Aerodynamic Design of Axial Flow Compressors & Fans
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Lecture 04
Introduction (Contd.)

Hello and welcome to lecture 4 for the course on Aerodynamic Design of Compressors and Fans.

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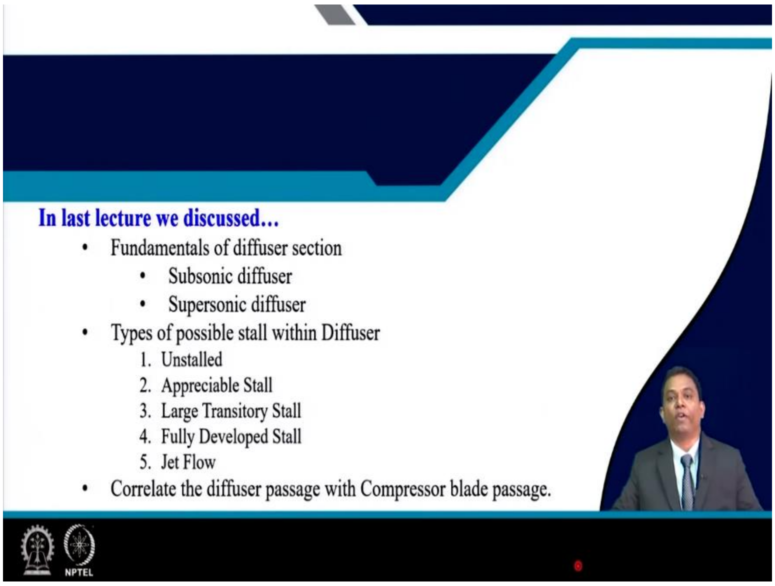

In last lecture, we were discussing about the fundamentals of diffuser section where we have discussed what is the effect of area change, that's what is with effect of your inlet Mach number. And if we realize here, that's what has given us the concept of subsonic diffuser and supersonic diffuser. We need to understand when we say diffuser that means this is what is pressure rising device; when I say nozzle that's what is say pressure decreasing device or velocity increasing device.

So, we have discussed when we are having our inlet Mach number that's what is say subsonic region, then our diverging passage, that's what is making the rise of pressure. Suppose if we are talking about say supersonic compressor, for supersonic diffuser, we will be having the passage area and that will be initially say… converging passage and that will be followed by diverging passage. So, it will be convergent-divergent kind of diffuser.

Then we have discussed about the types of possible stall within the diffuser. And if we recall, we have categorized that into 5; it says un-stalled, appreciable stall, large transitory stall, fully developed stall and jet flow. So, for all these conditions, we have realized, if you are changing our inlet condition, if you are changing our outlet condition, if you are changing our flow conditions, if you are changing our geometrical dimensions that is what will be bringing this kind of situation for the diffuser.

Then slowly we move towards say, comparing this diffuser section with our compressor blade, because we need to understand this compressor is a device that’s what is used for rising the pressure, okay! So, this is what is in line to what we are discussing from our fundamentals of aerodynamics. That’s what is a diffusing passage.

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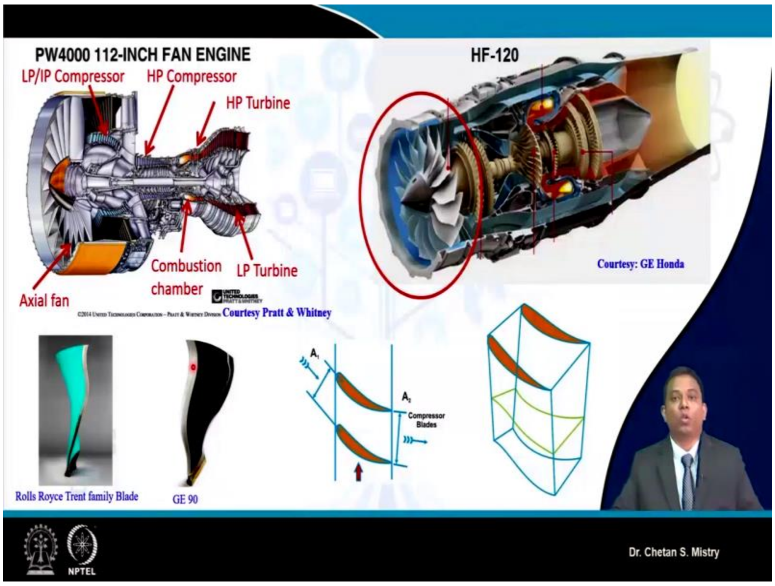

So, let us move with this part. So, in last lecture, we were discussing, say this is what is one of the Pratt and Whitney engine and that’s what is having say… big size fan that will be followed by your say… LP compressor that will be followed by say… your HP compressor. That HP compressor, that will be run by HP turbine; and this fan and LP compressor, that’s what could be run by your LP turbine.

