IC Engines and Gas Turbines
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Lecture – 45
Axial Compressor: Basics, Velocity triangles, T-S diagram and Work Intraction

Welcome to the class. Having looked into the centrifugal compressor and the velocity triangles and the performance estimation like work input, pressure rise, temperature rise for the centrifugal compressor; we are moving towards the next compressor which is Axial Flow Compressor.

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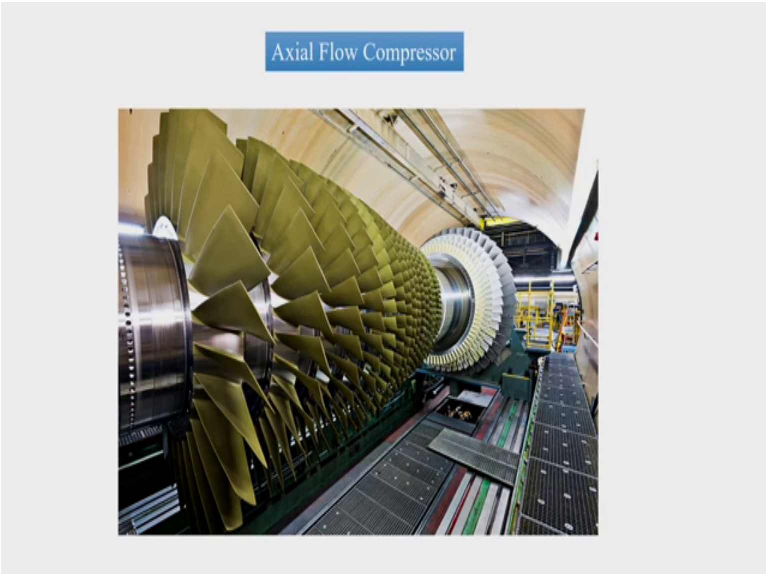

So, typical axial flow compressor is there shown in one of the photographs in a first slide. So, this is an industrial scale very big axial compressor.

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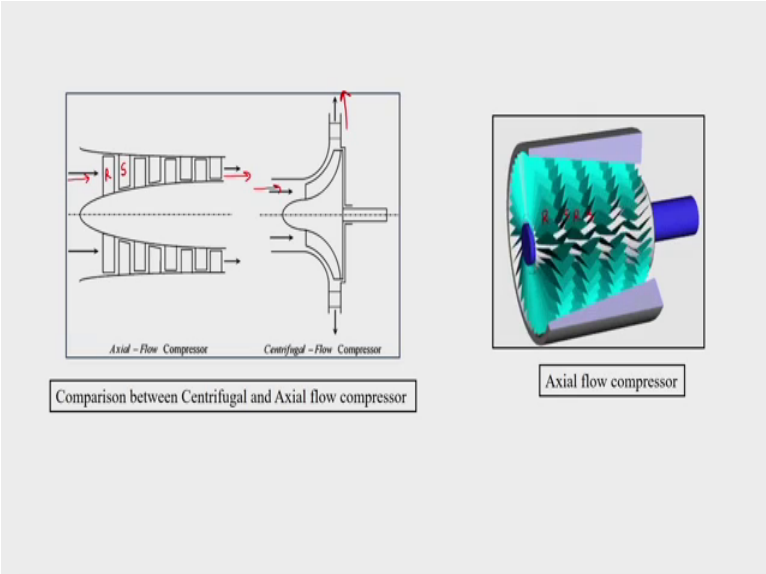

Now, axial flow compressor is different from the centrifugal flow compressor from the perspective that the centrifugal compressor we have seen that flow comes enters axially but it goes radially out from the compressor. And then, we have in between we have impeller vanes where inducer was a taking care for the smooth entry and then there was radial outlet from the impeller and then we had diffuser to raise the pressure further. So, this is how centrifugal compressor was working. But axial flow compressor is having different composition, then the centrifugal compressor where flow comes axially and flow also goes axially out.

So, here we are having rotor blade and stator blade arranged in a series in the direction of the flow. So, first we will encounter rotor, then we will encounter stator and then there will be series of stages which will be encountered by the flow as per the requirement of the pressure raised. So, we can see in this animation also where we are having rotor blades rotating and then these are the rotor blades and these stationary are the stator blades. Again we have rotor and again we have stator. So, this is how axial compressor is composed off.

