Aerodynamic Design of Axial Flow Compressors & Fans
Professor Chetankumar Surreshbhai Mistry
Department of Aerospace Engineering
Indian Institute of Technology, Kharagpur
Lecture – 24
Cascade Aerodynamics (Contd.)

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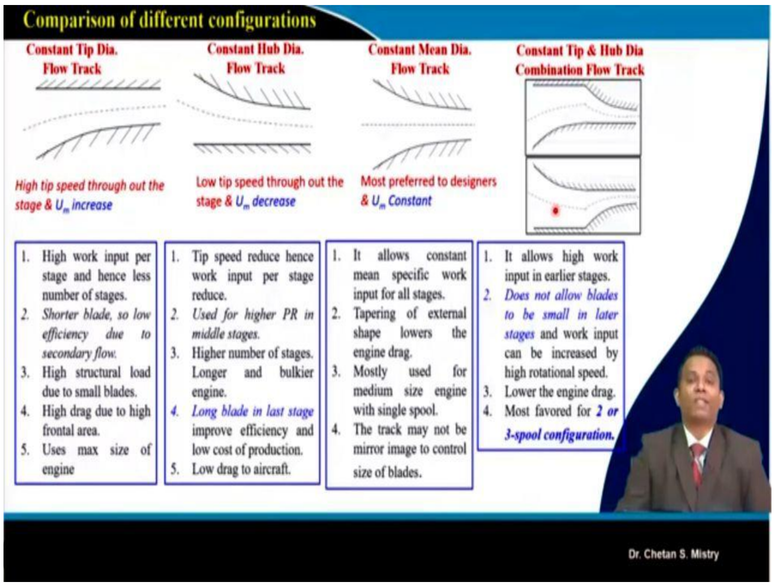

Hello, and welcome to lecture 24. In last lecture, we have started discussing different flow track configurations. And we can say, this is also a part of aerodynamic design of axial flow compressor. We were discussing about different flow tracks, we can say; we can have constant tip diameter flow track, we can have constant hub diameter flow track, we can have constant mean diameter flow track. We can have combination of constant tip and hub kind of configuration. And we realized, like, once we are decided with say…total pressure ratio required by say LP compressor or HP compressor, we need to decide with number of stages.

Once we decide with the number of stages, systematically we need to do our calculation for per stage pressure rise. And for that, at the initial stage, we will be configuring with some tracks; maybe say constant tip track, maybe constant hub track, or say…maybe say… constant mean track. So, once we are deciding with that track configuration, systematically we will do all our calculation at the exit of this stage; and then after we will be smoothing out that track. Let us recall what all we have discussed in the last session.

So, if we look at, say… constant tip kind of configuration, we realize at the initial stage, because we are having constant tip configuration, we can achieve per stage pressure rise to be large. That means in order to achieve particular pressure ratio using number of stages, then the number of stages required will be lower. If that's what is your case, that's what will be reducing the length of your engine. But, at the same time in the later stage, when we are moving on the rear side, my blade height that will be going to be reduced; if that's what is your case, that will lead to increase of your secondary losses.

And we can say, that will lead to reduce in the efficiency. If you are having say shorter blade, it will be having very high stress, that is giving mechanical constraint. And if we are using this kind of configuration, we can say, we are having drag to be very high, okay. And it uses the maximum size of the engine, that's what is available with that; that's what is we can say… it is a constant tip kind of configuration. Now, in order to mitigate what we have limitations in sense of last stage height of the blade, we are moving with say… constant hub kind of configuration. Now, in constant hub configuration, if we look at, our radius or we can say our diameter at the tip, that's what is going to reduce; that means my per stage pressure rise that's what is going to reduce.

So, in order to achieve the required pressure ratio, you may need to go with say more number of stages. But at the same time, because this is what is having tapering shape, that's what is giving benefit in sense of reduction of your drag. And what limitation we have in sense of losses and in sense of efficiency, that's what we can mitigate by going with constant hub diameter configuration. And we were discussing mostly for your high bypass ratio engines; HP spool, that's what has been designed with this kind of configurations. Then, we were discussing about the constant mean diameter configuration.

If we go with constant mean diameter, that's what is… it says… you are having per stage pressure rise you can get to be more. Under that configuration if we go, we are having the shape of our track; that's what is tapered shape, that's what is going to reduce your drag, okay. And, you know, in order to address the problem with the height of the blade, maybe in the later stages or in the rear stages, we can adjust our shape of this track. So, that's what is a flexibility we have with constant mean diameter. And, you know, this is what we can say, we can use mostly for our medium size engines, okay. And later, we have discussed about the constant tip and hub diameter kind of configuration.

