Aerodynamic Design of Axial Flow Compressors and Fans

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Lecture 03

Introduction (Contd.)

Hello, and welcome to lecture 3 for the course on Aerodynamic Design of Axial Flow Compressors and Fans.

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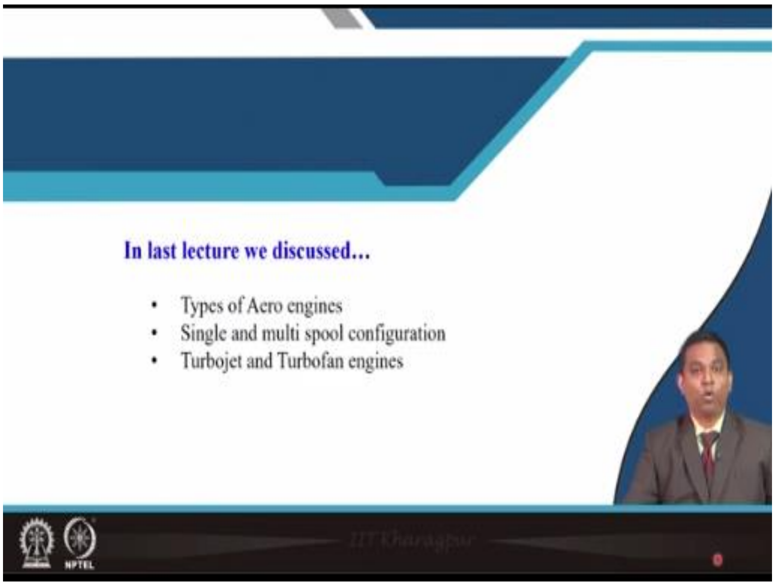

In last lecture, we have discussed about different types of aero engines in which we have taken brief description about different engines. That's what has given you idea about what all are the application of gas turbine engines for aero application. We have discussed about the single spool configuration, we have discussed about the multi spool configuration. Understand the thing like there are having the special requirement. We are having different constraints with the single spool configuration, and that is the reason why we are moving with say, multi spool configuration.

You may be aware of say… performance map of my compressor, where we have discussed about say… when the compressor that's what is rotating at the low speed, then there are chances for my front stages to get stall or it will go under surge. Same way when it is operating at the high speed, my rear stages that will be going under the surge condition. So, in order to meet the requirement for say… wider operating range, people, they are moving with the multi spool configuration.

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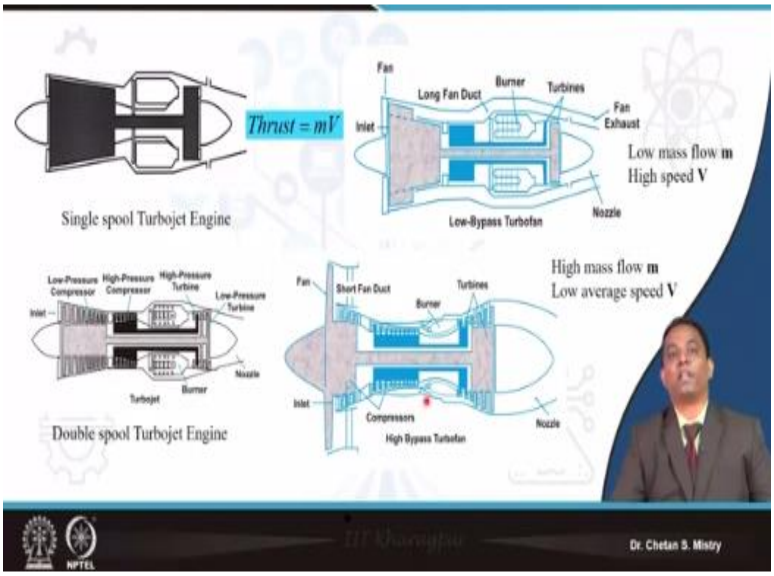

Now, we have seen this configuration of the single spool turbojet engine, double spool turbojet engine, high bypass ratio turbofan engine; we have seen low bypass ratio turbofan engine. Now, let us move towards, say… high bypass turbofan engine. So, recent trend for the use of these aero engines, the high bypass ratio engine is a major contributor; because we can say, we are having wide range of application for say your commercial aircrafts, okay!