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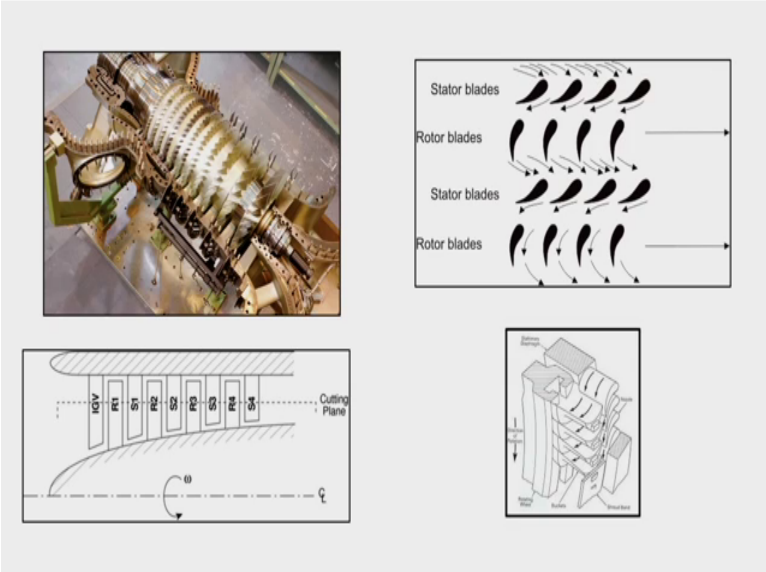

So, having said this axial compressor in general we will be analysing as what we had done for the centrifugal compressor. In case of centrifugal compressor, we drew inlet velocity triangle and the plane which is containing the axes of the rotation. And we drew outlet velocity triangle in the plane which is normal to the axis or rather which was containing the radius vector of the impeller. So, that is how we consider two different planes which are mutually orthogonal to each other for drawing inlet and outlet velocity triangles. And then for that we consider that there can be three types of outlet triangles possible depending upon the blade, shapes. But here what we would have is, we have rotor and stator both having the possibility of flow to be going axially.

So, our analysis whole analysis would be based upon the central mid plane height of the blade. So, this is the mid plane height of the blade. So, our 2 D analysis whatever we would be dealing with is at the mid height of the blade that is why this is the top view of the axial compressor. And then this is the corresponding possibility of the cutting edge plane where we are going to draw the plane and then on that plane, we will draw the velocity triangles and we will find out corresponding work interaction for the axial flow compressor or pressure rise or temperature rise as it is required.

In this case, then we first we will have rotor. So, from the rotor we will have blade rotor blade will pass the flow and it will impart the kinetic energy to the flow and then that would enter into the stator and then the stator will raise the pressure; the stator will raise the pressure and then for again it will go to the rotor. So, the flow passage is from the rotor, stator rotor in this passion in case of the centrifugal axial compressor. We can also see the how the flow is going in the stator and rotor combination in case of the axial flow compressor.

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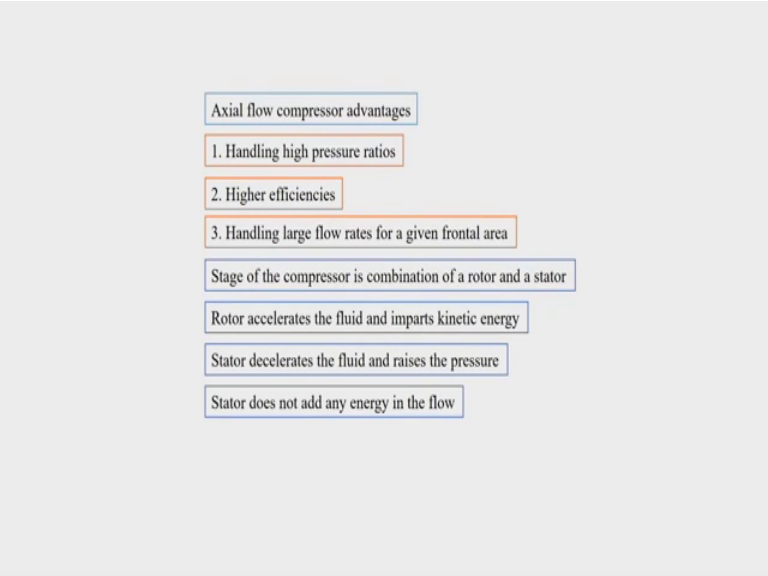

So, here what we would have axial flow compressor generally is getting used for various advantages of its and those advantages include that it can handle very high pressure ratios. However, it does not handle the high pressure ratio in a single stage, but overall pressure ratio which is required for high power generation in case of electricity generation or may be higher thrust requirement in case of the air craft repulsion. So, high pressure handling possibility is there with a axial flow compressor. Further for high pressure ratios, this compressor exhibits higher efficiencies. So, this is also an economical point for the axial flow compressor for which it will be considered.