And what we realized? What all problems we have, say… we are able to achieve high pressure ratio with earlier stages; the problem with my blade height that can be rectified by using constant hub diameter kind of configuration. So, you know, this is what is helping in sense of reducing our drag. So, mostly for 2-spool and 3-spool configuration, this kind of flow track, that's what is most preferred, okay. Now, this is what is giving us initial background for having our track. Now, let us move towards what exactly we are looking for; that's what is called compressor cascade.

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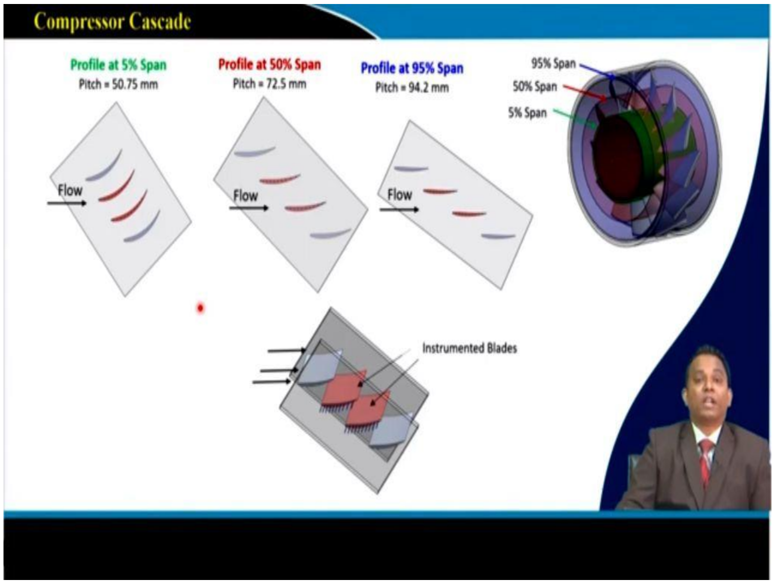

Now cascade, that's what is need to be understood thoroughly, what exactly is a meaning of cascade. Suppose, if I consider, this is what is say… my rotor; and we know this rotor throughout my span, it is comprising of number of airfoils. Suppose, if I consider say 5%, 50%, 95% of my span, if I look at these all airfoils are of different kinds. So, let me show you here. So, here if you look at, this is what is my profile at 5% span. So, you can say, when we are looking at our $\Delta\beta$; that's what is giving me this kind of curvature. This airfoil, it is a indigenous airfoil; it is individual airfoil.

If I am going here with the 50% span, you can understand when we are moving away from my hub; my radius, that's what is going to increase. And let me introduce the parameter what earlier also we have discussed, that's what is called pitch. So, pitch of this blade, that's what is defined as $\frac{2\pi r}{z}$. So, distance between these two blades if you look at, that's what is called the pitch of my blade, okay. And if you consider here, this is what is my pitch of cascade. If I am moving at 95%

span, we will be having this kind of configuration. So here, what arrow that's what is showing; it says this is what is my flow direction, okay.

Now, these airfoils if you look at, at particular station, they are arranged in a linear manner; and that is the reason why this is called linear cascade. Or you can say suppose if I will be having this as one of the circle, I will be opening that circle and put it on plane wall or say plane paper. So, if we are putting like that, we will be having this kind of arrangement; that's what is called linear cascade, okay. Now, at all stations we are having different airfoils; at all stations we are having different $\Delta\beta$, okay. So, you know, in order to select the airfoil at particular station, we need to have a data.

What data we are looking for is what will be my C_p. C_p is nothing but that's what is representing, say… pressure rising capacity for particular airfoil, when we are talking about application to say… axial flow compressor. So, what we will be doing? We will be arranging our blades in this manner. So, here if you look at, these are two blades; that's what is called instrumental blade. And if you recall, I was showing you the cascade blade in which at different spans, say suppose if you consider this is what is near say… my one wall, I am having pressure tappings; say here at the mid station, I am having pressure tapping; near the other wall, I am having pressure tappings.

So, similar kind of tappings we are having on pressure surface as well as on suction surface. So, when we will be fixing these test blades, these blades and this is what is my test section in tunnel, that tunnel it is called linear cascade tunnel. And that's what will be giving us idea about what is happening with my C_p distribution. Now, if I consider my flow that's what is entering at particular angle. Suppose, I want to check if I will be changing the angle at which my flow is striking on this blade, that also can be done.

And that's what will be giving us idea when my airfoils are working under off-design condition, what all will be the changes, okay. So, just realize, this is what is my linear cascade. So, during say… initial stage of development of axial flow compressors and axial flow turbines, people they have done a whole lot of experimentation with different kinds of airfoils. Some of them we have already discussed, they are say…subsonic airfoils, transonic airfoils; say, we have discussed about C4 airfoil, we have discussed about NACA airfoil, we have discussed about CDA airfoil, we have discussed about DCA airfoil; all those airfoils, they have been developed.

