Fluid Machines.
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Lecture-36.

Basic Principles and Energy Transfer in Axial Flow Compressor Part I.

Good morning and welcome you all to this session of the course. Today we will be discussing the axial flow compressors. Last class we have more or less completed a brief discussion on the centrifugal compressors. Now we will be discussing the axial flow compressors. The basic principle is mostly the same as that of the centrifugal compressor. What is the basic principle, that by absorbing the mechanical energy from outside, the working fluid, which is usually air, gains its static pressure. That is the basic purpose of the compressor, whether it is centrifugal and axial flow compressors.

And axial flow compression, like a centrifugal compressor also consists of a rotor and a stator. Rotor is the rotating part of the compression, where the mechanical energy is being supplied and it consists of them number of blades which rotate and the mechanical energy is supplied in the form of an external torque, under which there is a rotational motion of the rotating blades, the blades which rotate. And the air acquires energy and ultimately what happens, its velocity and static pressure is increased.

And the stator part of the compressor, which is known as the diffuser, the function of which is that, here, we gain the static pressure from the velocity of the air by allowing the air to have a decelerating flow in this passage, this is known as diffusion process, the diffusion takes place where we get more static pressure by virtue of the at the expense of kinetic energy, and finally at the outlet we get air at high-pressure but at low velocity. So the basic principle is same but the major difference between the axial and the centrifugal compressor is that the flow takes place in the axial direction.

Whereas in the centrifugal compressor, you have seen that the flow takes place in the radially outward direction. So the inlet and outlet of the flow varies in the radial location and varies in the peripheral speed of the rotor. But here what happens, the flow takes place in the axial direction. So therefore the inlet and outlet of the flow takes place at a particular radial location also is radial locations, and all such radial locations the flow inlet is there in flow outlet is there, that will be explained when I will explain through the diagram.

So the major difference is the entire flow takes place in the axial direction and there are different number of stages, each stage consists of a rotor blade or the rotor and a stator, consisting of stator blades and this way, a stage is considered that a rotor and a stator and number of stages are there. This is the overall structure of an axial flow compressors, that differs from a centrifugal flow compressor which is the radially outward flow type. It is an axial flow type through number of stages.

At the same time, you should know that these axial flow compressors, the advantage over centrifugal compressor is that it can handle a large amount of air, the flow rate is more as compared to the centrifugal compression and it can run more efficiently with high flow. So therefore where the high flow is required, the axial compression is more, axial compressor is important, high flow and also the weight is low.

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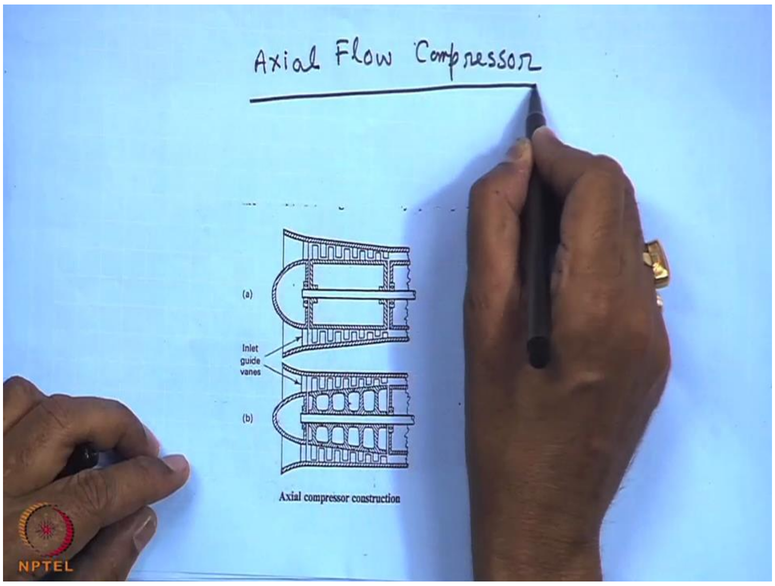

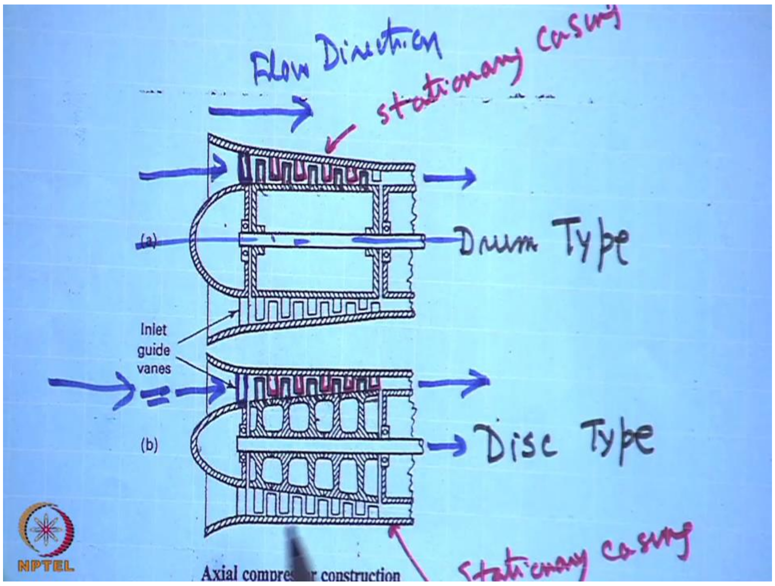

Okay, now let me explain the overall structure of an axial flow compressors, you see that, this is an axial flow compressor, axial flow compressor, axial flow compressor. Now you see an axial flow compressors, how does it look, here. There are 2 types of axial flow compressors, one is the drum type, this is the drum type, I tell you, drum type, what is the difference, I will tell you. This is the disc type. Now the basic system consists like that. There is either a drum, rotating drum, this is the shaft or a disc on which these rotor blades are being mounted.