With the increase of number of passengers, the requirement for the aircraft, its increase; with increase of number of aircraft, we are looking for more engines, but there is a global competitive market amongst these airline companies. That is the reason why they are looking for most efficient engines. And this is what is one of the priority for the future requirement of commercial Aircrafts.

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Now, here if you look at, these are the big size fan, which are being used for turbofan engine. These fans are from Rolls Royce engines. If you look at here, this fan, what we are talking of that fan, it is connected with all blades. They are connected with the fence. This fence that's what is having the special application, like this is what is a taller size blade, and we can understand this blade that's what has been fixed on the hub. And this is what is acting like a cantilever beam.

Now, if you look at when I am having my inflow condition, say… we are having say… different kind of inflow condition; it may be say… smooth flow, it may be say… your distorted flow. Distorted flow, I mean, there is a variation in pressure, temperature, total pressure; there is a formation of wake that is what will be striking, atmospheric turbulence that will be going inside the engine. All these things, that's what is creating the disturbance of the floor that's what is going inside.

And since this is what is a taller blade, we discuss these blades, they are made up of airfoil shape. So, when I say Airfoil shape, it will be having its own differential pressure on pressure side, as well as on the suction side. And because of this differential pressure, there may be chances there that there will be failure of this blade, or maybe it will be having the flutter of the blade.

And in order to avoid this kind of problem, for say high aspect ratio blade, or for say turbofan engine fan blade, there are using these fans. Now when I am incorporating these fans, that's what is having some aerodynamic penalty, okay! So earlier engines, when we are discussing, say… during nineties, people, they used to use design of this kind because high bypass ratio engine, as we have discussed, that's what is having higher thermal propulsive efficiency.

Now, on this side if you look at, these are the recent turbofan engine blades - fan blades, that's what is having a special kind of shape! Just look at carefully! This is what is having highly three-dimensional blade, okay! So, near the hub region, it is having some kind of design configuration, on the top side - towards the shroud if you look at, this is what is having say different kind of configuration.

Let me show you here, so, this is what is one of the blade; that's what is been provided by this Rolls Royce, okay. And, here if you look at, say… up to some 50 percent of my span of this blade, this leading edge, that's what is having, say… circular shape or elliptical shape and they are thicker. Now, if you look at on the top side, this blade, that's what is having, say… thinner kind of configuration.

So, this particular section we are defining as a leading edge. So, the leading edge of my turbofan blade that's what is having say… elliptical or circular shape up to initial span and then I will be having sharp leading edge. This sharp leading edge, that's what is because it has to handle the transonic flow, in the sense, the formation of my shock.

So, this blade that's what will be handling this shock. So, that shock will be standing at the leading edge. And that's what is a special kind of design. And this is what is our most recent development that is what these aero engines they are doing at this moment, okay. Here, if you look at earlier, they were having number of blades. This blade may be in the size of say… 1 meter, 0.8 meter; it depends on what is a bypass ratio, okay.

And, you can understand if I will be taking one of the blade, that's what is having its own weight. Suppose I am making that blade from metal, okay. And such number of blades that's what will be increasing the overall weight of my fan. Now, in order to avoid this kind of situation, people they move with the composite configuration. So, Rolls Royce is a company, who has initially started with the development of this fans using composite structure.

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Now, this is what is a parallel configuration, you can see for GE engine. They were also having the fans that's what is in order to provide the equal spacing between the blades and that's what is handling the problem, what we are discussing in sense of structure. Later on, they have developed the three-dimensional blading, okay. Here if you look at, this is what is one of the GE engine blade.

Here also, we are having say GE GenX turbofan. These are the developments, you can see, this is what is with CF 60, this is what is with GE 90, and this is what is most recent engine that's what is GenX, okay. So, all these blades, as I discussed, that's what is having its own weight. And in order to address that, people, they are using carbon composite; along with the leading edge, that's what is made up of your metal, okay.

So, this course has mainly been focusing on the aerodynamic aspects. We will not be discussing details about the structure and we will not be covering anything in sense of aero elasticity. These problems are the major problem when we are talking about say… our axial flow fan and compressor, but because of our constraint with the time and content, we will be focusing more on aerodynamic design, okay.

Those who are interested can move forward with the understanding of the structural part. That's what is called aero elasticity of these blades. That is also one of the challenging area. So, based on your understanding of your aerodynamics, you can move forward with the structural part or those who are having the background of structural, they can move with the aerodynamic design. And that combination is rare. And these days industries, they are looking for such combination. So, this is what is giving you hint in sense of in what direction you need to plan your activity, okay.