Third is handling large flow rate for given frontal area. This was the problem for the case of centrifugal compressor this turned out to be the advantage for axial flow compressor and then for given frontal area it handles large flow rates and then within that the since frontal area is also less then we get lesser drag which is the most requirement for the aircraft operations. So, lesser drag is also an advantage for axial flow compressor for a given frontal area ok.

So, then stage as what we have seen that compressor will be designed in multiple stages. In that case it a stage of a compressor is comprised of as what we have seen in last slide that there is a rotor then there is a stator. So, rotor and stator composition or combination is called as a stage of a compressor. So, the both together would impart certain pressure rise to the compressor they would add together certain rotor would add the energy and then the stator will convert it into the pressure rise

So, this is how combination of rotor and stator would comprises stage of the centre of an axial compressor. In this case rotor accelerates the fluid and increases its kinetic energy; in the simplest case this is the job of a rotor. So, rotor is supposed to put the kinetic energy into the fluid and it would increase its energy content; it is energy adding component of the compressor and then this partially it would also help to raise the pressure, but not completely, but then the there is a stator which decelerates the flow and raises its pressure completely whatever it is the required value after that stage. However, stator does not add any energy into the flow. Stator is a stationary object it does not add any energy into the flow. So stator does not add any energy into the flow it is basically a diffuser which converts the energy which is present inside the flow and then it raises the it actually raises. So, stator which is stationary object of a compressor, it necessarily does not add any energy into the flow, but it is job is to increase the pressure from the available energy within the flow. So, this two are the components which are comprising the centre axial compressor.

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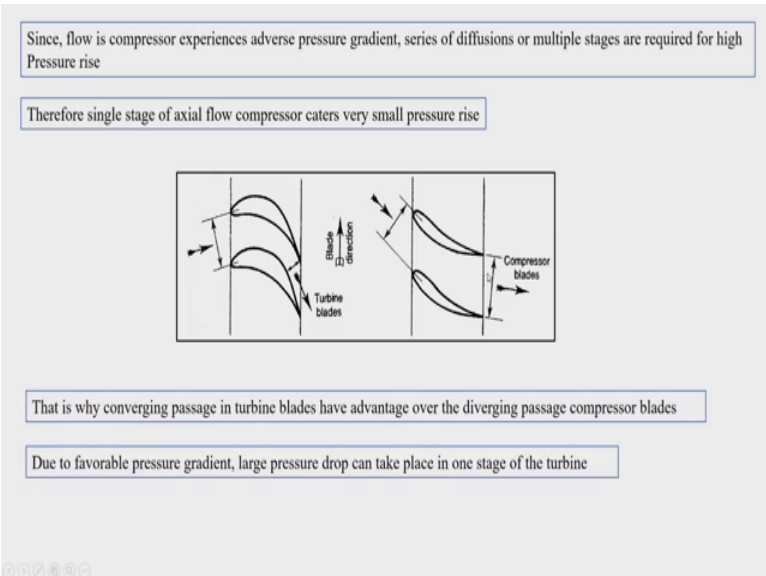

But then since the flow is flow in the compressor experiences adverse pressure gradient, series of diffusions or multiple stages are required for high pressure rise. Basically in case of centrifugal axial compressor, we expect that we are putting the compressor for pressure rise but the whole pressure rise is not going to happen in one stage since the flow is going to experience the adverse pressure gradient. So, every stage partially add the diffusion and then there are series of diffusions or series of stages are required to raise the pressure to the desired value.

Since we are having adverse pressure gradient in the direction in which flow is taking place. So therefore, stage of single stage of axial flow compressor caters very small pressure rise. Basically the reason is we are having the adverse pressure gradient or the increase in pressure in the direction of flow that is why we have to rise the pressure smoothly so every stage adds small amount of pressure into the flow and that is why we need multiple stages. However, it is contrary in the case of turbine where the blade passage in the case of turbine as it is shown in the figure that this is entry this is exit of the blade. So, entry is having larger area exit is having smaller area. So, this act as an nozzle. However, in case of a compressor we are having smaller area at the inlet passage of the blades, but we are having larger area at the outlet so this acts as a diffuser in case of a subsonic flow.

So, since it is a diffuser there is a pressure rise since it is a in case of compressor, but in case of turbine since it is a nozzle there is a pressure decrement. So, for the turbine there is a favourable pressure gradient, but for the compressor there is adverse pressure gradient. So, boundary layer separation is a trouble in case of compressor, but there is no such danger in case of turbines. So, turbine can cater the large pressure of in one stage however, in one stage compressor has very small amount of pressure rise ok. So, that is what the accelerating flow is an advantage for the turbine, but decelerating flow is the disadvantage for compressor.