We have discussed this fan and compressor, that’s what is made up of a number of airfoils; it is a stacking of airfoils, okay. And if I will be putting this all the airfoils together, and if I will be putting an I will look at what is happening within the passage, then we will realize it is comprising of whole three-dimensional geometry. That is means like my diffusing passage within the compressor that’s what is a three-dimensional diffuser.

Additionally, we need to understand it is a diffuser along with it is having rotating component, that means if I am considering this as a rotor, then this diffusing passage it is rotating also.

Now, the question is, say… like geometrical dimensions what we are talking of that is what will be deciding my inlet area and my outlet area.

So, here if you look at, this is what is most recent engine, that's what has been developed by GE and Honda. And the beauty of this engine, if you look at, that's what is the front fan! This front fan what you are looking at, that's what is having say wide chord. So, let me show you what we were discussing about is, you know, like, we have discussed what will be my inlet area, what will be my outlet area; based on that we were discussing, we were calculating our diffusing angle and suppose this diffusion angle that's what is coming larger, then we have seen there will be a separation of flow that will be happening.

If you are talking about the compressor, then we realize, for this compressor there may be possibility that my flow separation that may be happening from my suction surface, sometimes it may happen from my pressure surface, okay! So, this is what is we need to understand. So, in order to avoid such kind of situation in order to increase our margin for stall and surging, this is what is one of the recent concept people they have adopted. That's what is called wide chord fan, okay.

Now, here if you look at if you compare these two fans, that's what is having different aspect ratios. So, you know, here if you look at, this is what is lower aspect ratio blade and for this Pratt and Whitney engine if you are looking at, that's what is having higher aspect ratio blade. So, the phenomena that's what is happening is, you know, like, you need to manage your flow within the blade passage in such a way that you will be trying to avoid the flow separation that to happen within this passage.

And, that is the reason why recently people are working on the development of blades! So, if you look at, this is what we have discussed earlier. And, if you look at carefully, these blades, they are having highly three-dimensional shape, it is not because, like it looks nice, we discuss earlier. This is what has been systematically been studied using your computational tool, using the experimentation; and that is how they come up with this kind of shapes. Same for GE also the people they have developed this kind of configuration.

So, the situation is until and unless we are having the background, what we say, the aerodynamics of a diffuser, that is what will be giving you the idea how do we move forward with.

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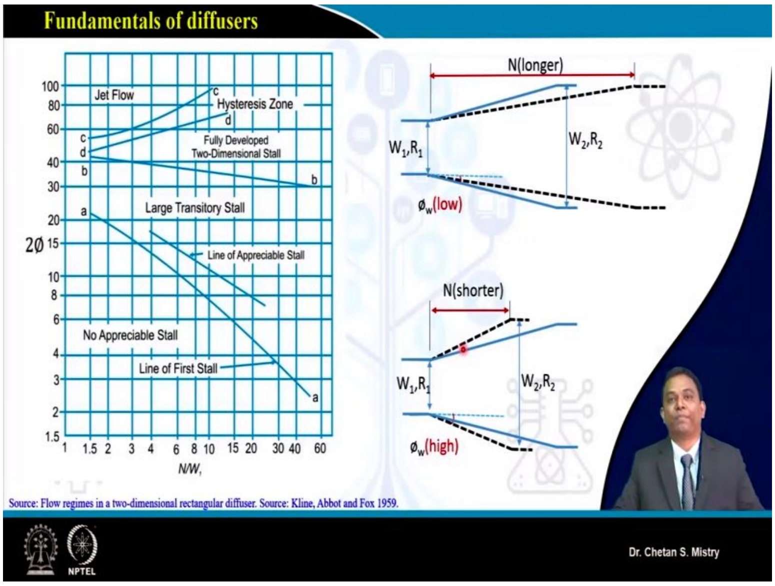

So, let me discuss here, this is what we have discussed in sense of my selection of say… length to say… inlet dimension; and this is what is representing my, say… diverging angle. So, if you look at here, this is what I was discussing. So, you can compare this inline to what I have discussed about wide chord blades. This is what you can compare if I am going with, say low aspect say, when I will be going with say… you know, high aspect ratio kind of blade, where I will be having these angles to be large.