They have been developed for particular pressure rise, for having particular kinds of C_p distribution. So, these all data, they are of great importance. So, systematically people they are doing experimentation, they are making the bulk of data for particular kinds of airfoils with different angle configuration. And they are having whole lot of data with all different kinds of airfoils as and when required, they are recollecting those data; and those airfoils they are being incorporated in particular blade for particular engine development, okay. That's what is the importance of this cascade and cascade data, okay.

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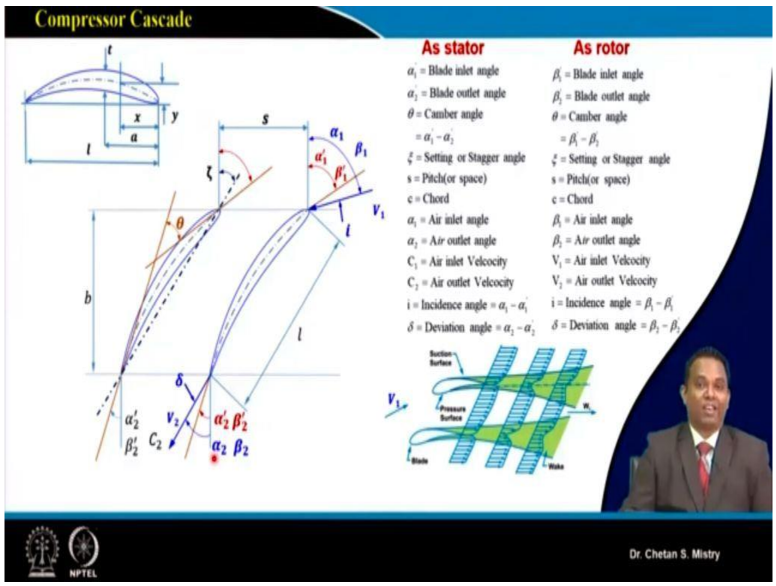

Let me show you here. So, if we consider, say…this is what we can say as one of the airfoil; we can say it is a cambered airfoil. Because, you know, it is not symmetrical, but it is cambered one. So, you can say this is what is my camber line, okay. At particular station, I am having my thickness to be maximum, this is my location where my thickness is maximum. And, here if you look at, this is what I am defining as a chord of my airfoil. Now, if you recall, the upper surface, what we are defining as my suction surface; a lower surface, that's what we are defining as pressure surface.

Now, you know, based on understanding, based on the experimental data, people have come up with different numerical schemes. They are having different equations for pressure surface, they are having different equations for the suction surface; and based on that new kinds of airfoils people they are developing, okay. So, initial start that's what is working with already standardly available airfoils; and later on, they are modifying as per the requirement. So, let us try to understand what all is our cascades, okay. So, here if you look at, these are two blades, okay; you can say two cascades; they have been arranged in a linear manner.

If I consider, this is what we can say as my camber line; that's what is dividing my blade in two equal halves. You can say, the distance between my leading edge and trailing edge that's what we are defining as chord. If I am measuring my vertical distance here, in axial direction, that's what is called axial chord. So, remember the chord and axial chord, they both are different things, okay. So, this 'b', we can say it is my axial chord. Now, if you look at, if I am measuring my distance near leading edge from one point to next coming point, and that's what we are defining as a pitch; or we can say that's what is nothing but $\frac{2\pi r}{z}$.

So, if you consider near the hub, my pitch will be smaller, my 's' will be smaller. Near my tip region, we will be having our 's' to be larger, because it is $\frac{2\pi r}{z}$, okay. So, my radius, that's what is changing; that means my pitch, it is changing. Now, if I consider, say this is my axial direction, okay; you just remember this part; again and again we are saying, we are measuring all our angle with reference to axial direction. So, we can say this is my axial direction. My flow that's what is say… this is what is angle, we can say, it is a blade inlet angle; I say this as $\alpha_1{}'$ and β_1', do not get confused here.

So, people when they are using this cascade data or when they are doing analysis for cascade data; if that cascade is of say…stator, they are putting that as α; if this cascade is of rotor, they are putting that as say β,okay. So, do not get confused here. So, it is written separately. If we are considering as a stator, then I am putting α; if we are considering for the rotor, we are considering that as a β. So, you can say, this is what is my blade inlet angle, okay. Now, here at the exit if you look at, this is my angle at the exit; that's what I am defining as say…blade outlet angle β_2', okay.