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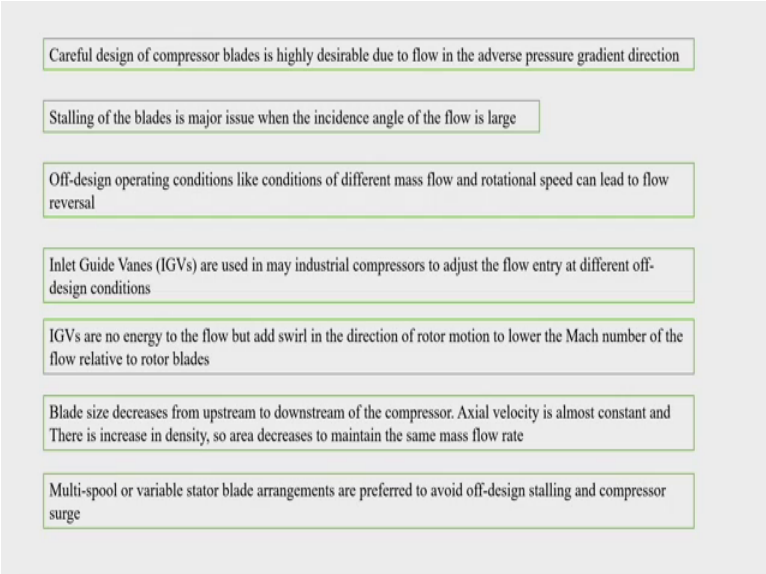

Then we need that is why carefully design of the centrifuge of the any compressor axial compressor especially for this class that we have to design it properly in since it is facing the adverse pressure gradient in the direction of flow. Basically the problem what adverse pressure gradient would lead to is the stalling of the blades which are the specific cases where the flow will impart on to the blade with higher relative angles on the blades. So, this would lead to stalling of the blades. And then that would may lead to this flow separation and then off-design operating conditions are again problem for such conditions which are the reasons for the stalling. So, stalling would lead to flow separation and the reason for stalling is off design operating conditions of the compressor.

Compressor is designed to work for certain mass flow rate compressor is designed to operate for certain r p m, but if it not operating for those conditions then the blades would experience the different angle of incident of the flow and then that would lead to stalling of the blades. In such cases inlet guide vanes are used, but inlet guide vanes are generally used for industrial compressors since they are to the weights and then that is why they are not generally preferred for the aircraft compositions but inlet guide vanes are generally used for industrial applications. So, that we can avoid the off-design problems operating problems of the turbine of compressor blades. But inlet guide vanes do not, basically add any energy they are again stators, but they add swirl to the compressor flow such that the velocity in the direction of the rotor increases so, as to have lesser relative angle with respect to the rotor.

So, these would help us to go with very high speed of the rotor. So, in the direction of the flow again we know that we have to satisfy; we have to work with the compressor for a steady state machine. So, our mass flow rate at the inlet and mass flow rate at the outlet would be similar, but within that in the axial flow compressor axial velocity is almost try to keep constant in the direction of the flow; however, due to pressure rise density increases. So, axial velocity is constant, but density is increasing in the direction of flow. So, to keep the mass flow rate constant inside the axial compressor we should have converging passage which is rather the passage of decreasing area in case of the axial compressors. So, area decreases from the inlet or downstream to the from the upstream to the downstream of the axial compressor ok.

So, there are different options in case of off-design catering of the compressor one of the options is use of multi spool arrangement and other option is to have variable stator blades for avoiding this stalling or surging of the compressor

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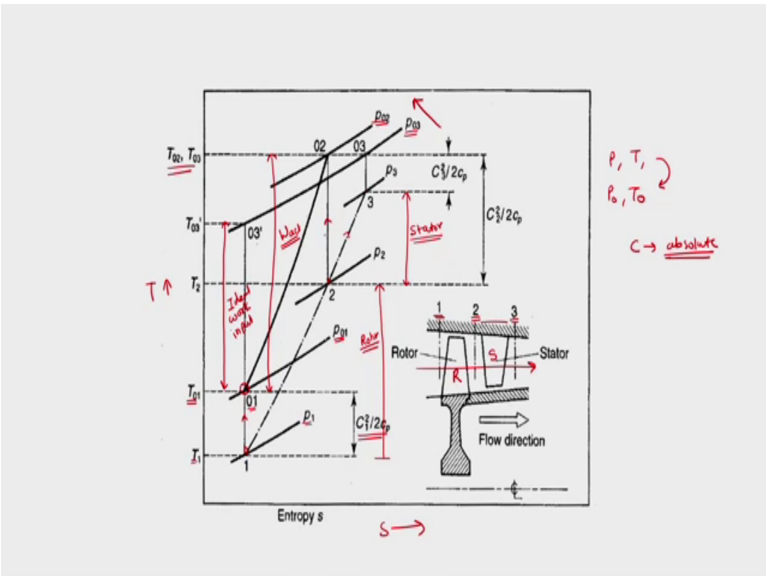