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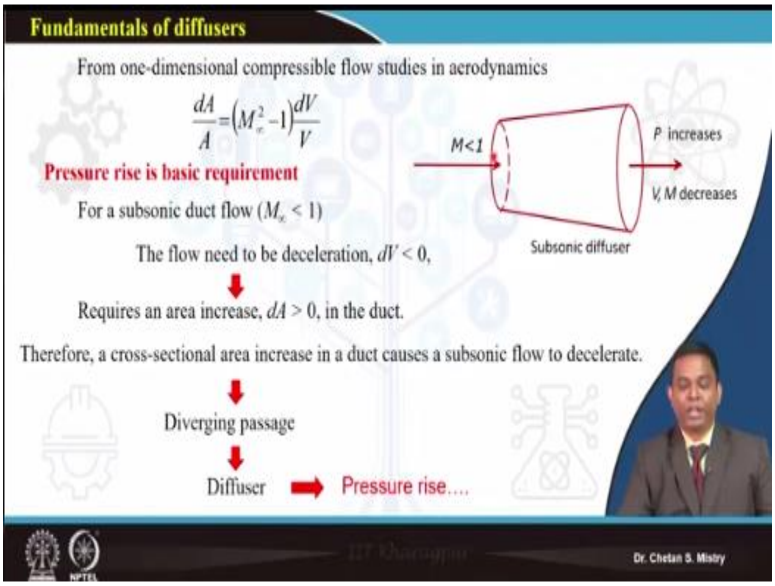

Now, let us start with the fundamentals of your diffuser, okay. What we know, we have our one-dimensional compressible flow, and for that, we have derived the equation based on my continuity equation. It says my change of area, it is a function of Mark number, and this is what is a function of change of velocity.

Now, let me consider, suppose say I am having subsonic flow. If that subsonic flow, that's what is entering inside my duct; my expectation it is to rise the pressure at the exit. So, you can say, at the exit I am looking for the rise of pressure. Suppose I am having my flow to be subsonic, so, this term, if you consider, this is what is my positive term. And here if you look at, this $\frac{dV}{V}$, you can say, I am looking for increase of pressure, that means I need to decrease my velocity.

$$\frac{dA}{A} = (M_{\infty}^{2} - 1)\frac{dV}{V}$$

So, what it says, I am looking for, say… the rise of pressure and that's what is indicating my $\frac{dA}{A}$ should be increasing. So, that is what if I am putting, it says, this is what is giving you the shape where my inlet diameter or my inlet passage area that's what is smaller and my exit diameter that's what is larger. Now this shape, that's what is aerodynamically people used to say as a diverging passage, okay! This shape, it is known as say… diffuser.

So, basically what we say, we are looking for increase of pressure in our compressor; we can say, we are diffusing our flow, okay. So, do not get confused with the terminology of rise of pressure or diffusion of my flow, okay. So, basically with this fundamental, we are having some idea. If I will be having my flow to be subsonic, in order to increase my pressure, I am looking for the passage area, that passage area is of diffuser shape.

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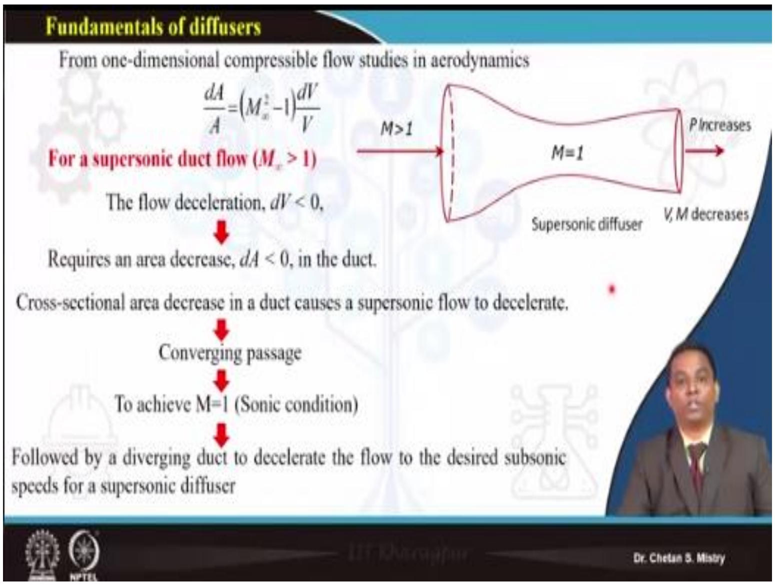