This is the rotor blade and these rotor blades, this is the drum type, it is mounted on the rotating drum and with the rotation of the drum or disc in a disc type, this is the rotor blades, this is the rotor blades. So rotor blades rotate, so in rotor blades, a number of blades are there along the periphery of the drum. So at any axial location, you see there are number of blade, if you see this view, from view, you see one blade, the number of blades in the periphery which are being attached to either drum or disc known as disc type.

And there is a stationary casing, this is stationary casing, I write, this is the stationary casing, this is stationary casing. Here also this is stationary casing, stationary casing. And the stator blades are screwed or attached to this stationary casing, these are the stator blades. And one rotor and one stator, one rotor and one stator comprises one stage. So here also, the stator blades are fixed to the casing. And there is an inlet row or guide vane upstream of the 1st rotor, this is actually not, this is stator, this is also a stator, static part attached to that.

And these are known as inlet guide vanes which 1st direct the air properly in the axial direction. So this is the flow, flow direction, this is the airflow like that, flow direction. So this is the flow direction and this is the direction of the axis. Axis, this is the direction of the axis. The flow takes place in the axial direction. 1st it comes to the inlet guide vanes, then threw rotor and stator, then rotor and stator, a number of rotor blades, number of stator blades, number of rotor blades, number of stator blades and a combination of rotor and stator comprises the stage.

This is an overall view of the axial flow compressor, the air enters in this way, the air enters in this way. So therefore the air flows through this annulus area formed by the blade passages. So this is a*n* overall diagram of an axial flow compressors, air goes out. So axial flow compressors, there are other things that I will tell you that while designing this annulus area, it is made a convergent type. That means the annulus area goes on decreasing in the direction of the flow, why?

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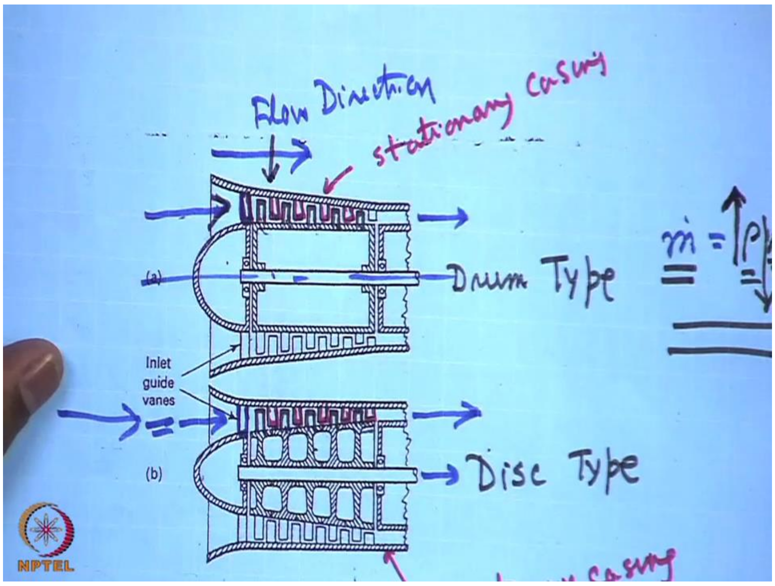