So, there is always, you know, the discussion - hot discussion amongst the designers, what needs to be the aspect ratio! So, you know as and when we will be going ahead, we will be discussing about this aspect also, where we will be discussing how do we decide with the aspect ratio of the blade. So, this is what will give some of the idea how we will be using our diffuser concept for the development of compressor blades, okay.

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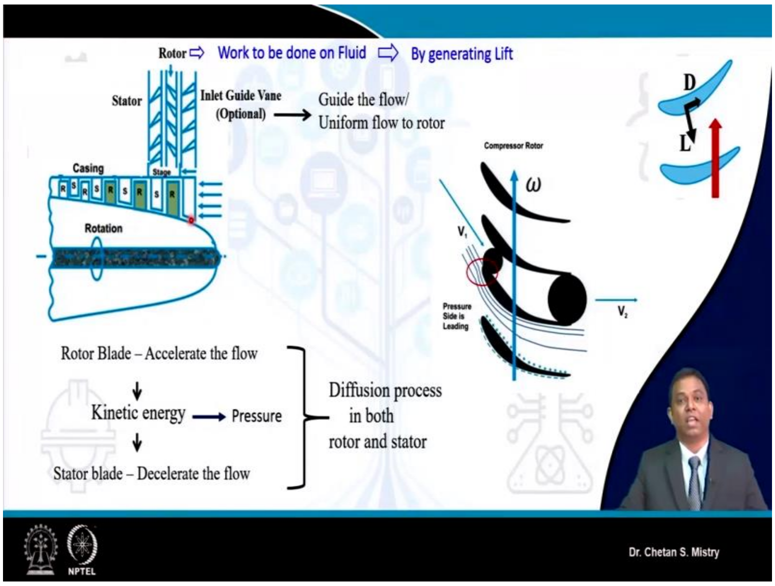

Let me move ahead. So, here if you look at, this is what is representing the construction of my, say… axial flow compressor. If you look at here, if I consider this is what is say my inlet area. Now, this inlet area if you are looking at, say… where I will be having my air that's what is entering, I say, that's what is having say… mass flow rate that we can represent from continuity equation as a density into area into velocity.

Now, if you look at this compressor, that's what is comprising of, say… number of stages, say… five stages we are having, okay. So, what is happening? From 1 stage 2 stage to 3rd stage, if you are going downside, my pressure ratio that's what is increasing. When I say my pressure is increasing from your fundamental you can realize my density also is increasing.

Now, for all flow devices, what we are discussing from our fundamental, they all must satisfy the continuity equation, okay. So, what we can say? What is entering inside my flow device that need to come out, if that's what is your case; at the exit, your density is going to be very high, okay.

Now, if that's what is your situation, you can say, if I want to satisfy my continuity equation, and if I say, I am assuming my flow velocity or my axial velocity with which flow is entering, if that's what is constant, we can say my exit area is going to decrease. And that's the reason why, if you look carefully, these blades are taller blades and if you are looking on the backside, you will say these blades are the shorter blades.

Now, based on what pressure ratio we are expecting people they are going with different kind of or different number of stages. And, once they are doing their calculation, it may be possible that, on the rear side, the height of the blade will be coming very small.

If you consider from your fundamentals, we can say, if I consider, I will be having say… the growth of boundary layer from inlet towards the exit, both from the wall - casing wall as well as from the hub, then we can say it may be possible that later stage, whole blade that will be covered with your boundary layer growth.

And, that is what will not be giving what pressure rise we are expecting, okay. So, that's what is; so, we need to realize, how do we do our calculation, how do we decide our compression ratio! Once, my compression ratio, that's what is decided with, we need to decide with how many stages we will be going with, okay!

Now, when I am going with the more number of stages, that is also a problem! What we realize? if I will be having more number of stages, my length of the engine will be increased, my weight of the engine will be increased; in sense of aerodynamics, my drag will be increasing! If I say drag is increasing, that's what is directly impacting on your fuel economy, what we say thrust specific fuel consumption, okay! So, the selection of number of stages, that's what is also important.

Now, here if you look at, this rotating blade, that's what has been placed on the disc, okay! Now, if you look at on the front side, this is what is defined as inlet guide vane; and it is written it is optional, okay. So, conventional understanding for people is say, this is what is named as inlet guide vane, means, this is what will be the guiding the flow; that means it will give the uniform flow at the entry of the rotor.

Now, here, there is argument, say… on both the sides of Pacific, people they are having different understanding; they are taking this in a different way. Suppose if I say, European Union, they people they say… if I will be incorporating my inlet guide vane, that is what will be increasing my weight of the engine. Because, this is what is a stationary device and that will be reducing my performance what we are saying in sense of fuel economy. But, on the other side, if you are looking at, for say USA - those companies, mostly they are preferring to use inlet guide vanes, okay.