Now you say, Sir, let us move with the next requirement. That's what is say, when I will be having my flow area that's what is say… supersonic flow. So, similar in line to what we have discussed my area ratio that is what I am putting it as $(M_\infty^2 - 1)\frac{dV}{V}$. Now, for the supersonic flow, I am looking for the diffusion to happen.

$$\frac{dA}{A} = (M_\infty^2 - 1)\frac{dV}{V}$$

Now from this equation if you look at, since my flow is supersonic flow, this term, that is what will be coming negative term. And our requirement, it is for compressing the flow. That means my $\frac{dV}{V}$ also will be coming negative, okay. So, here in this case, this is what it says, my passage area for supersonic flow, that is what will be giving me that decreasing area kind of configuration, okay. So, here in this case, you say, when my flow is a supersonic flow, and if I am looking for the diffusion of my flow, I need to have my passage as a converging passage.

Now, this converging passage, we have studied in our guest dynamics; what it says, that is what will be subjected to thermal chocking. So, you know, I will be having my diffusion of flow or say deceleration of flow from supersonic flow to $M_\infty = 1$ condition. So, this is what is a region, I say, this is what is my thermal chocking region. So, further deceleration of flow that's what is not possible for my supersonic flow.

Now, in order to have that kind of configuration, I need to follow with say further diverging passage, okay. So, you can say, now further deceleration of my flow from Mach, $M_\infty = 1$ towards the subsonic flow that's what is happening with my diffusing passage, okay. So, here at the exit, I will be having my increase of pressure, I will be having my decrease of velocity or my decrease of say… Mach number. This is what we are defining as supersonic diffuser.

So, you know, with fundamentals what all we have learned in our gas dynamics, we will try to understand, we are looking for some devices that's what has been used for raising of the pressure. And this raising of the pressure for subsonic flow, we are looking for the diffusing passage that's what is having diverging shape. We are looking for supersonic flow in which my passage area that will be decreasing initially, and that will be followed by say… increasing area that is what we say… converging diverging kind of diffusers, okay.

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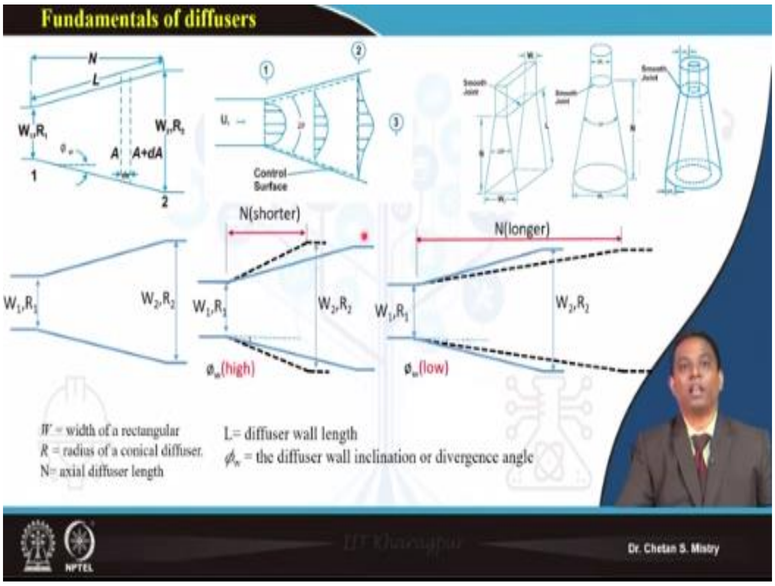

Now, let us try to understand what is application of what all we are learning here or what all we are discussing here. So, this is what you can understand, we are having one diffusing passage. So, you can say, this is what is one of the diffuser that may be of rectangular shape, it may be circular shape. That is the reason why dimensional geometry that's what is say, W_1 and R_1. That will be having certain amount of length, so, this is what is representing the length of my diffuser. This is what is my exit dimension, we can say, that may be R_2 or W_2.

Now, this diffusing passage or diverging shape, we are having certain angle with the wall; that's what is defined as a diffuser angle. So, you can say, this is what is my diffuser angle. Now, based on our fundamentals of fluid mechanics, here if you look at, suppose if I consider my flow that's what is entering inside my diffuser; that's what is a fully developed flow! So, this is what is representing the profile of fully developed flow.