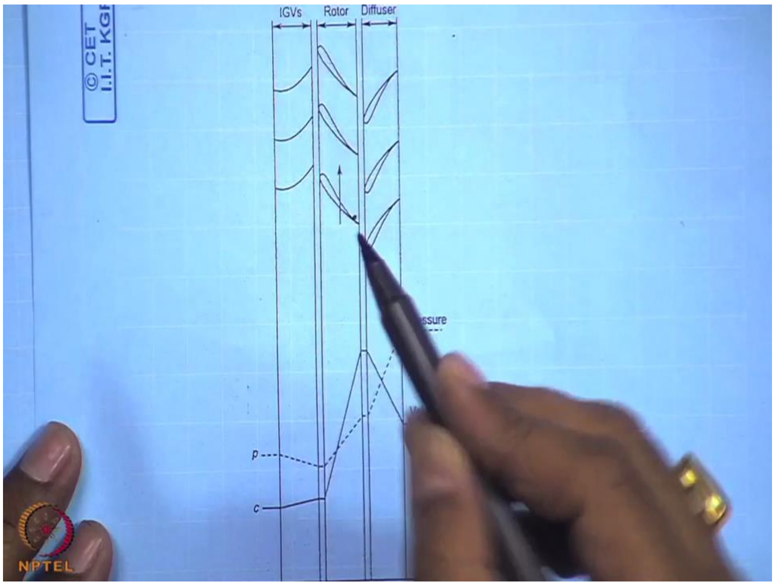

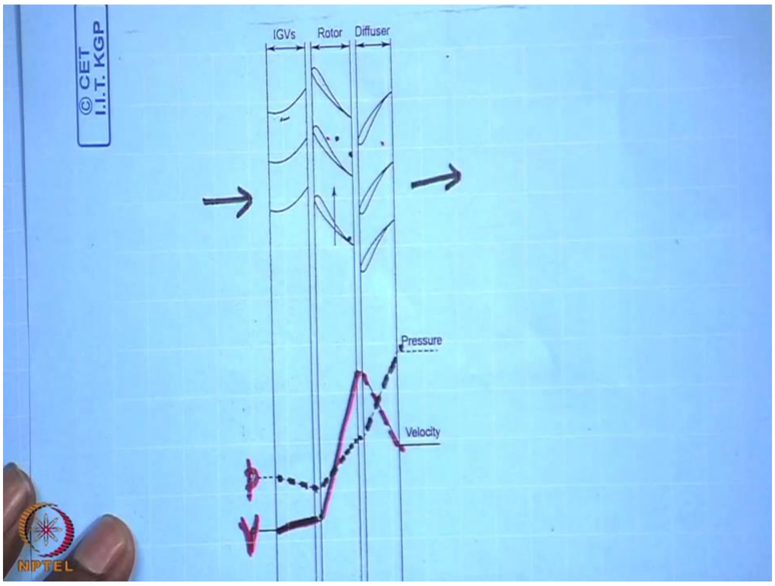

This is because you know from the continuity mass flow rate is written as, mass flow rate can be written as rho times the flow area times the velocity of flow VF. And this we consider an average flow velocity over a cross-section. And this is the annulus area, the cross-section, the area provided to the flow and this is the average density at that section. Now as the flow takes place here by the action of the rotor and stator, the pressure increases, this is the increasing direction of the pressure, so density increases.

So for a given mass flow rate, because of the steady state, from continuity, the mass flow rate will be same throughout the machine, so if we want to make the axial flow velocity constant, we have to decrease the cross-sectional area. And the main motto is to make the axial flow velocity constant despite the increase of rho for which we have to decrease the annulus flow area. Same for drum type and disc type, this is one of the major considerations in the geometrical design of the compressors.

The blade height and other things, will come afterwards but this is one of the main considerations. So this gives you a overall picture of an axial flow compressor, how does it look like, what is the basic direction of flow, the flow takes place in the axial direction. Now if we see the number of vanes, now before that, we consider, now if you see from the top view, then you will see a particular row is like this, including the guide vane, it looks like this.

When you look from the top, okay, over the periphery, then you will see that this is the direction, that is these are the rotor, this is the rotor, this is the diffuser and this is the inlet guide vanes. Rather I think you can see this way. This will be the way actually, yes. So therefore these are the number of blades that you can see or better you see this way, now this way it is better. So that this goes from this, in this direction, why they have made a flow direction like that, I do not understand, this direction will be here.

I think the flow, this is a peripheral direction, I number of blades are there, so this will go like this and will come like this. I think this is the direction, now this is the direction. So the flow takes place like that, there are inlet guide vanes which direct the flow in such a way, ultimately it goes through the rotor series of rotor blades in the diffuser, this is the diffuser where the velocity is decelerated in the pressure is increased. If you see this diagram, you see that pressure in the inlet guide vanes decreases slightly because of the skin friction.

Because the inlet vanes, there is no energy interaction, this is the static vanes, so pressure loss takes place because of the friction. Then in the rotor, the energy interaction takes place, it moves, so therefore rotor imparts mechanical energy to the fluid by virtue of which its pressure, its velocity and similarly if you see the velocity, velocity should remain almost constant but this inlet guide vanes cross-sectional area is slightly converging type, so that the velocity slightly increases. So this is the velocity part, I just do it by red, velocity.

Then what happens, virtue of this mechanical energy given to it, the both, velocity and pressure increases. This is the increase in the velocity, this is an increase in the velocity in the rotor because it gains energy there and this is the increase in the pressure. And this is the static pressure, the increase in static pressure takes place because there is a divergence in the area. This flow passage area is made in such a way, there is an increase in the static pressure while it flow through them.

This is being reflected or manifested by a change in the relative velocity, that I will tell afterwards. Then it comes to a series of stator blades known as diffuser. What happens in the diffuser, we get a rise in pressure, that is known as typical diffusion process in respect to this deceleration of flow, that means the flow velocity is reduced. So this is the typical pressure velocity diagram, this is the pressure, this is the velocity diagram while flowing through the rotor and diffuser vanes and upstream.

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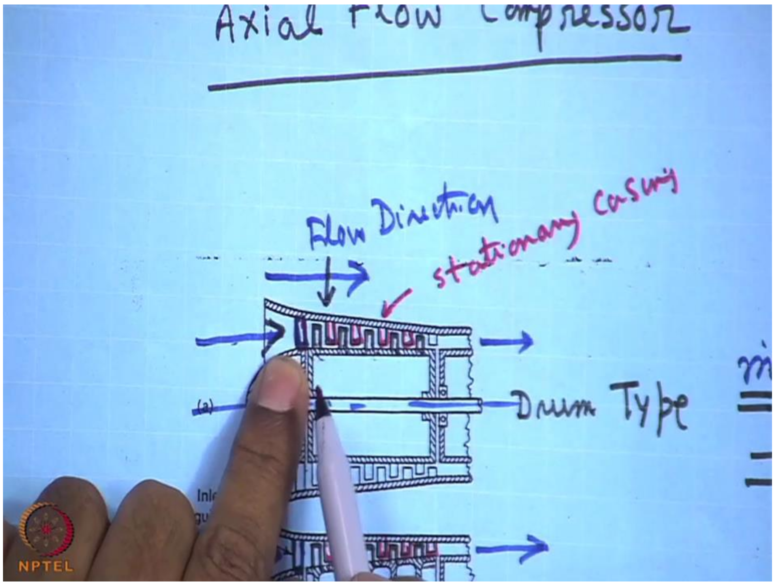