So, as and when we will be moving forward, we will be discussing, what is the reason? Why we are adopting? Or why people they are preferring to go with inlet guide vanes or why they are not going with the inlet guide vanes, okay! Now, next component if you look at, that's what is say my rotor, and this is what is say my stator, say… the combination of my rotor and stator that's what is defined as a stage. So, when I say stage means it is comprising of rotor and stator.

Now, let us try to look at what is the purpose of rotor! So, here if you look at all these three, say inlet guide vane, rotor and stator; they all are made up of airfoil shape, okay. So, it has a specific reason; it has a specific meaning behind that. We will see, what is the reason behind that? Okay! So, for rotor you can say, we are using this rotor in order to work on my working fluid, because we are rising our pressure. So, for rising our pressure, we need to do work on our working fluid.

Now, this is what can be done by using the concept of lift. Now, you will say, lift, that's what is related with my airfoil, okay. So, let us see, say… this is what is representing my airfoils of the compressor blade; this is what is my entry and this is what is my exit, and as we have discussed my passage will be diffusing passage.

Now, here if you look at this airfoil, we can say, here it is represented positive sign and this is what is representing negative sign; do not get confused, this is not meaning that there is a positive pressure on my pressure side and there is a negative pressure on my suction side. This is what is representing I will be having higher pressure on my pressure side, I will be having lower pressure on my suction side.

So, this is what is inline to what we have discussed in our fundamentals of aerodynamics. Say, we are talking about the wings, where, for wings, this is what is used for generation of lift; means this differential pressure that's what is generating a lift. So, inline to that, what we are doing? We are using our airfoil for the compressor blade.

So, here if you look at, say… this is what is my lift force; I will be having perpendicular component, that's what is say my drag force, and I want to utilize this lift force, for what purpose? I want to utilize this force for compressing my fluid. And that is the reason why, if you look at, remember carefully, I need to have my rotation of my rotor from suction side towards the pressure side.

So, you can understand, my flow is entering from this side, I am utilizing my force of lift generated by my airfoil. And if I am giving this rotation, what it will be doing? It will be diffusing my flow within this passage. So, you can say, this diffusion within the rotor that's what is happening by two means. One, that's what is because of my passage shape; and second, that's what is because of my lift force, that's what is generated by airfoil, okay.

So, now onwards suppose say you will be realizing what is the use why people they are using this airfoil for the compressor or axial flow compressor, you need to be clear with, okay; do not get confused! Here, I am saying, we are having this airfoil at one station; we can say my blade, that's what is comprising of number of airfoils. So, each airfoil will be generating that lift and each airfoil that will be having contribution for the compression of my fluid, okay. Now, let us see, suppose if I consider, say… my flow, that's what is entering here, in this particular region.

So, if I will be putting at some infinite distance, I will be having a streamline; and if I will be putting nearby streamline, you will realize, this is what is a region where I will be having my passage to be looking like a nozzle. Now, the question is, what is the purpose of this kind of shape? So, you know, we need to say, when my fluid that's what is entering in my compressor, that must be sucked inside. So, the question will come how this suction that's what is happening?

So, realize one thing, because of this passage area, what we are having; you know, it is acting like a nozzle, and that's what is decreasing area passage, where your flow will get accelerated. And that is how the suction, that's what is happening in axial flow compressor; there is no other means by which my flow is entering inside.

So, many times people they are getting confused how the suction is happening! But, just realize because of the shape of my airfoil near my leading edge, that's what is making the area, that's what is a converging passage and that's what is accelerating my flow that is nothing but there locally my pressure will be lower; I say, that's what is responsible for the suction of my air, okay.

Now, in overall if you are looking at, this rotor blade what we are saying, where I will be having the acceleration of flow, and you know, there I will be converting my kinetic energy of inflow into the pressure! Next component, if you look at, this is what is my next component, that's what is called stator!

Now, conventionally people used to say, the stator, it is used to guide the flow to the next coming rotor; but realize when we will be discussing about the design, you will be realizing the thing, like, stator also is contributing for rising of our pressure, okay. So, we will be introducing some terminology that is what will be helping us in sense of understanding how we are using this stator also as a defusing passage.

So, for rotor and stator both will be having this diffusing passage. So, here for rotor we are having rotating diffusion as well as because of my passage diffusion and for stator it will be having only passage diffusion. So, you can see here we are having the deceleration of flow, that's what is happening in my stator blade. So, in overall if you are looking at, my diffusion, that's what is happening, I say both in rotor as well as stator, okay. So, this is what is happening in my one stage; similarly, that is what is moving downside.