Now, what is happening, if I am moving further downside, the shape of my profile - velocity profile, that's what is changing. Now, you know, near these two walls, if you look at these two walls, I will be having this profile that's what is changing, and it is deforming. It says my velocity is going to be, say… 0, near the end-wall region. And in the center, I will be having the flow to be having say… uniform velocity.

Now, if I will be putting my velocity triangle further down, I will be having different kind of configuration. So, this is what is one of the application, you say. Now, you know, like we will be looking for some kind of configuration, say… people, they will be going very choosy. They will say, unnecessarily why do we increase the length of this duct? So, they will say, let me reduce the length of my duct, say… this is what is shorter duct. And if you look at for this shorter duct, you will be having my divergence angle that's what is coming to be higher, okay.

So, you know, like, without understanding of your aerodynamics, if you will started thinking of, yes, this is what is one of the possibility. We will be discussing what is that. Next configuration; it says I am having sufficient amount of length that's what is available. So, let me go with say… longer size of duct. So, this is what is say… my longer size of duct, okay. So, this is what is my longer size. And if you look at I am having my angle, that is what is say… lower.

Now for all these three configurations, if you look at carefully, that's what is having specific meaning, that's what is having specific application, okay. So, let us try to understand what is happening within this flow passage. So, this is what we say in sense of my application, let us say.

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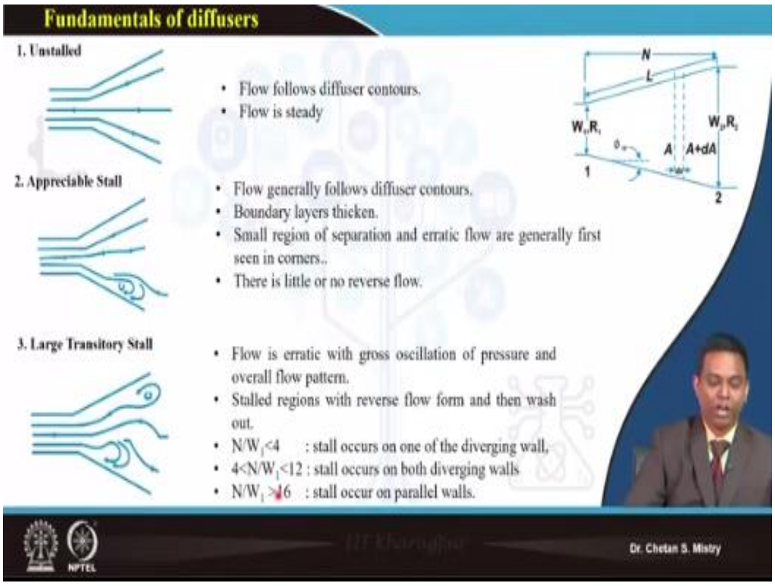

So here, if you look at, this is what is representing my streamlines; these streamlines, they are following the curvature of my diffusing duct. You can say, my flow is more uniform and steady in sense. So, we can say, this is what is, say… un-stalled kind of configuration. So, for most of the application, for many application, as aerodynamist, we are looking for this kind of configuration in which we are having this un-stalled condition, okay.

Now, you know, like, as we discussed, we will be having the change of dimension for my diffusing passage. And what it will be doing, if you look at carefully, from one of the wall, I will be having the formation of Eddie or flow separation that's what is happening. That's what is giving thicker boundary layer, okay, and that's what is giving erratic flow in that particular region. There may be little or say… reversal of the flow that's what is happening in that region. That's what I am putting that as say… appreciable stall, okay!

Now, you know, like if I will be going very choosy and if I will be changing my dimension, so here if you look at, maybe I will be putting larger divergence angle, what will happen? My flow will be having separation to be taking place from both the walls, okay! So, you know, this is what is very erratic flow. You will be having oscillation operation and my overall flow pattern that's what is getting disturbed.

So, in overall, if you look at, it says, when you are having your $\frac{N}{W_1}$. So, here if you look at, this is what is my length of the duct and this is what is my entry dimension. It says, if this is what is less than 4 ($\frac{N}{W_1} < 4$). So, I will be having my flow separation that will be happening from one of the wall, okay. If I will be changing that, say… in the range of 4 to 12, it says I will be having my separation of the flow that will be happening from both the walls, okay!

Now, if I will be going very choosy, and if I will be putting that to be say… more than 16, then you will be having other kind of flow structure. Let us look at what is that flow structure!