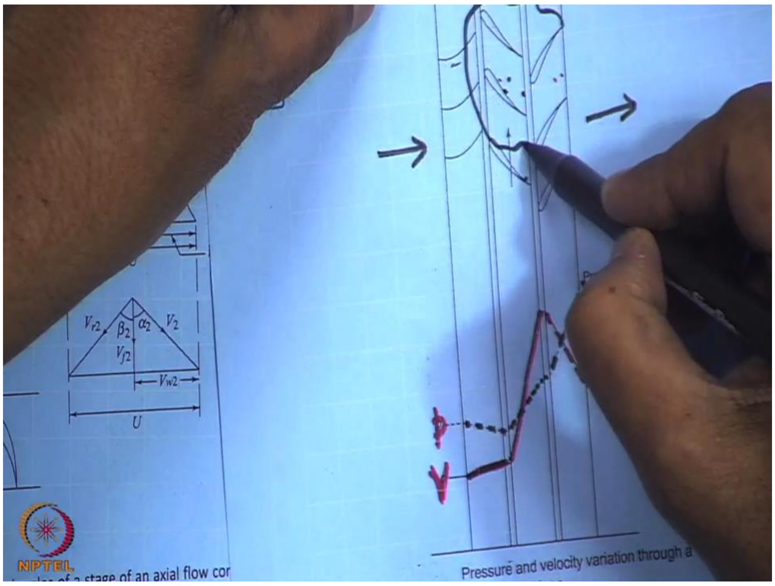

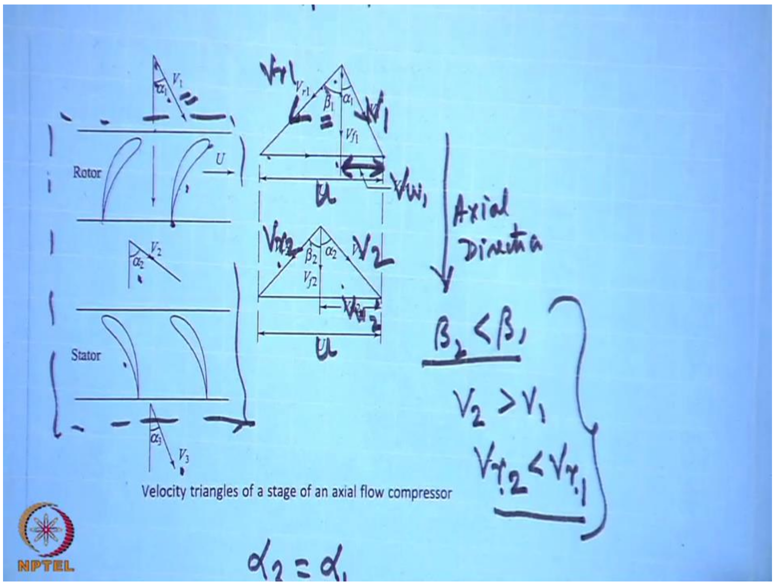

This you consider the, the 1st row of rotor blades, so that upstream of that, there are inlet guide vanes. Okay. Now if you consider, you come to this diagram, that flow takes place at all radial locations. Now if we consider the flow velocity VF is uniform over all radial locations and if we consider the flow at any mean height, that means at the mean height of the plate, it mean radius from the Centre. Here the flow is basically two-dimensional, the flow has got an axial component and a tangential component, the radial component is relatively less.

So if the radial component is less, you can consider the 2 components of flow, mainly in the axial, another is the tangential, which is perpendicular to this plane of the figure. And at the same time if you consider the VF at any cross-section, along the blade height, okay, at different radial locations, if you measure from the centreline is constant, that means the uniform velocity distribution which is also constant in the axial direction for which the annulus area is reduced, that is different.

But radially if we consider, it is uniform and 2 components of velocity, then it is almost a two-dimensional flow. This is a two-dimensional representation of a three-dimensional flow. So with this representation, now you can have a look of the velocity triangle. Now if you see that the same thing, that we already shown that the, a blade passages formed by the rotor and the stator, you see this rotor and the stator, that means this part, if we draw like this.

That means is we see from the top, a, this side, okay, sorry, sorry, now it is, now it is. If we see from the top, the 2 rotors, earlier things were visible no? Okay. So 2 rotor blades and 2 stator blades, just a representative figure. I will show you, this is what a representative blade passages formed by the 2 rotor blades and 2 stator blades of a stage. Now this is a stage, this is a stage, this is a stage.

Now what happens, the stage at the inlet to the stage, the air comes with some velocity V1 with an angle alpha-1, which is nothing but the velocity coming out of the stator of the previous states with some angle alpha-1 and this angle is made in the axial direction, this is the axial direction. You understand, this is the axial direction. So this is the, well, axial direction. This is the axial direction, axial direction, axial direction. Okay.

Now what happens the rotor blade shape is like that if you see the velocity triangle, you see the velocity triangle is that, here we can write that VR1 is a relative velocity as you know, that is V1, -, oh, not visible that we, then problem with this, it is not actually made in this proper way. VR1 is V1 - U. Now another difference is this, from the centrifugal compressor, here, the, if you see this again, that the flow takes place axially. If we, this diagram is drawn at a section taken at the mean radius, mean height of the blade.

So therefore here what happens, the inlet and outlet takes place at the same radii. We can take it at different radial location. So therefore when we see the picture from the top, we see that the inlet and outlet of the air flow takes place at a given radius. So the peripheral speed of the rotor is same depending upon the radius at that point. So therefore U remains the same, you see the inlet velocity triangle is like this, this is the absolute velocity with which the air strikes the rotor blade with an angle alpha-1 with the axial direction.