Then we will see the T S diagram for the centrifugal axial compressor where we have T as y axis and S as x axis. Here we are having we can see that the flow is going in this direction first it encounters rotor, then it encounters stator. So, we are at 1 first, then 1 to 2 is what static pressure rise in the stator in the rotor blades and 2 to 3 is the static pressure rise in the stator blades. So, this is the diagram T S diagram for static pressure. But we had seen in class where we had seen that there is a static pressure, there is static pressure, there is static temperature similarly there is total pressure and there is total temperature. So, for that sake we are assuming the flow to be istentropically stopped. So, that, we will transform the static temperature to total temperature or stagnation temperature static pressure to stagnation pressure. So, if at the inlet if we stagnate the flow isentropically then we will reach not 1. So, this is our total temperature at the inlet of the compressor, this is 1. Then when we go from 1 to 2 then we are basically in this range we are in the, we are in the rotor. So, in the rotor we are from 1 to 2. So, at the 2 if we isentropically stop then we will reach to not to. So, not to is the stagnation condition at the outlet of the rotor.

So, P naught 1 is the pressure at the outlet of the at the inlet of the rotor and P naught 2 is the pressure at the outlet of the rotor. But then we have stator. So, here onwards we have stator. So, in case of stator we have again static pressure rise 2 to 3, but at 3 if we isentropically stop then we will reach naught 3, but there is no work addition in the stator. So, there will not be any change in total temperature between naught 2 and naught 3 or rather in the stator. So, total temperature at naught 3 is same as total temperature at naught 2, but the problem is that there is decrease in total pressure due to friction since total pressure increases in these direction on the T S diagram. So, this is naught 3. However for this pressure rise we would have isentropically if you would have compressed or if we would have compressed it without any friction and inert any losses then from naught 1 we would have raised to naught 3 dash here. So, this is corresponding to ideal work input into the compressor, but this naught 1 to naught 3 this is the actual work input in case of the compressor ok.

So, we would have otherwise needed smaller work as input if we would have done isentropic compressor. So, this is the T S diagram as what we know that if we are at 1 which is static pressure P 1 and which is a static temperature T 1 then if we stop isentropically then we get naught 1 condition the corresponding difference is half C 1 square upon C p. Similarly, this height is half C 2 square upon C p and this height is half C 3 square upon C p where C is absolute velocity of the flow. So, this is what we had seen till this time.

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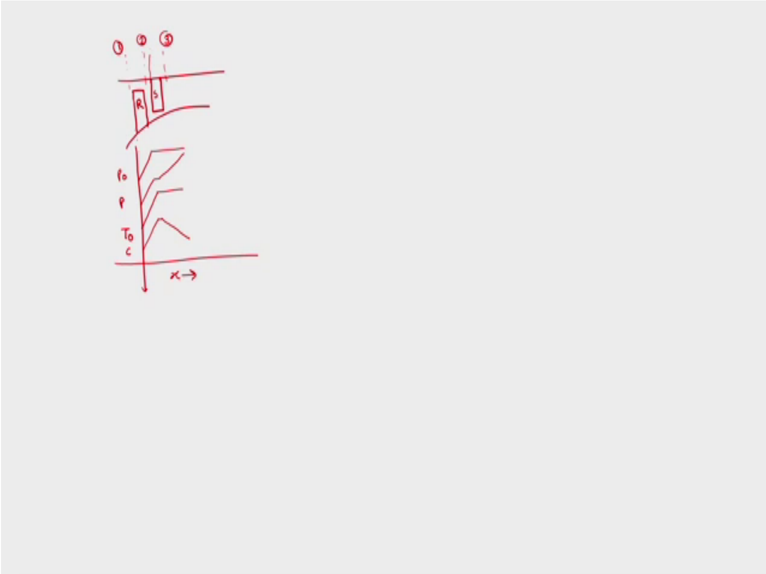