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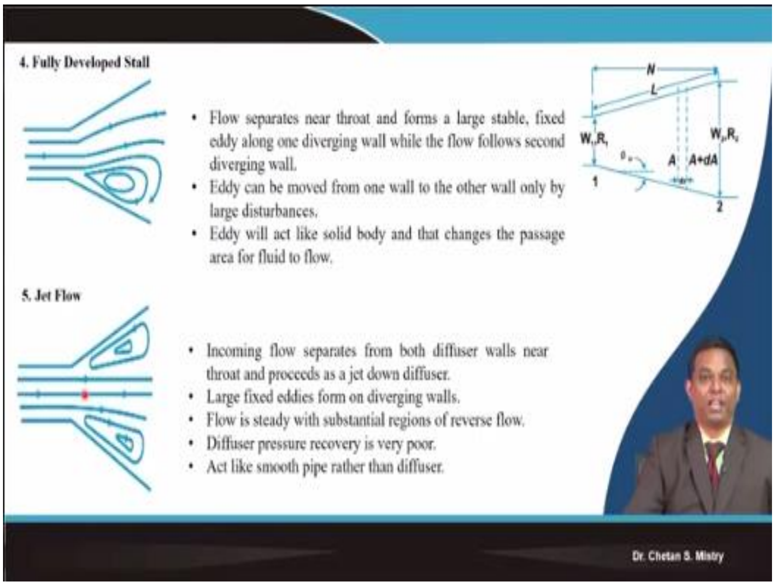

So, here if you look at, what is happening, I will be having my flow that's what will be getting separated from the one of the wall, and that's what is giving the flow reversal. So, you can say, this is what is a region that's what is making Eddy, okay. You can say, there is a low momentum fluid that's what is present in that particular region. So, if I consider low momentum fluid, I can say, in that particular region my velocity will be nearly 0.

So, this particular region that will be acting like a solid wall. So, what will happen? My flow will be getting deflected towards the other wall. And if this is what is your case, we will not be getting what pressure ratio we are expecting or what pressure rise we are expecting at the exit. So, that's what is called fully developed stall, okay. There may be chances you will be going very greedy and for going to greediness, it may happen you will be having two such kind of bubbles; that is what will be forming near your end wall region, okay, near your diffuser wall region.

Now what will happen? This is what is acting like a wall for both the wall side. And that's what will be giving you nearly jet kind of configuration or constant area configuration. What we are looking for here? We are looking for rising of pressure means we want to diffuse our flow. A rather going for diffusion, what is happening, here we are accelerating our flow, okay! So, this is what is very important when we are discussing our understanding, for say… diffusion process, okay.

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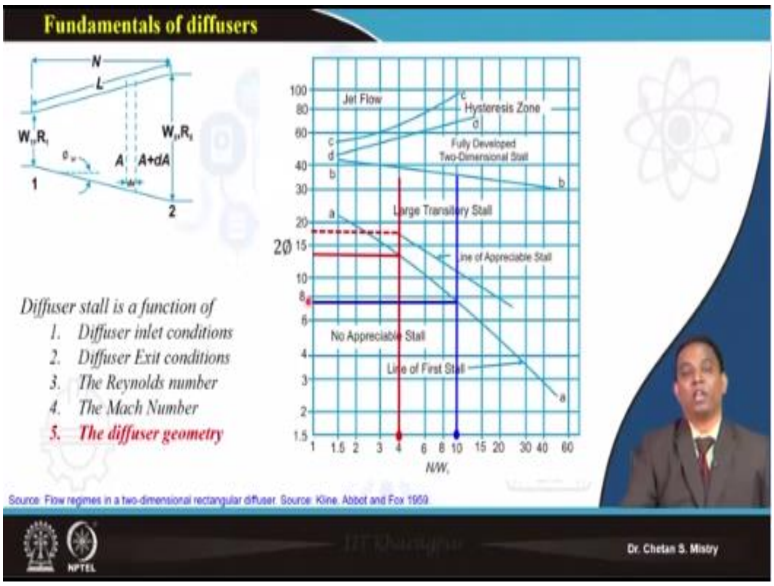

Let me move towards the next. This is what it says; my stall diffuser that's what is a function of my inlet geometry, it is a function of my outlet geometry, it also depends on my Reynolds number, what is my inflow condition, what is my outflow condition, and you know, like, the geometry of my diffuser, okay.