Then if you make the vector diagram, vector triangle diagram, the velocity triangle, then this is your VR1, this is the VR1, I think you can see, this is V1, this is V R1 and this is the U and this is the VW 1, this part, this is the whirling component tangential component of velocity V1, this is your velocity triangle. And this velocity, because of smooth flow without incidence last, this beta 1 should glide, that means it should match the angle of the blade at the inlet and this is the beta 1.

So beta 1 is the relative velocity which is the angle of the blade at the inlet. Similarly if you see the outlet diagram, the outlet is made like this, so that the flow area increases in the direction of flow, this is the flow direction, okay. So this is the flow velocity VF1. So at the inlet. Now at the outlet if you see the velocity diagram, this is the relative velocity, VR2, this is V 2, this is the same U and this is VW2. Okay this is alpha-2 and beta-2. Now beta-2 is less than beta 1, this beta-2 is less than beta 1, fluid is directed more towards axial direction.

This happens because of the camber of the blade in a way that the annulus area increases. Okay, the annulus area, that means this area, sorry increases, decreases, no sorry the annulus area increases because of this increase in the velocity VR2. So what happens here you see that V1 and V2, that another important thing is that VR2, then V2, V2 is more than V1. V2 has to be more than V1 because in rotor the fluid gains the energy. But VR2, VR2 is less than VR1, why?

This is because there is an increase in static pressure. If VR2 has to be less than VR1, so this area has to be more. So make the annulus area, the camber of the blade has to be such that beta-2 is less than beta 1. These are the important considerations of this velocity triangle. Now when it comes to the stator blades, then what happens, this is the absolute velocity V2, it comes, makes an angle alpha 2 with the axial direction. So stator blade does not move, so there is no velocity triangle, simply the velocity direction is changed as far as the camber of the stator blade of the curvature of the stator blade.

Here also the stator blade velocity is changed in such a way that Alpha 3 is reduced from Alpha 2, it is directed more towards axial direction and the design is made in such a way that Alpha 3 becomes again equals to Alpha 1 so that it can smoothly glide or enter to the rotor blade of the next stage. So we make this Alpha 3 is equal to Alpha 1, these are the important considerations. So this way you can draw the velocity triangle at inlet and the velocity triangle at outlet of the rotor blades and this is the velocity, how does it change in the stator blade.

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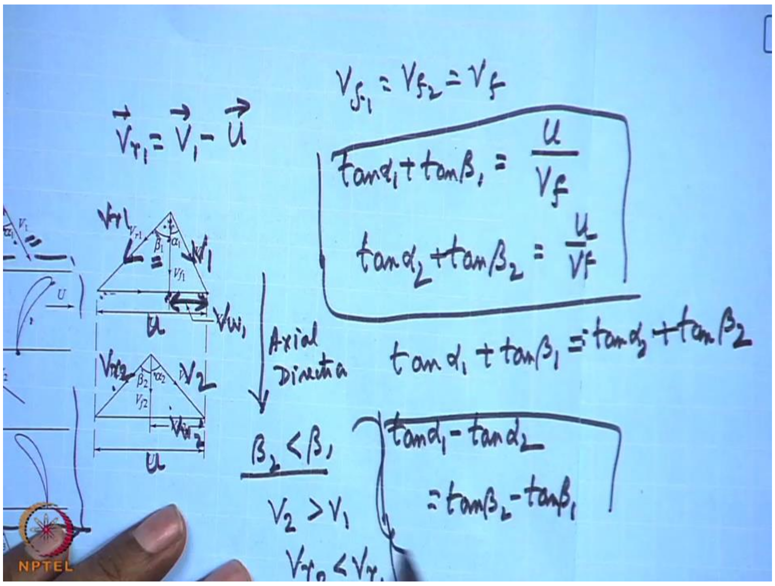

Okay, now we can write certain formula from this. But problem is that this cannot be shown here at the, same diagram, okay, let me adjust it, this is the stage, if you can see, if you can see. We will blade you can discard, so you can go little here. So now if you see this triangle, what we can write from this, now VF1, as I have told in the design is made VF 2 and VF. That means this axial flow velocity. Now from the geometry of this, tan alpha-1 is what, this base divided by VF1. Tan beta 1 is this base divided by VF 1.

So if you add these 2 things, then we get tan alpha-1 + tan beta 1 is equal to this + this is the U, U by VF. Because VF1 is VF 2 is VF. So this is I am writing VF. Similarly from the outlet velocity triangle, tan alpha-2, if you make the tan alpha-2 from the simple geometry tan beta-2 is equal to U by VF, okay, U by VF. Now if you equal, make these 2 equal, now we can write tan alpha-1 + tan beta 1 is equal to tan alpha-2 + tan alpha-2 +, okay, tan alpha-2 + tan beta-2.

Okay, that we can write, we can write tan alpha-1 - tan Alpha 2 is equal to tan beta-2 - tan beta 1. This is one very important relationship, these 2, this relationship and the geometrical relationship, these 2 relationships we can get from the 2 velocity triangles. Okay, now if we come to the work, here itself I can write.