Now, if I will be drawing my tangent from say leading edge and tangent to my camber line; and from here, from trailing edge to tangent of my camber line, what angle we are getting, that angle is defined as a camber angle; this is what is very important. This is what we say as a camber angle, okay; so, this is what is my camber angle.

Now, you know, we are setting this airfoil in respect with the axial direction. So, here if I will be joining a line from leading edge to the training edge, and what angle it is making, that angle is defined as a staggered angle, okay. So, this is what is my stagger angle. Now, if you look at, what will happen? Suppose, if I consider my flow that's what is incident on my airfoil or on my cascade at certain angle, say α_1 or β_1, okay.

Do not forget this $\alpha_1{}'$ and β_1'; that's what is my blade inlet angle, and the α_1 and β_1, that's what we are defining as say air inlet angle, okay. This is what is my air inlet angle.

So, what we mean here is, you know, my blade it is been designed for particular β_1' or $\alpha_1{}'$. In spite of that, my flow that's what will be entering at angle other than $\alpha_1{}'$ and β_1'; and the difference of these two, that's what is defined as an incidence angle. This is what is an incidence angle. So, you know, if we are looking carefully, if I am putting say $\alpha_1 - \alpha_1'$, or maybe $\beta_1 - \beta_1'$; that's what is defined as incidence angle. Remember, this kind of logic you have studied for your wings also in aerodynamics; there we are defining that as angle of attack.

But for our case, when we are discussing about say…our turbo machinery, for axial flow machines or for radial machines, we are not writing that as say angle of attack; we are considering that as incidence angle. So, do not get confused with angle of attack and incidence angle. Now, here if you look at, this is what is representing my blade; and as we have discussed this is what is the velocity with which my flow is striking on my blade, okay. What will happen? We know, since my airfoil…this airfoil, it is working under adverse pressure gradient; we will be having say… flow separation that maybe happening on the suction surface.

Or, we can say there is a presence of low momentum fluid on my pressure surface; presence of low momentum fluid on my suction surface and pressure surface. So, if this is your case, if you look at, my exit velocity needs to be uniform. In spite of that, I will be getting this kind of deficit; that deficit is nothing but that's what is called wake, okay. So, in actual case what will happen? It maybe possible or it is required to come out with angle α_2' and β_2'; in spite of that, my flow will be coming out with some angle other than that of $\alpha_2'$and β_2'. That's what is say α_2 and β_2, okay.

And difference of this, that's what is called deviation angle; that's what is called deviation angle. So, this is what is very important for us when we are doing our design for axial flow machines, okay. So, incidence angle, deviation angle that's what will be coming into the picture during our design, initial stage of design. We literally need to sit down and we need to do the calculation of incidence angle and deviation angle. So, whole this week what we have defined, we will be dedicating that for cascade mechanics, okay; or say… we can say, that's what is on cascades study, okay.

Now, you know, like we have introduced now new angles. Other than α, β. We are now introduced with say angle θ; that's what we have defined as a camber angle. We have introduced angle ζ, that is nothing but that's what is my stagger angle. We have introduced angle that's what is my incidence angle (i); we have introduced new angle that's what is my deviation angle δ, okay. So, we will be discussing in detail for all these aspects.

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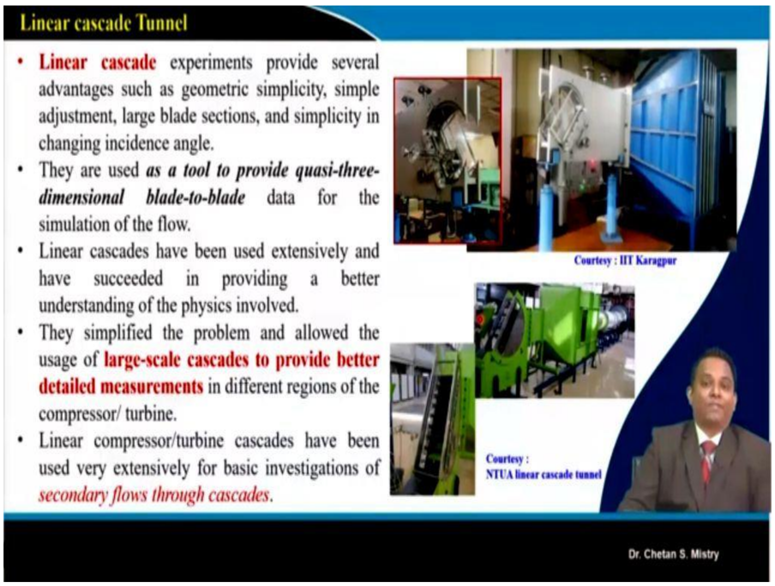

Now, coming again; so, you know, like the question is what all are the uses of our cascade tunnels? So, here if you look at, this is what is cascade tunnel - linear cascade tunnel; that's what is available at IIT Kharagpur. And here if you look at, we can put our blades between these two test sections. And we will be having the measurements of inlet angle, measurement of outlet angle, what will be the distribution of C_p; all those things that's what we can measure, okay. Downside if you look at, that's what is say NTUA linear cascade tunnel; compared to this cascade tunnel, the size of test section that's what is larger, okay. So, you know, we will be realizing what all are the importance of having larger size; but you can realize here, say for low speed testing, this cascade tunnels are of great importance, okay.