So here, this is what is a very good compilation of data that's what was given by Kline and Fox. They have done the experiment for say… different shapes of diffusers, and they have come up with this kind of plot. That's what is universally people they are using for the design of different diffusers for various applications, okay. So, here if you look at, as we have discussed, let me go selectively, let us say we are selecting my $\frac{N}{W_1} = 4$, and if I am extending that on my Y axis, that's what is giving me my divergence angle.

What it says, if I will be having my divergence angle, that's what is say less than 14 degree, I will not be having any stall that's what is happening. And that's what is my requirement – that's what is my requirement, okay. Now here, if you look at, if I will be going slightly greedy and if I will be putting my angle slightly larger, say… I am taking that angle say… 18, without understanding! So, what will happen, if we are going with this, we will be having your appreciable stall that will be forming, okay.

So, being engineer, we always need to have our understanding for the design for our diffuser. So, when we are designing our passage, it should not be without understanding. And this is what is one of the best example. Let us see, suppose say I will be going slightly on the higher side, I say, I will be having my $\frac{N}{W_1} = 10$, okay. I will be making my diffuser that's what is a short diffuser in that sense, okay, with larger diameter. So, if that's what is your case, you will be having your 2ϕ or your divergence angle that is what is coming to be different, okay.

Here, it says you need to go with the angle of say… 7° or 7.5°. If I will be increasing my angle other than that, that's what is giving me all kind of flow configuration, okay. So, this is what is one of the fundamental that's what is required for the design of my diffusing passage. Let us try to understand what is application of that, okay.

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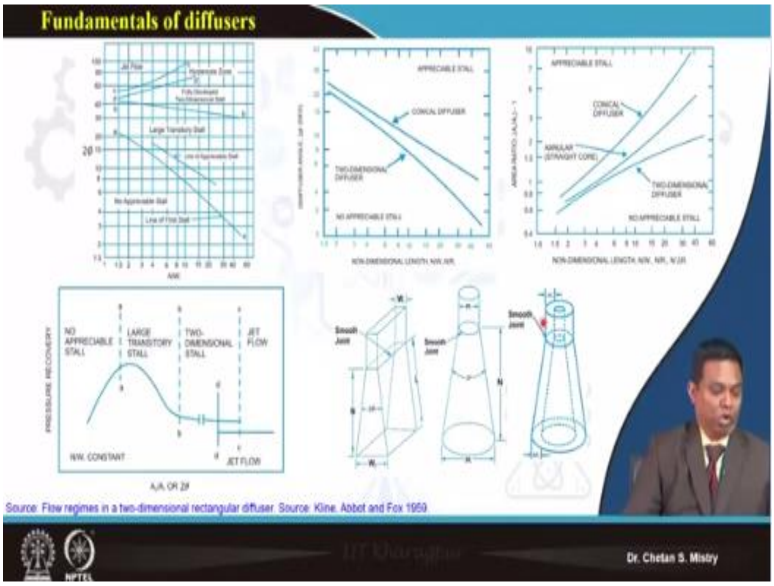

So, let me go to the next slide. Here if you look at, this is what is representing my area ratio and my divergence angle with respect to my pressure recovery. Let me tell you what we say in sense of my pressure recovery; that's what is nothing but rise of my pressure, means, what I am expecting in sense of my diffusion of the flow!

Now, for that configuration, as we look at, it says, when I am not having any appreciable stall, I will be getting higher total pressure recovery. That means we are getting what diffusion we are looking for, okay! Now, if I will be going with the increase of my area ratio, here if you look at, it says that will be going to say large transitory stall and you know, my pressure recovery that's what is going to reduce, okay.

If I will be going so greedy, then there may be chances that I will be having two-dimensional stall. And further increasing it may give you jet flow, okay! So, this is what is very, very much required when we are discussing for say… designing the diffusing passage. The question may arise in your mind, Sir, why we are discussing about this diffuser, okay! What is the use of this data? I will be correlating this with the design of my compressor passage.

If you remember, we were discussing about the high bypass ratio engine, where my duct, that's what is connected with say… low-pressure spool and high-pressure spool. That's what is connected with the passage area, that's what is called diffusing passage. So, there also, I will be having the application for this. So, there are different kind of shapes we are having; rectangular shape, or maybe we will be having circular shape, we will be having say co-annular kind of shape. So, this is what the fundamental that is what will be helping to us, okay!