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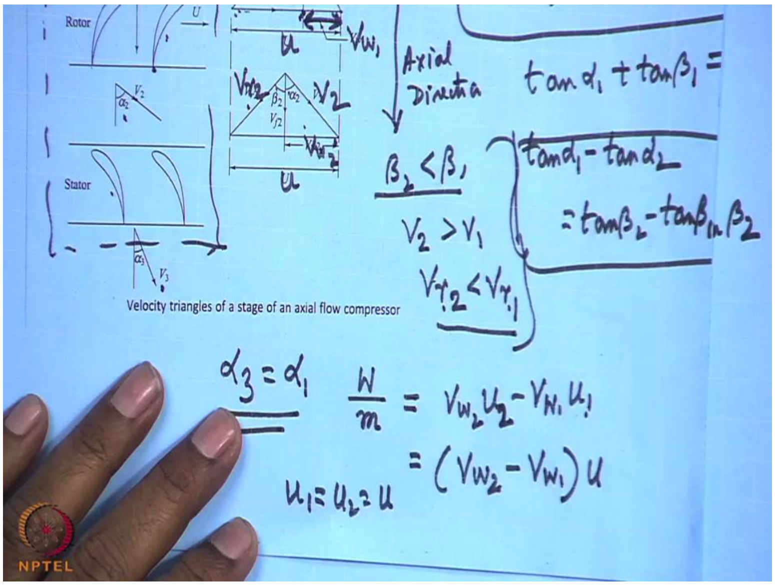

Now work, if you write here, now work unit mass, W by M, work per unit mass is nothing but, what is work per unit mass, we know from the Euler's equation that VW2 U2, that is V W1 U1. Alright, here U2 is U1 and that is equal to U, so therefore it becomes equal to VW2 - V W1 into U. Why because, because U1 is equal to U2 is equal to U.

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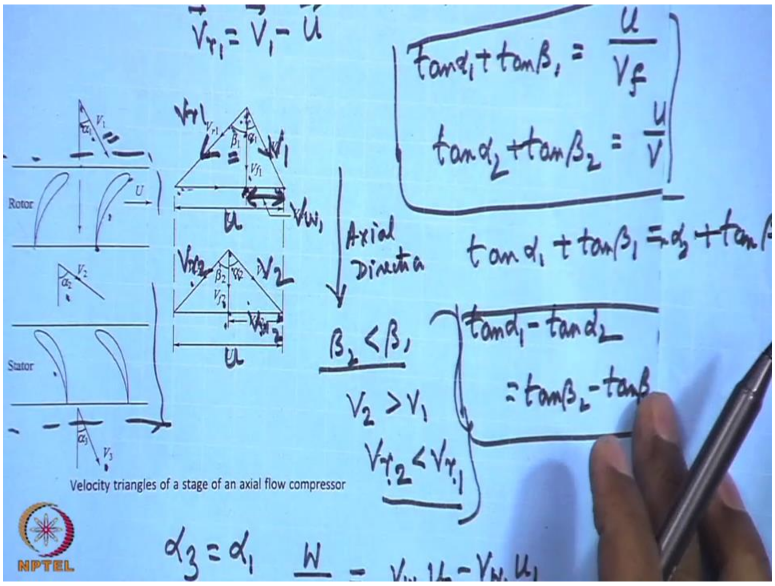

Okay, now we see that if this is true, then we can write W is equal to, what is VW 1 - VW 2? Let me see again, now VW 1 - VW 2 is the, what is V W1 - VW 2 from this diagram? Now VW 1 can written as, this one VW 1, VF1, tan alpha-1. Similarly VW2 is VF 2 tan alpha-2. VF1, VF 2 is VF. So therefore this equals to VF tan alpha-1 VW 1 and VW2 VF tan alpha-2.

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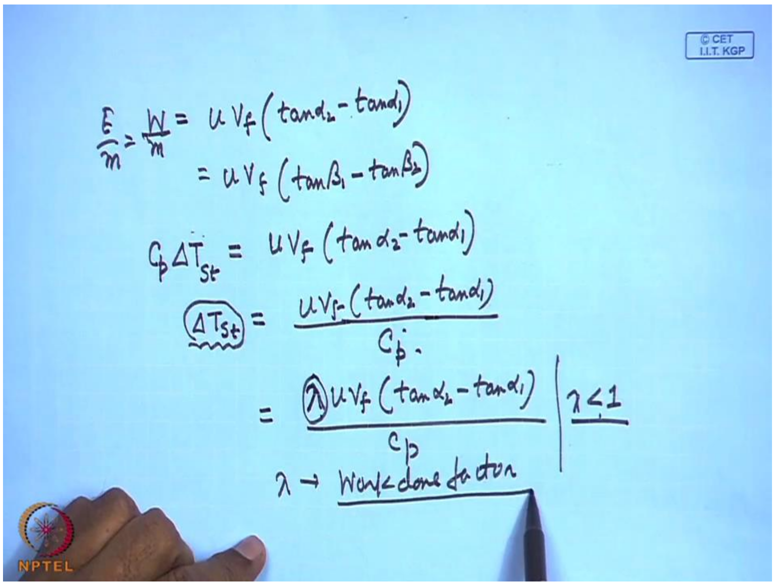

So if you follow this velocity triangle, then you can write this is equal to U VF into VW2, that is tan alpha-2 will come 1st, - tan alpha-1. Again from the equality as I have done already, that tan alpha-2 - tan alpha-1 is tan beta 1 - beta-2. So we can write U VF tan beta 1 - tan of beta-2. Okay wherefrom, because we had this thing earlier shown that that earlier we shown this thing that, actually this is a problem here. This is tan alpha-2, tan alpha-1 - tan alpha-2 is tan beta-2 - tan beta 1.