So, what it says? That's what is, say…it provides several advantages such as…geometrical simplicity, because my… my airfoil, it is say same airfoil; that's what is we can, we are extruding for a particular span. You can have simple adjustment. Here if you look at, we are having the knob; by tilting that knob, we are able to change the angle of incidence to my cascade, okay. And you can say, we can go with the large blade sections. So, here if you look at, this is what is providing the large blade section. Now, let me tell you, as we have discussed, on the suction surface of my compressor blade, we are having all three flow phenomena that’s what is happening; means laminar flow, transition flow and turbulent flow.

Now, in order to have systematic study of that kind of flow, where exactly your transition is happening, how my flow is behaving on suction surface; you can imagine, the size of my blade required that will be larger. Then, only we can go with the detail measurement of each phenomena happening on the surface, okay. So, we can say, by using this linear cascade, we can provide the quasi-three-dimensional blade-to-blade data. Now, many code development companies - they are looking for validation of those codes; and they are looking for, you know, dedicated data, that’s what is available from cascade tunnels. So, this is what is providing the helping hand to them, okay.

So, this is what is also been helpful in order to understand what is happening in sense of flow physics within the passage, okay. We are, since we are having the largest scale of tunnel, we are able to do systematic measurement by available instrumentation that is benefit. Here if you look at, say… this is what is required low capacity blower. But, at the same time if my size of this tunnel, that’s what is of test section is increasing, my blower capacity or compressor required capacity, that also will be increasing; and it will be an expensive affair, I will show you. This linear cascade, that is also been used for studying the secondary flow field.

So, those who already have done the course on aerodynamics of turbo machinery, they will understand that part. Since, this is beyond the scope; but you can understand, secondary flow is nothing but that’s what lead to losses. And when we are having this kind of flow, that’s what is happening between the passage; that will lead to increase the losses and decreases the efficiency. So, the thing is we will be studying what is happening in sense of secondary flow, and we will try to mitigate that by having systematic design of these airfoils. That is also a kind of study we can go with.

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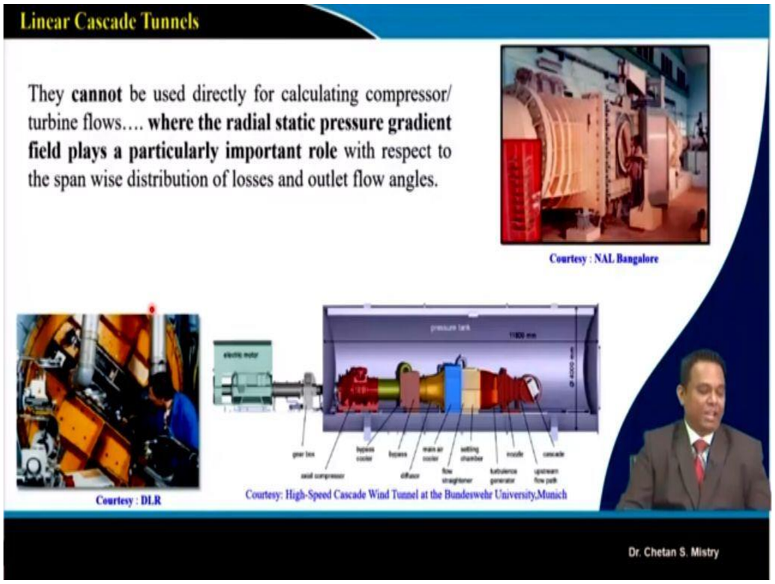

Now, here if you look at, say…we are having subsonic airfoils, we can test by using subsonic cascade tunnels. In line to that we are having say transonic. So, this is what is a trisonic tunnel that’s what is available at NAL Bangalore. And here if you look at, these are the airfoils, that’s what they are testing. So, they are transonic airfoils; they are testing there, okay. This is what is one of the cascade tunnel, linear cascade tunnel available at DLR for transonic airfoils testing, this is what is a recent development at Munich. And you can understand, this is required large capacity of my flow, it is required large capacity of my pressure ratio.