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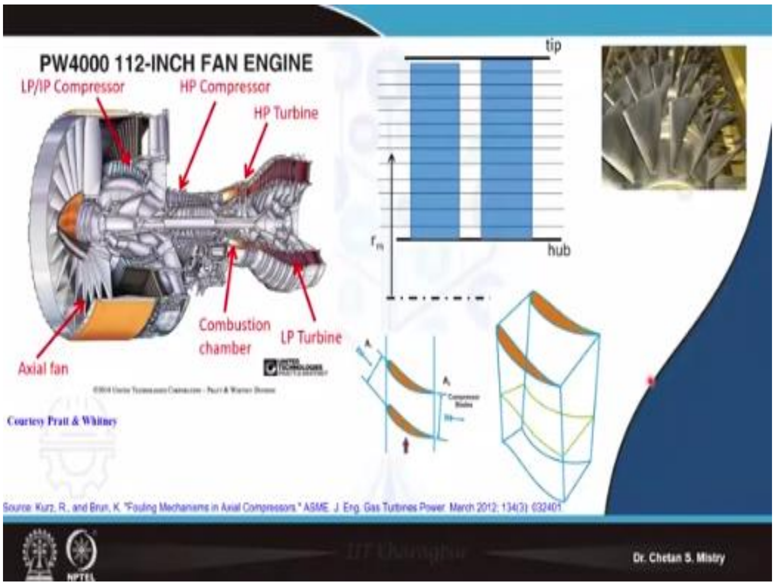

Now, say… this is what we are planning to discuss, okay, in sense of our application for the understanding of the diffuser. So, here if you look at, this is what we have discussed. So, this is what I was talking to you in sense of my LP compressor stages that will be followed by HP compressor stages. And here we are having interconnecting duct, okay. Now, if you look at carefully, this passage, that's what is having a specialized shape! Here Also, we are having the specialized shape, okay. We will be discussing about this in fundamental, okay.

Now, if you look at carefully, this is what is representing one of the cut section. So, if you look at, we are having 2 blades, that is what has been arranged in one rotor, okay. Now, if I consider, I am having my rotor and stator, okay. So, at particular station, say… my mid station, if I will be cutting my blade, that will be having say… airfoil shapes.

So, you know, like, remember one thing, this blades of rotor and stator that is made up of number of airfoils, okay. We will be discussing what all is the meaning of the airfoil. But, here just look at, this blade, it is comprising of number of stations; at all stations we may be having different airfoils, okay. They are been stacked in a systematic way in order to meet the requirement, okay.

Now, if I look at the passage between these two blades, here if you look at, my entry area, that's what is a smaller area and my exit area that's what is say larger area, okay. So, if you recall, we were discussing about the diffuser that diffuser is having similar kind of structure, okay. So, we can say, between the blade passage we are having the shape that's what is a diffusing shape. So, what all fundamentals, what we have learned for the diffuser that's what is straight way applicable here, okay.

Now, if I will be putting these blades, if I will be putting that together and in between passage, if I will be putting, you can say, this is what is my hub section, my mid-section, and this is what is my shroud section or tip section. So, this is what is giving you highly three-dimensional shape within the passage. So, you can understand the diffusion, that is what we are doing in my compressor that's what has been done within this blade passage.

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Let me show you, say… this is what is we are discussing about. So, here in this case, we are having say… 2 blades. So, these are the 2 blades which are being arranged, okay. So, here if you look at, we are having leading edge, we are having trailing edge, okay. This is my leading edge. This is my trailing edge. And if you look at within this passage, I am having my flow, that's what is getting diffused; that's what is having diffusing shape. If you look at, we are having larger area and smaller area.

Let me put this in a way, so, as I told my compressor blade, that's what is made up of number of say… airfoils. So, if you look at, this is what is one of the station. So here on this side, what we are looking at, that's what is my success surface, this is what is say my pressure surface. And if I will be putting this, it says this is what is having diffusing shape. So, this is what is near your say… tip section; this is what is near to my say… midsection; this is what is near to my say… towards the hub section.

So, all these, if you look at carefully, this is what is making a diffusing passage, okay. So, you know, like what all fundamentals, what we have studied for our diffuser design and diffuser aerodynamics that straightway will be application to this axial flow compressor and axial flow fan, okay. So, here we are stopping with these fundamentals. In next lecture, we will be discussing further. Thank you. Thank you very much for your attention. Thank you!