Now we will see how the pressure and temperatures are going to vary in case of a axial compressors. So, this is axial compressor. So, this is rotor, a stage and then this is stator. So, this is R and this is S. And now we are here at 1, here at 2, and here at 3 ok so, 1, 2 and 3. Now here if we plot x as the direction of flow and then if we say that there is there is h as the enthalpy or T as the temperature at the inlet to the rotor. So, if T is the temperature at the T naught is the total temperature at the inlet of the rotor, then from in the x axis along the x axis total temperature increases in the rotor. And then total temperature remains constant in the stator. Similarly we have static pressure P which is increasing in the rotor partially then in the gap it is constant and then it is increasing in the stator. This is for the static pressure, but if it is for the total pressure then total pressure increases in the rotor, but then it remains constant in the stator which is ideally. What we are trying here is an ideal gas; however, in the stator there will be partial loss in the total pressure.

But in case of velocity c there is increment in velocity in the rotor and then it would remain constant in the gap and then it decreases in the stator. That is how it would have raise in pressure In case of the compressor. Now having said this, now we will try to draw the velocity triangles for the rotor.

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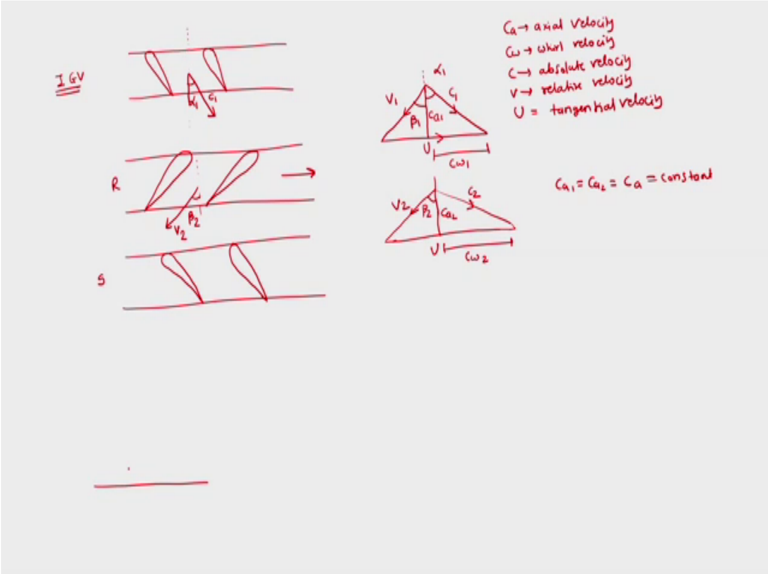

Here let us consider that we are having a stator rotor combination. So, such that this is a stator S and then these are the blades of the stator and then this is x axis this is axis of the flow ok. And then in this case, in this case flow is coming out like this and then this is going towards the rotor. So, this is the rotor. So, for the rotor this is the, this is the rotor and rotor moves in this direction. This is the direction of rotation of the rotor and then it would further go into the stator. So, this is rotor and then this is or in this case this is a inlet guide vane. Inlet guide vane this first for the first stage stator is called as inlet guide vane this is inlet guide vane this is rotor and then this is stator ok.

So, these is absolute velocity C 1 which is making certain angle alpha 1 with the flow while coming in it. But when we are on the rotor then we will say have to talk about relative velocity. So, with this relative velocity flow is going out. So, this angle is beta 2 ok. Now having said this the flow here as it is seen that flow is coming with velocity C 1 into the rotor, flow is coming with velocity C 1 into the rotor where rotor is moving with velocity U and then that is where we get the velocity V 1 which is relative to the rotor and then we know that this is alpha 1, this is beta 1. So, since this is this case further this is C a 1 and this is C w 1 ok. C w 1 is, so C a is axial velocity, C w is whirl velocity and C is absolute velocity and V is relative velocity. Further U is tangential velocity.

Then while coming out, we know that it would come out, but we are at the same height since we are considering same plane. So, our U velocity is same, but it would approach with velocity V 2 like this. So, we had V 2 here and now V 2 is beta 2 and then this V 2 leads to this C 2 in the outlet ok. So, we had C 2 in the outlet and then we had C a 2 as the height and then we would have C w 2 as the whirl velocity ok. However, C 2 is C 2 should be increased in the flow. So, having said this since we are considering C a 1 is equal to C a 2 is equal to C a which is constant for our present analysis and then having said this we can draw both the velocity triangles together and then in that case we would get, this will draw it in next slide.