So, they have used a 3-stage axial flow compressor for this testing, okay. Now, the problem with this linear cascade tunnel or we can say the limitation is we are not considering the effect of variation of my static pressure along the span. So, you can say… my radial pressure gradient, that’s what is we are omitting here. And that is the reason why many times this data, that cannot straightway be applicable for the blades. Let me tell you, it is straightway applicable for airfoil - particular section of airfoil, not exactly applicable for blade; blade and airfoil that you must understand, they both the things are different in that sense.

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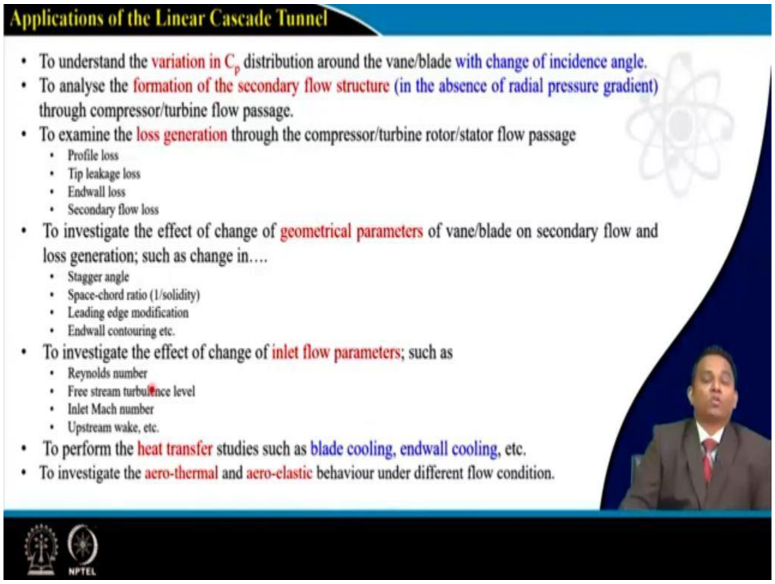

Now, these are some of the application as we have discussed for linear cascade tunnel. We can say, we can study what is the variation of C_p with the change of incidence angle because that's what is very important. Suppose, if I am selecting particular airfoil, and that airfoil I am putting at some station in my blade; so, what will be the effect of change of incidence, that's what is very important. So, based on the available data, people they are selecting particular kinds of airfoil, okay. We can analyze what is happening in sense of my secondary flow structure.

Here, we are neglecting the radial pressure gradient. We can examine the different kinds of loss generation; it may be say…profile loss, tip leakage loss, endwall loss, secondary losses. So, this loss mechanism also can be understand and study by using these linear cascade tunnel. Now, in order to study the effect of change of different geometrical parameter; very soon we will be discussing about this, okay. So, what will be the change? So, you can realize, if I will be making my rotor of different configurations, and if I will be doing my testing, it will be very expensive affair.

Rather, in order to have quick solution or estimation, people they are studying this variation of geometrical parameters like stagger angle, solidity change, leading edge modification, endwall contouring; those all things can be done by using this linear cascade tunnel, okay. We can also investigate the effect of inflow parameters, like change of Reynolds number, maybe free stream turbulence, inlet Mach number, upstream wake effect, all those things that's what is, you know, affecting my performance of axial flow compressor. So, before making design, people they are doing all these kind of study by using linear cascade tunnel.

This linear cascade tunnel equally we can use even for turbine. So, for cooling study, endwall cooling; you can use this cascade tunnel. These days people they have started exploring, say aero-mechanical or aero-elastic study using this cascade tunnels. So, this is what is all with the linear cascade tunnel. So, books, they are discussing about the linear cascade tunnel, but in limited edition; since this is a dedicated course, though it is for design, but this is what is very important. As a designer, how you will be using this data and from where this data is coming; that's what need to be realized and understood by you, okay.

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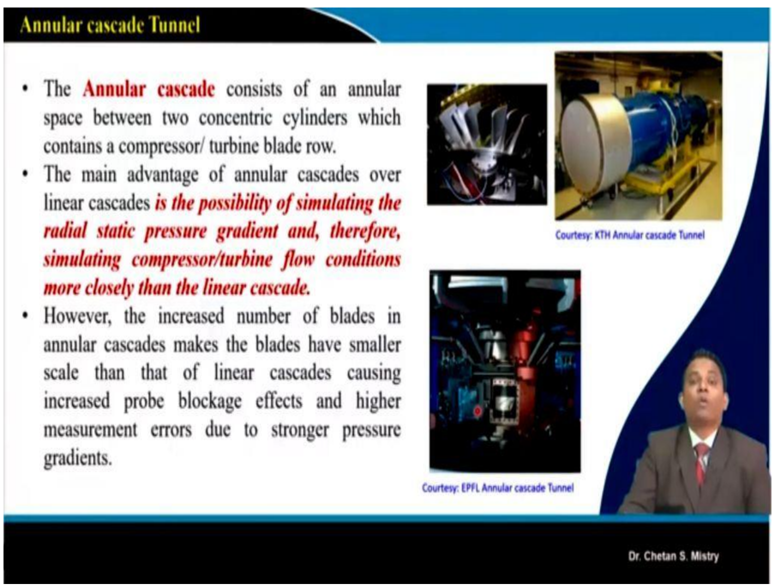