Okay, so therefore tan beta 1 - tan beta-2, so this is the work done per unit mass, or energy added per unit mass, whatever way you can write, it is your concept energy added. Now if you consider that the change in the stand stagnation temperature, which we call the total temperature, I give the nomenclature Delta T, that means changed in the stagnation temperature of the compressor, total change, that CP is the total energy added to the air or the working fluid per-unit mass, that will equate this one, VF tan alpha-2 - tan alpha-1.

I can write tan beta 1 - tan beta-2, does not matter. Either of these 2 I can write. These 2 are equal. Therefore the increase in the stagnation temperature is given by this formula which is very important that increase in the tan alpha-2 - tan alpha-1 divided by CP. Now what happens is that, the actual stagnation temperature rise is less than this. And this is taken care of by a coefficient lambda, by a coefficient lambda, 1st of all let me write that which is less than lambda, this is lambda less than 1.

Lambda less than 1 by this coefficient lambda which is known as the work and factor. This is the lambda which is known as the work done factor, lambda is work done factor, work done factor. Now this is mathematical, what is the physical meaning of that? And this lambda is constant, that means that theoretically the energy per unit mass work done per unit mass which you calculated is not actually imparted to the liquid, sorry to the fluid, to the air here. Less amount is being imparted because of this lambda factor which is less than one, which is known as work done factor.

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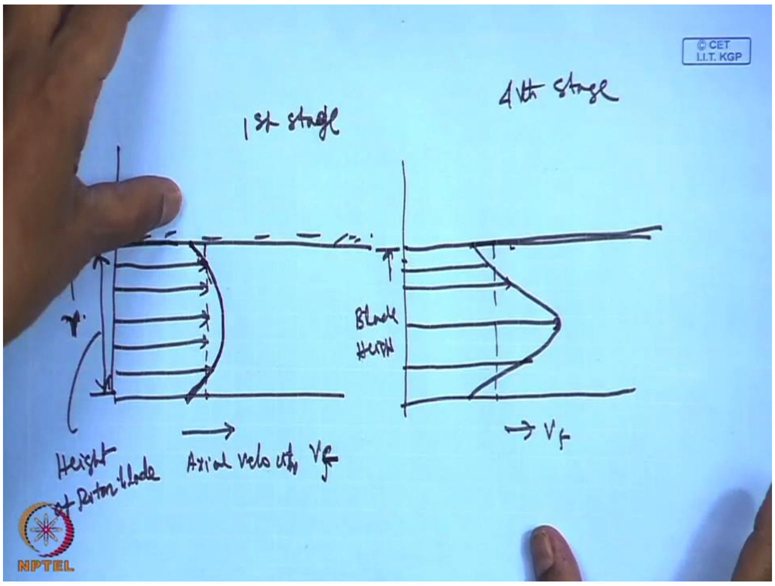

This is because of the fact that we assumed at the beginning that this axial flow is uniform over the entire blade height, this is not so. And that creates a problem. Now let us see that thing. That if we consider the, this way, if we consider the axial velocity, axial velocity, axial velocity, that is VF, and if we consider this is the radial direction, this is the radial direction, R. And if we consider this as the blade height, rotor blade height, this is, then, this is the blade height, this is the height of rotor blade, height of rotor blade.

Let us consider the 1st stage, 1st stage, stage. Now according to our two-dimensional assumptions, we have considered that the, this is the dotted line I am showing, this is the axial velocity distribution. This is the axial velocity distribution over the blade height, this is the playwright, here I cannot write because this space is not there, so it could have written, the ordinate is height of the, that is the radial direction, and this is the height of the rotor blade, just make a hatched line for your understanding.

So uniform distribution but what happens in practice because of the three-dimensional effect, the velocity distribution is not uniform. The flow velocity distribution, this is the axial flow velocity VF, so distribution becomes like this, some peak here at the Centre and then again it reduces. So this becomes the distribution of the axial velocity, axial distribution becomes like that, instead of this uniform one. And if you go to further stage, for example, for example a 4th stage, 4th stage, 4th stage.

Number of stages are there, or 5th stage. Some representatives, blade height also will change as you go on that, there is a reduction area, however I will show you with the same height. 4th stage for your understanding. So if this is the VF, this is the blade height, blade height, the same diagram but it looks like that. This is the uniform one, the axial velocity, this becomes more peaky, little this side and after certain stage, this velocity distribution which is skewed with a peak becomes almost same, like the fully developed flow type.

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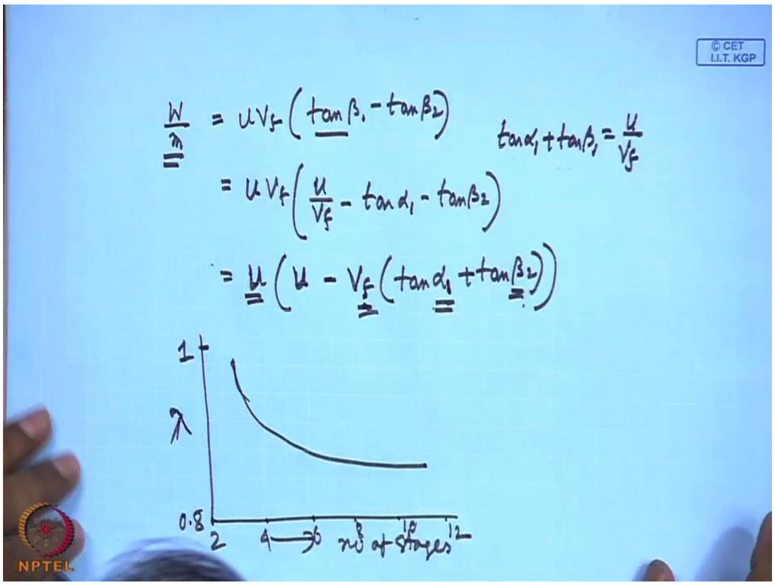

But because of this distribution, not being uniform, what happens, the work done per unit mass is changed, which is taken care of by the lambda. Now after this, I will show you that you can have some idea that if I express the work done per unit mass, W by VF, now W per-unit mass, now we can write W per-unit mass as U VF into tan beta 1 - as I have done earlier tan beta-2. This I can write. Now we know that tan alpha-1 + tan alpha-2 is tan beta 1+ tan beta-2, that we know.