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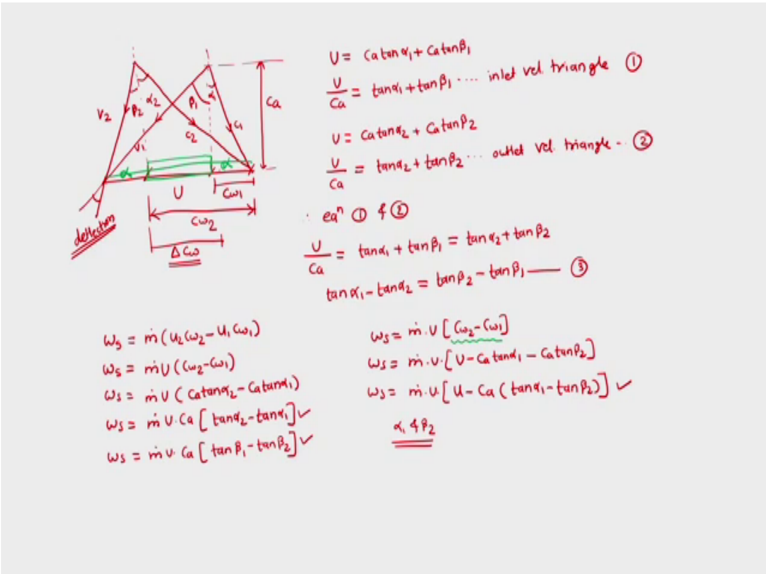

We would get both the velocity triangles in this fashion we would have U velocity here and then initially we had C 1 velocity like this then we had V 1 velocity like this, but then we had V 2 velocity, but we had V 2 velocity here and C 2 velocity like this and in this case we had constant height, this is C a and then we had this as alpha 1 this as beta 1 and corresponding to this we have beta 2 and this as alpha 2.

Sorry this is alpha 1 and this is beta 1 and this is beta 2 and this is alpha 2 ok. So, this is C w 1 and then this is C w 2. So, we have this difference as delta C w which is required for us for further calculation. Looking at this velocity triangle we can write down certain expressions, where U is equal to this length which is the base of the both the triangles is equal to C a tan alpha 1, C a tan alpha 1 is this length which is C w plus C a tan beta 1 which is rest of the length for the U. This length is C a tan beta 1. So, U upon C a is equal to tan alpha 1 plus tan beta 1. This is from inlet velocity triangle and we would name it as equation number 1. There is one more thing to tell that is this angle is called as deflection of the flow.

Flow needs to have pressure risen and so, for that flow will be deflected. So, beta 1 is the relative angle by which flow is coming beta 2 is the relative angle by which flow is going. So, there is a small deflection in the case of axial compressor. So, that there is a small pressure rise in one stage. So, beta 1 is beta 1 minus beta 2 is the angle which is the flow deflection angle for the flow. Having said this from the outlet velocity triangle we can also write U is equal to C a tan alpha 2 C a tan alpha 2 is this length plus C a tan beta 2 is this length. So, we have U upon C a is equal to tan alpha 2 plus tan beta 2 this is from outlet velocity triangle and we can make it as equation number 2. So, from equation 1 and 2 we have U upon C a is equal to tan of alpha 1 plus tan of beta 1 is equal to tan of alpha 2 plus tan of beta 2.

So, we can write tan of alpha 1 minus tan of alpha 2 is equal to tan of beta 2 minus tan of beta 1. So, you remember it as equation number 3. Now let us try to find out 3 things which are of our primary interest which we did for centrifugal compressor also. First thing is to find out work interaction, second thing is to find out temperature rise and third thing is pressure rise from the velocity triangle. We have done same thing from the thermodynamics now we are trying to do it from the point of view of velocity triangle. So, w stage work of a compressor is equal to our shaft work requirement for a compressor is equal to m dot into u 2 C w 2 minus u1 C w 1. We know this formula this is Euler Turbine pump expression. So, w s is equal to m dot, but u 2 is equal to u 1 since we are working on the same mid plane height so, that is what our u is. So, which is C w 2 minus C w 1.

What is C w 2? C w 2 is this length which is C a tan alpha 2. So, w S is equal to m dot U C a tan alpha 2, what is C w 1? It is C a tan alpha 1. So, we have w S is equal to m dot U into C a and then we have tan alpha 2 minus tan alpha 1 ok. And then we have from equation 3, we can also write w S stage work input in case of compressor is equal to tan beta 2 beta 1 minus tan of beta 2.