Now, there is other possibility, people they are moving with, that's what is called annular cascade tunnel. So, you can say, we will be making full scale. So, here if you look at, this is what is with KTH annular cascade tunnel, okay. So, you can make all your blades, you can make your whole passage, and you can do the simulation, or you can do the experimentation for that. But, just realize, when we are moving, suppose say if I am doing my testing for say… LP compressor, you can realize the numbers of blades for those LP compressors are more, diameter is more; and in order to do this say… the testing, we need to have whole lot of power, that's what is required. And, that's what is one of the limitation.

Now, in order to address this limitation, people will say… just reduce the size or do scaling of your blade. When I will be doing the scaling of the blade, the measuring instruments also need to be reduced in the size. Because, if I will be using say larger dimension instrumentation, that's what will be having blockage effect; that's what will not give what we are expecting. So, this is what is the people they are using for aero-elastic study, people they have used this, say for annular tunnel for say… heat transfer study. So, this is what is the flow visualization, what they are doing, what is happening near the tip region.

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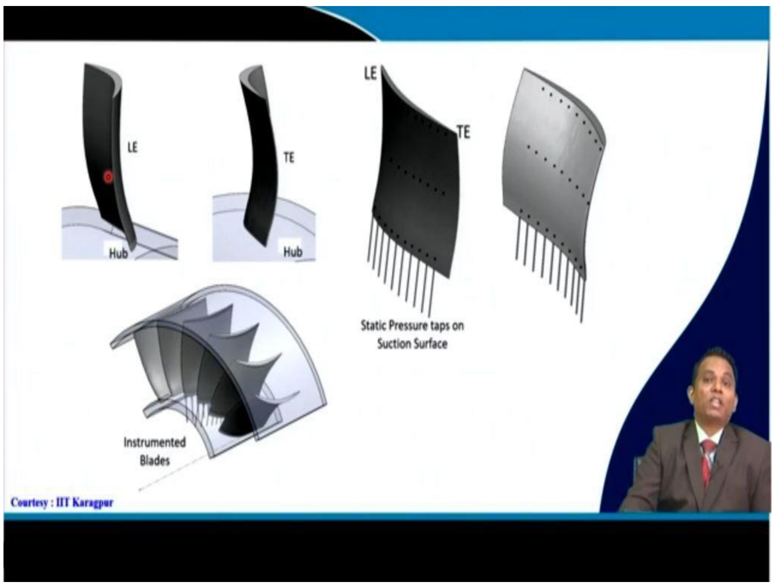

Now, here if you look at, say…you know, this is what are the blades, what we were discussing about say… tandem bladed axial flow compressor, where we have discussed we are having our blade; that's what is a three-dimensional blade. Now, if this is what is a three-dimensional blade and if we want to realize; we want to analyze what is happening with my flow physics, we need to go for the testing. And for that testing, I cannot go with the linear cascade tunnel. I literally need to go with say annular cascade tunnel. When I say, we are going with annular cascade tunnel, we have discussed, based on my power requirement, based on my dimensions; we are having a whole lot of limitations.

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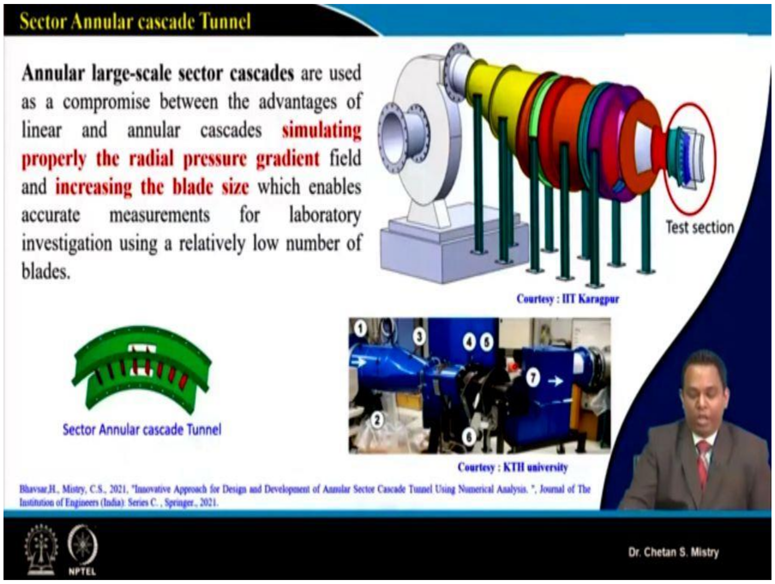