We can replace tan beta 1, another result I know, that what is this, that tan alpha-1, again we know that tan alpha-1 + tan beta 1 is U by VF. That I know, now I can replace tan beta 1 in terms of tan alpha-1 and can get this expression, U into, now VF… Now VF tan beta 1 I can write tan U by VF - tan alpha-1 - tan beta-2. This is the way I can write. Why, you will understand now. If you take U here, then you can write U - this VF cancelled, VF into tan.

Now this tan alpha-1 and tan beta-2, this alpha-1 and beta-2, this is fixed, this is the outlet angle of the rotor blades and this is the alpha-1. That means this is the outlet angle of the stator blades or the angle of the absolute velocity at the inlet of the, that is the, at the inlet of the rotor blade. Okay. So if these are fixed, then it is seen that for a given peripheral speed, at any height, the work done per-unit mass depends upon VF. So when there is a reduction in the flow velocity, work done per-unit mass is increased, when there is an increase in flow velocity, it is decreased.

So therefore with this, if you compare this we will see that it changes with the radial locations. Here in this radial location, here the work done per-unit mass is decreased. While the work done per-unit mass is increased because of the reduction in VF, near the tip and the roots. But the overall effect of this reduction of the work done per-unit mass at all radial locations where it is more than the axial velocity, because we have made the calculation based on the uniform axial velocity is count, it counterweights the gain at the root and the tip because of the reduction in flow velocity VF by the formula.

So what happens finally, the work done per-unit mass based on the uniform flow velocity is being reduced by a factor known as work done factor. Clear, now this work done factor ultimately decreases with increasing number of stages. This work done factor, typical graph is like that, usually this value lies from 1, 0.8 to 1. And which number of stages, number of stages, let, I start with stages 2, 4, 6, 8, 10, 12, like this. The work done factor goes like this, this is for idea, this is the work done factor lambda.

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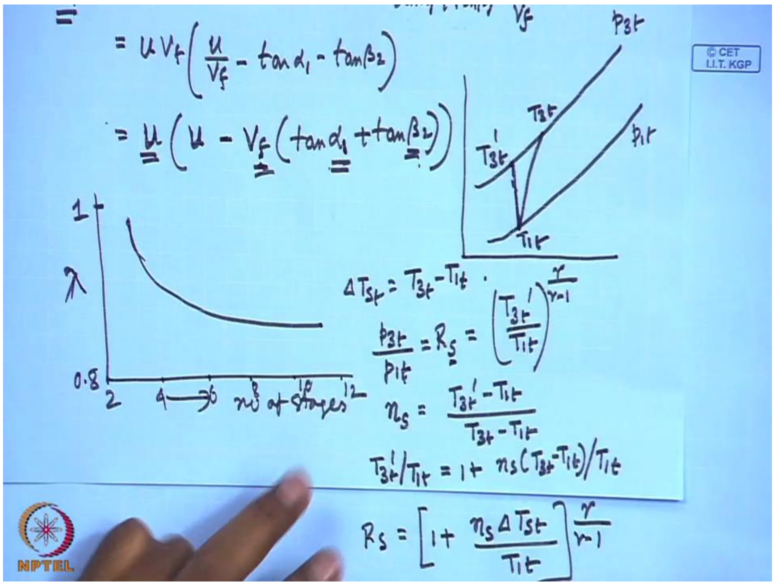

So more number of stages, lambda is less and less number of stages, lambda is high. Okay. Now we come to the pressure rise. Pressure rise is very simple, again, in this page itself I will do. Now if we consider the 2 pressures, just like we did earlier, that P3 T and P1 T, if we consider 3 and our this thing, then what happens, that this is our, so that this is dotted, this is our isentropic 1, this is our actual one. That means if this is P1 T, this is T3 T dash and this is T3 T. So our Delta TST is T3 T - P1 T.

But our pressure rise P3 T by even P1 T, which usually we write here is the RS. Here S suffix is given per stage, per stage the pressure rise is, the pressure ratio is P3 T, not rise, it is P1 T. That is related to this T3 T dash by T1 T to the power gamma by gamma -1. And again we know that, again we know that Eta C, okay, we know that the isentropic efficiency, again it is stage efficiency which is defined as T3 T dash -, same thing I am repeating again and again, T3 T - T1 T.

Which gives that T3 T dash by T1 T from here is one + Eta S into T3 T - T1 T divided by T1 T. So therefore we have to place it here, so that we get RS is equal to, same expression, 1+ Eta S and this is defined as Delta TS T. So that it is expressed in terms of this, in terms of this thing, T1 T to the power gamma by gamma -1. Alright. Okay. Now with this I tell you, the overall principle of action of a stage often axial flow compressors. Okay. What happens in the rotor and the stator. Okay, thank you, today up to this.