Now, here I want to put one important point, if you are looking at, we have discussed about the change of area. Now this change of area, that's what is very important; if you look at, this is what is giving you your converging shape, okay. So, within the passage, we are having diffuser shape and within the flow path we are having converging shape.

Now, you can understand what is the complexity of aerodynamics, that's what is happening in axial flow compressor. So, people, they conventionally used to say this compressor - axial flow compressor is very delicate device, this is what is very fragile device and it is very sensitive device, okay. Let me tell you for all engines, this axial flow compressor that is what people used to say it is a heart of the engine; if this is what is not working fine, then your engine is of no use, maybe you will be having the failure let it be land base power plant, let it be aero-engine, okay.

So, this is what is giving you overall idea in sense of construction, there are so many minute details inside, but with the interests of this course, we are focusing more on the aerodynamics. That is the reason we will not be discussing in detail for this in sense of mechanical part, okay.

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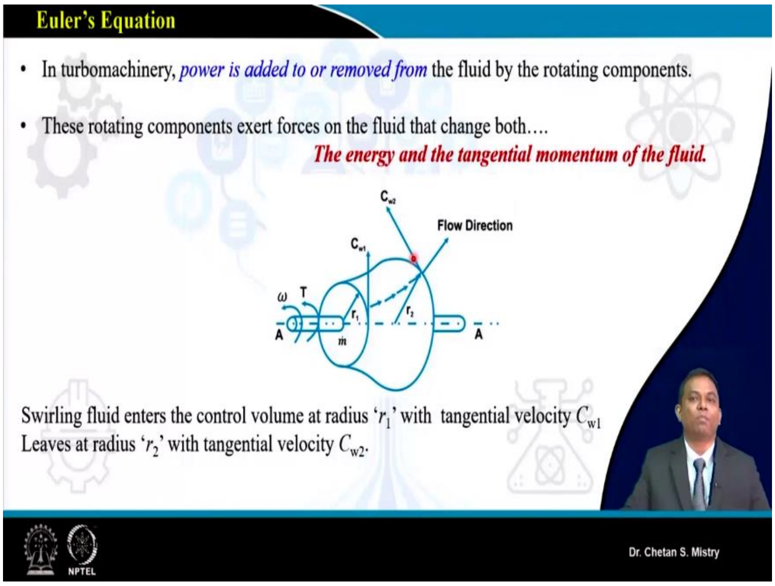

Now, in order to move; now we have our fundamental equation, that is what we are using. This fundamental equation that used to say it is a Euler's equation. Now, let us learn, you might have studied that in your basic course, but just brush up that knowledge what we have understood in sense of Euler's equation.

So, what it says in turbo machinery power is added and removed from the fluid, okay, by rotating component, that rotating component, we would say it is a say rotor, okay. Now, this rotating component, that's what is exerting the force; and that is what is bringing the change both in energy as well as tangential momentum of the fluid.

So here, if you look at, let us see, suppose say, my fluid it is entering at with some mass flow rate, say $\dot{m}$, that's what is entering at some radius r_1. If I consider, I will be having suppose let us say, I will be having my tangential component of velocity, that is what I am writing as C_{w1}; at the exit, I will be having change of radius r_2, and I will be having my tangential components C_{w2}.

Let me tell you this Euler's equation, that's what is very fundamental equation. This fundamental equation is equally applicable for both the cases, for your axial machine, as well as for your radial machine, okay.

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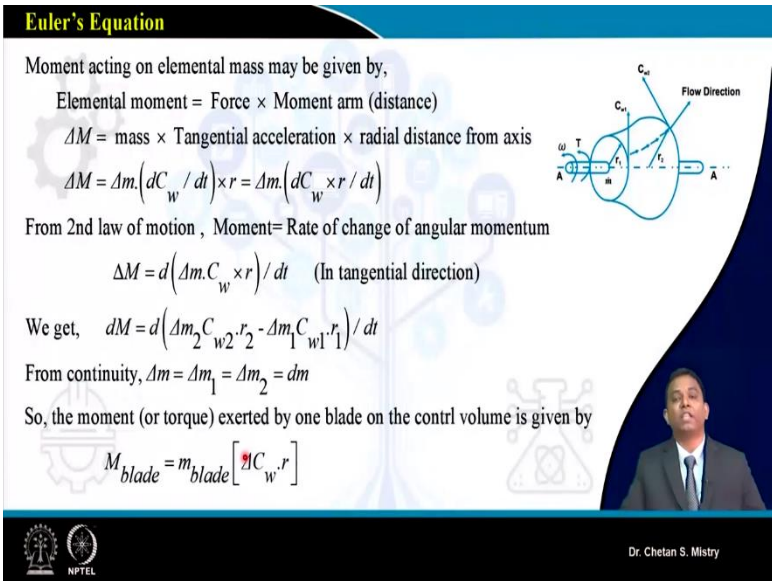