So, in order to avoid that kind of situation, people they found with the solution. That's what is called sector annular cascade tunnel, okay. In which, we will be having say limited number of blades; that's what we will be testing with, okay. And the working condition, that's what will be in line to what we are expecting. The flexibility here is we can do geometrical scaling. If we are looking for detail flow physics, we can increase or decrease the size or height of the blade or maybe the aspect ratio of the blade; and we can do testing for that. Such sector annular cascade tunnel, that's what has been available at IIT Kharagpur. So, this is what is a sector annular cascade tunnel that's what is available at IIT Kharagpur.

And the beauty of this setup, that's what is we are able to do our testing at equivalent to engine Reynolds number, and equivalent to engine Mach number. So, presently what nozzle we are having, say…at the exit of nozzle we are able to achieve Mach 0.6, okay. And if we want to go with say slightly higher Mach number or say lower Mach number, as per the expectation we need to replace this nozzle with the new nozzle; and that's what will serve the purpose. So, now this is what is giving us flexibility to study all three-dimensionality effect, okay. So, this kind of facility, that's what is unique facilities, okay.

So, similar to this at KTH, they are having their facility in order to do testing for HP turbine; and this is their sector annular cascade tunnel, okay.

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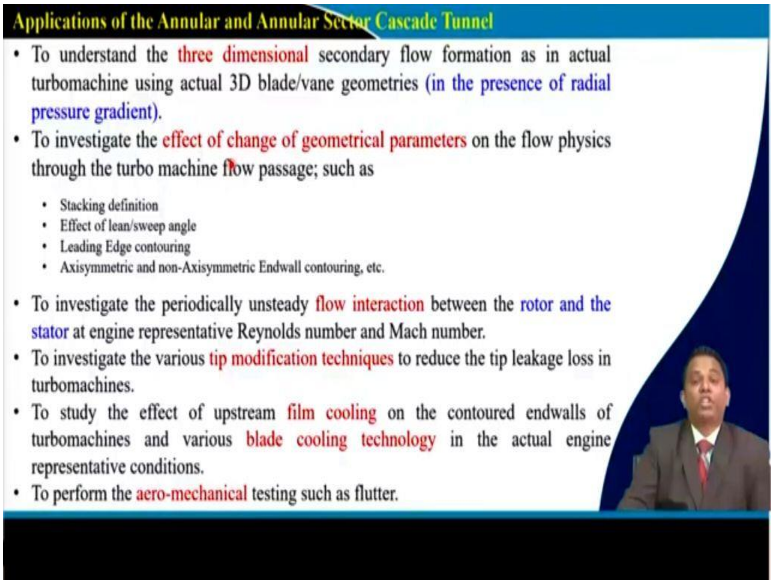

Now, when we say… what are the applications of this annular or sector annular cascade tunnel; we are looking for three-dimensional effects. When we say we are looking for three-dimensional effect, we are looking for what is happening with say application of pressure gradient, okay. So, we can have study of effect of change of geometrical parameter. As I was showing; these days, people they are making blades, compressor blades, turbine blades of funny looking. They are having highly three-dimensional shape. In order to do that kind of testing, this is a tunnel we can use. We can say, we can study a stacking definition, effect of lean and sweep, we will discuss all these things; leading edge contouring, axisymmetric or non-axisymmetric endwall contouring.

So, where we are looking for the flow three-dimensionality, we want to study experimentally; that time we are using annular tunnel or sector annular cascade tunnel. So, we can investigate what is flow interaction, what is the effect of upcoming wake from the rotor to the stator that we can go with, we can study the tip shape modification, okay; we can go with the cooling study; we can also do aero-mechanical study. So, in overall, if we look at, these cascade tunnels are of great importance. So, let us… let us say, what all we have discussed in this lecture? We have started with configuring what we say as a cascade or compressor cascade.

And we have introduced new flow angles which we say as a camber angle, stagger angle, incidence angle and deviation angle. Then, we started discussing about say linear cascade tunnel; we started discussing about say annular cascade tunnel, sector annular cascade tunnel. What all are the applications of these tunnels, okay, and how this data that will be used for our purpose; that's what we will be discussing in next lecture. So, thank you very much for your kind attention.