There is one more way we can write down this expression as we will take this w S is equal to m dot into u into C w 2 minus C w 1. So, w S is equal to m dot into U C w 2 in case of C w 2 we will write it as U minus C a tan alpha 1. So, this big length minus this small length which is C a tan alpha 1; so, minus C w 1 C w 2 is written then we have to write about C w 1. So, C w 1 is equal to C a tan beta 2. C a tan beta 2 is this length. So, this is what an expression, what we can write for C w 2 minus C w 1. So, basically what we are trying to write is this big length, what we are trying to write is this big length from here to here is U and then we need you just calculate this small length and this small length is delta C w which is C w 2 minus C w 1. So, this small length is equal to this big length minus this, minus this and this length is C a tan alpha 1 and this length is C a tan beta 2. So, we have basically w s is equal to m dot into u into u minus C a into tan alpha 1 minus tan beta 2. This is very much required since alpha 1 and beta 2 they are most of the time the design parameter.

So, alpha 1 and beta 2 would be known to us. So, for that factor we wrote 3 equations for work interaction, one equation in terms of angles of the stator, one equation in terms of angles of the rotor and one equation in terms of the one angle of the stator and one angle of the rotor. So, having said this we would now calculate the temperature rise in case of the say one stage of the axial compressor.

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$$W_s = \dot{m} \cdot U \cdot C_a [\tan\beta_1 - \tan\beta_2] = \dot{m} \cdot C_p \Delta T_0 = \dot{m} \cdot C_p \cdot (T_{03} - T_{01})$$

$$\Delta T_0 \big|_s = T_{03} - T_{01} = \frac{U C_a}{\underline{\underline{C_p}}} (\tan\beta_1 - \tan\beta_2) \checkmark$$

$$\eta_s = \frac{W'}{W_{act}} = \frac{T_{03}' - T_{01}}{T_{03} - T_{01}}$$

$$T_{03}' - T_{01} = \eta_s [T_{03} - T_{01}]$$

$$T_{01} \left[\frac{T_{03}'}{T_{01}} - 1 \right] = \eta_s \left[\frac{U C_a}{C_p} \cdot (\tan\beta_1 - \tan\beta_2) \right]$$

$$\underline{\underline{\frac{T_{03}'}{T_{01}}}} = 1 + \eta_s \cdot \frac{U \cdot C_a}{T_{01} C_p} (\tan\beta_1 - \tan\beta_2)$$

$$\left(\frac{P_{03}}{P_{01}} \right)^{\frac{\gamma - 1}{\gamma}} = 1 + \eta_s \cdot \frac{U C_a}{T_{01} \cdot C_p} (\tan\beta_1 - \tan\beta_2)$$

So, we know now that W stage is equal to what we have found out now U C a we had said that m dot U C a tan beta 1 minus tan beta 2. So, this is m dot U C a tan of beta 1 minus tan of beta 2. But this is also equal to m dot C P into delta T naught which is rather m dot into C p into T naught 3 minus T naught 1. We had seen in one of the previous slide the total temperature raises while raising the total pressure and that total temperature raise is corresponding to the work input to the system and then this can be useful to find out the temperature raise. So, this delta T naught in a stage which is T naught 3 minus T naught 1 is equal to U C a upon C P into tan of beta 1 minus tan of beta 2 ok.

Now, this is going to give us from the velocity triangle we can find out what is the temperature rise total temperature rise in a stage. Where C p is the specific heat at constant pressure a rest of the things are there in the velocity triangle. Now we can find out the pressure rise, for that we know isentropic stage efficiency for the compressor is basically we have isentropic work input, isentropic work input divided by actual work input. So, we have T naught 3 minus T naught 3 dash minus T naught 1 divided by T naught 3 minus T naught 1.

So, we have T naught 3 dash minus T naught 1 is equal to isentropic stage efficiency of the compressor into T naught 3 minus T naught 1, but T naught 3 minus T naught 1 is known to us from right hand side. But from left hand side we will take T naught 1 common. So, we have T naught 3 dash upon T naught 1 minus 1 is equal to stage efficiency into U C a upon C p into tan of beta 1 minus tan of beta 2. So, we have T naught 3 dash upon T naught 1 is equal to 1 plus stage efficiency into u into c a upon T naught one c P into tan of beta 1 minus tan of beta 2 ok. But this is this side is isentropic temperature ratio. So, these is equal to P naught 3 upon P naught 1 bracket raised to gamma minus 1 upon gamma is equal to 1 plus stage efficiency into U C a divided by T naught 1 into C p into tan beta 1 minus tan of beta 2.

So, this would help us in finding out the pressure risen in case of the compressor if we know the velocity triangle. So, this is how we would have to utilize the tool of velocity triangle to find out different conditions or different interactions for a compressor. So, rest of the things which are dealt with the axial compressor will be discussed in the next class.

Thank you.