So, if I put, what all we learn, what all we know about our mechanics; what it says, the momentum, that's what is acting on my elemental mass, that's what is given by force into distance or say moment arm, okay. Now, this force I can write down this is nothing but mass into acceleration. So, this acceleration, we can say that is nothing but that's what is my tangential acceleration.

So, I will be writing mass into tangential acceleration into radial distance from the axis. Now, this ΔM if I will be putting, that is what I am writing here as a $\Delta m(dC_w/dt) \times r$, okay. Now, from our second law of motion, we can write down this change of momentum, it is nothing but it is rate of change of angular momentum, okay. If I will be putting that as a rate of change of angular momentum that I can write down my ΔM that is nothing but in the differential form, okay. And this is what is in tangential direction, we will realize what is the reason why we are interested in tangential direction, okay!

Now, this is what I can represent in terms of say $d(\Delta m_2 C_{w2} r_2 - \Delta m_1 C_{w1} r_1)/dt$. Now, what my continuity says like my mass, that is what will be remained same. So, I will be putting my Δm Δm_1 Δm_2, that's what it is same ($\Delta m = \Delta m_2 = \Delta m_1 = dm$). So, I can represent my momentum, that's what is say momentum generated by say… single blade, that's what is say… $M_{blade} = m\_blade[\Delta C_w \cdot r]$, okay. Now, what we know? Our machine, our say turbomachinery, that's what is comprising of number of blades.

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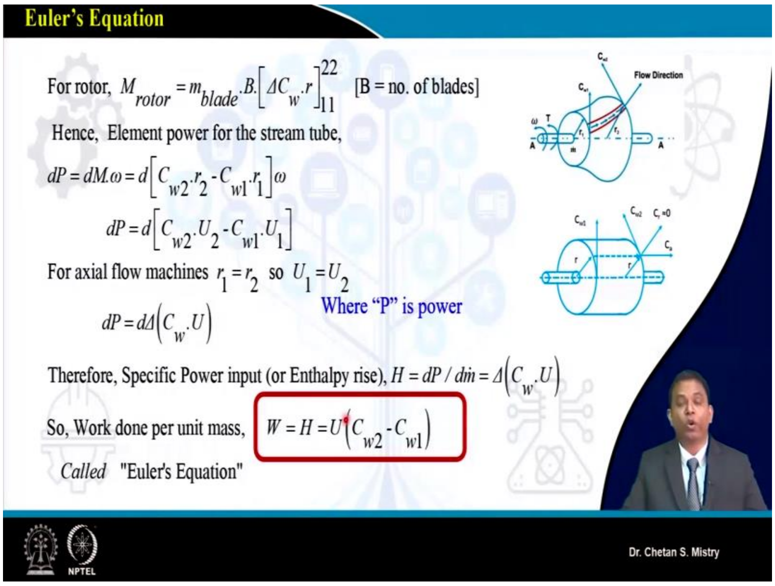

So, let me put that part. So here, I say… I am putting my number of blades suppose say B, then modification of this equation, we can write down like this.

$$M_{rotor} = m_{blade} \cdot B \cdot [\Delta \mathrm{C_w} \cdot r]_{11}^{22}$$

Now, the momentum of this rotor, that is what we are utilizing, in sense of generation of my power, or say, power consumption. So, that is what if I am representing this is what is a movement of my fluid I say, then I can consider this as a stream tube.

For that stream tube, I can write down, my elemental power is $dM \cdot \omega$; ω is nothing but that's what is my, say peripheral speed, okay. So, that's what we can write angular speed, or we can say, we are writing that in sense of my peripheral speed. So, say dP, that is what we can represent by this form $dP = d[C_{w2} \cdot U_2 - C_{w1} \cdot U_1]$, okay. This is nothing but $C_{w2} \cdot U_2 - C_{w1} \cdot U_1$.

So, if we consider we are having, say, axial machine. So, what we realize for axial machine, my entry radius and my exit radius, that's what is we are taking as a same, so if that's what is your case, you can write down my U_2 and U_1 that is what will be coming as same. So, if I will be putting that I can say my specific power input required for the compressor, that's what is given by $\Delta C_w \cdot U$.

