel or say fuel consumption that's what will be reducing a lot in that sense.

And that's what will be saving of maybe millions of dollar a year; and this is where we are looking for the special attention, okay. So, you can understand this is what we are looking at what is happening on the surface of our airfoil, okay.

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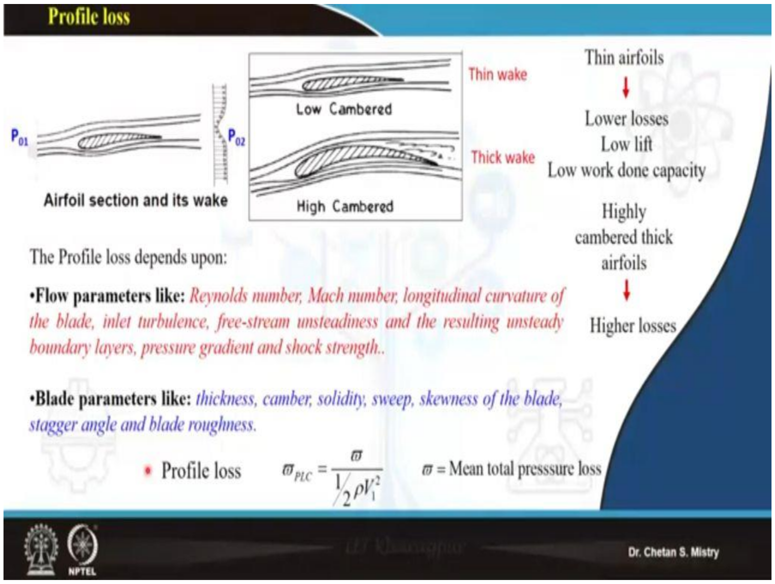

Now, let us discuss here, say…we are having other kind of configuration; we will be selecting our blades or say airfoils that maybe say…low cambered airfoil. We can have our airfoil to be say…high cambered airfoil. We can say here, my $\Delta\beta$ that's what is say lower; here my $\Delta\beta$ that's what is say larger. So, if you capture the physics at the exit, we can have thin wake that's what will be coming out. Here in this case for highly cambered airfoil, we will be having thick wake that's what will be coming out.

Now, what is happening? So, if we consider we are having say highly cambered airfoil; for that, we will be having higher losses, okay. Suppose, if I consider, we are having say thin airfoils or we can say we are having low cambered airfoil; that's what will be giving me lower losses. But, at the same time, my lift is also lower, and my work done capacity also is lower. Now, here I want to introduce the loss that's what is defined as a profile loss. So, this profile loss, that's what is defining my total pressure loss that's what is happening across my stage. Or we can say, if we are calculating across my rotor, I can calculate that across my stator, I can calculate across the stage; that's what is defined by this $P_{02} - P_{01}$, okay.

Now, this profile loss, that's what is depending on different flow parameters. So, if we say, that's what is depend on my Reynolds number, it depends on Mach number, say longitudinal curvature of my blade, inlet turbulence, free-stream unsteadiness; and, you know, it is also depending on what is my pressure gradient and the strength of my shock, okay. This profile loss what we are discussing at this moment, that's what is having relation for the future discussion; that is the reason why I have kept this here. Say, this course as we are discussing is for design.

So, we are more emphasizing on the design part, this loss, three-dimensionality, aerodynamics, all these that need to be read by you in advance, okay. If not, maybe you can go through the open literature, go through the books, what we have suggested; and that's what will be giving you idea what all losses we are talking of. It says, it is also depending on my blade parameter, because this is what is very important for our design. It says, what is my thickness of the airfoil? What is my camber angle? What is my solidity? If there is any sweep or not? The skewness of my blade, stagger angle and blade roughness.

So, all these blade parameters, that's what is affecting my profile losses, okay. So, here, we can say, we have started discussing about our stagger angle. We started discussing about what are the effects of my viscosity or the viscous losses? Then we started discussing about what is the effect of my change of leading edge on my flow physics. We started discussing about the profile losses, okay. So, with this background, we are stopping here. Thank you very much; see you in the next lecture.