Now, let me rewrite this equation in per unit mass, it says my $W = H = U(C_{w2} - C_{w1})$. This is what is my fundamental equation. This is what is my fundamental equation, that's what is called Euler's equation. Now, if I consider I am using these Euler's equation for the turbine, my sign will be changing here. In place of negative sign, I will be having positive sign, okay.

So, when we will be running the course on say axial flow turbine and radial turbine design, that time we will be discussing about this part; but you just realize now what we can say, my work input that's what is required for my axial flow compressor that's what I can say, it is a function of my peripheral speed, this is what is a function of my, you know, my tangential speed or say tangential velocity, okay.

So, now two velocities, that's what is of very much interest. If you recall when I was discussing about the construction of your engine, that time I was talking about, say... how we will be deciding with the pressure ratio, we will be discussing soon how this correlation we will be using for our purpose.

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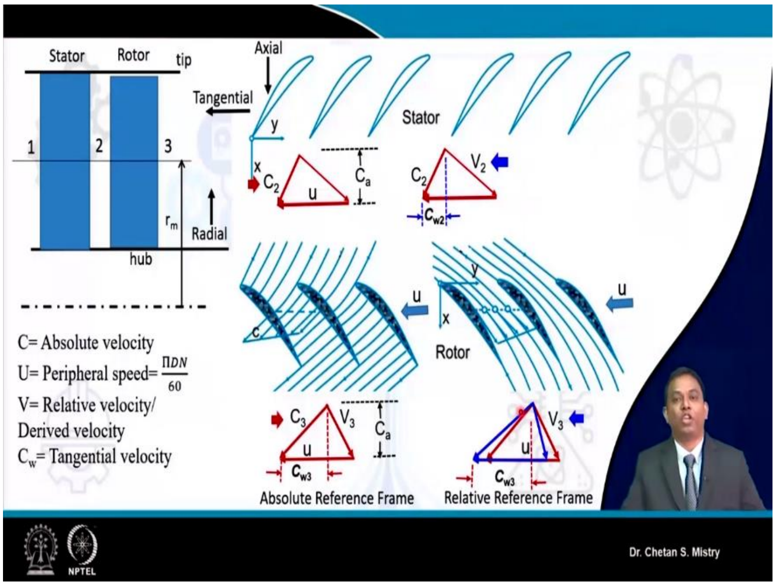

Let us move to the next slide. Suppose if I consider, this is what is a stage it is comprising of my stator and rotor, okay. My entry condition, I am writing as state 1 or station 1, this is my station 2 or say this is what is my station 3. If I will be putting, this is what is say my mid radius, okay. So, for this mid radius, if you are looking at I can put my airfoil. So, I am cutting my blades here. So, if you cut this blade here, it will be coming like this kind of airfoils; it says, this is what is my stator this is what is say my rotor.

So, these are the airfoils for my stator, as well as rotor. And, recently we have discussed I will be having my rotation of the wheel, that's what is coming from suction side to the pressure side, okay. So, this is what is representing my peripheral speed. Now, let us try to look at, let us try to understand what all is happening within this passage.

Let me consider suppose say my flow, that's what is entering inside my stator, okay. So, when I say… it is a stator, it is a stationary device, okay. So, my flow will be entering with some velocity, let me write that or let me say that as say… absolute velocity, okay. And my flow, that is what will be coming out from my stator, let me put, that is what as say C_2, it is my absolute velocity, that's what is coming out from my say stator, okay. If I know, what is my peripheral speed, let me put my peripheral speed. So, this is what is representing my peripheral speed.

Now, from your fundamentals of mechanics, you know, when I will be putting my velocity triangle, that velocity triangle need to be a closed loop, okay, it should be close. So, let me close this. So, I am putting this as a closer. So, it says this is what is my close velocity triangle. The connecting velocity component, that is what I am defining as relative velocity.

So, this V_2 is nothing but my relative velocity. So, you can understand my flow that is what will be coming out from my stator that will be coming out with absolute velocity C_2 and it will be living with relative velocity say V_2. Now, here if you look at, this is what is representing the streamlines, that's what is representing my absolute velocity component. Same way, this is what is my rotating device; we know our rotor, that's what is a rotating device and for that, I will be putting my streamlines so this is what is representing the relative velocity streamlines, okay.

Now, what is happening at the, say component part? If I consider, say… my flow that's what is entering in axial direction, because this is what is in my axial machine, okay. So, for this axial machine my flow is entering axially, recently we have discussed about our Euler's equation; what it says I will be having my whirl component that is what will be generated, I say… that I say… my tangential velocity component, okay. So, if this is what is your case, then you know, this vertical component what I will putting, that is what is defined as my axial velocity, okay.

Now, let me put my component of whirl, so you know, if I will be measuring my component with reference with my absolute velocity, this is what is representing my whirl component. So, this is a whirl component, that's what is coming out from my stator, that's what we say C_{w2}, okay. Now, what is happening at the exit of rotor, okay?

So, if you look at, my flow that will be coming out with some velocity, let us say… this is as say my relative velocity V_3, okay. What we know? We are having our rotational speeds; so, I will be putting my rotational speed here. And as we have discussed, our velocity triangle need to be a closed entity, if that is what is your case, you are putting that and this is what I am writing is my absolute velocity C_3, okay.

Inline to that, you know, like people conventionally they are assuming what velocity with which my flow is entering, that's what is my axial velocity, okay, that axial velocity that remains constant, we have made the assumption earlier. So, at the exit also, I will be having this component as my axial velocity component. And as we have discussed, I will be having this component that's what is my tangential component, what I say it is C_{w3}, okay.

Now, you have realized this part, we have discussed in our say Euler's equation, fundamental equation; what it says... my working capacity of my compressor that is nothing but the amount of compression that's what is happening with my compressor is nothing but $U[C_{w3} - C_{w2}]$. So, it says I will be having higher tangential velocity at the exit and I will be having lower tangential velocity at the entry of my rotor, okay.

Now, this is what people used to say as absolute reference frame, this is what they used to say as a relative reference frame. Now, just compare these two velocity components, say… this is what is my relative velocity component and this is what is say my absolute velocity component, you will get surprise! What is happening! Here if you look at, at rotor, my relative velocity is higher, yes, at entry of my rotor, my relative velocity will be higher; where it is coming out, it is having relative velocity to be lower.

So, conventionally the diffusion that's what is happening in my compressor, people used to say that's what is reducing the relative velocity, that's what is happening here. So, when you are getting your relative velocity to be lower, it says it is a diffusion process. Now, come to say… second point that's what is say my absolute velocity component, what is happening? Say, at the entry of my rotor, my absolute velocity component is say… lower. And here if you look at, my absolute velocity component at exit of my rotor, that's what is coming higher, okay.

So, we need to be very careful in sense of plotting our velocity triangle, okay. In sense of doing our calculation, all these aspects are very much important, okay. So, different authors, they are putting different kinds of velocity triangle, they are discussing velocity triangles in a different way. But, you know, this is what is most fundamental way of understanding what is happening.

And I am sure, with this understanding, you will be able to realize, okay, how this velocity triangle, that’s what is coming, okay.

So, this is what is derived from any fundamental approach for representing your velocity triangle at the entry of your say… stator, at the exit of your stator and at the exit of your rotor. Now as I discuss, what we are looking for, we are looking for high pressure ratio. The meaning is I need to have my work input to be large, that means my C_{w3} components that need to be large, from our basic Euler's equation.

So, let me put that is a case, I am looking for my C_{w3} component, that to be large. If that’s what is your case, what you are looking for! Just look at, it says I need to connect this by absolute velocity, this is what is my peripheral speed. And this is what is representing my relative velocity component.

So, if you look at what it says… if I am looking for high pressure rise, I am looking for high pressure ratio from my stage, I need to have my blade with angle, it should be designed in such a way, that I will be reducing my relative velocity coming out from my rotor, okay. But, this is what is we are discussing in sense of our understanding. Later on, you will realize, this airfoil what we are talking, that’s what is very sensitive device; the small change of inlet condition, that is what will be bringing big change at the later stage, in sense, at flow at my leading age, if it is getting disturbed, that is what will be disturbing my flow at the exit near the trailing edge. And that’s what will be known as say my flow separation, okay. And that is what we are discussing in sense of stall.

So, now you realize, what angles we are discussing at this moment, what velocity we are expecting, that’s what is restricted. So, this is what all we will be discussing. So, you can understand today we have started with our understanding for the diffuser. And later on, we have discussed what is the construction detail of my say… axial flow compressor, then we have realized what all are the uses of my airfoil in say axial flow compressor, how the suction that’s what is happening, then we have discussed about the fundamental equation, that’s what is our Euler’s equation.

And then, based on our understanding of Euler's equation, we try to discuss our flow or our velocity components and our flow components using this velocity triangle. Thank you very much for your attention! We will discuss later part in the next lecture. Thank you, thank you very much!