Aircraft Propulsion
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Lecture – 26
Centrifugal Compressor: Velocity diagrams, Workdone

Welcome to the class today, we will talk about centrifugal compressor, so centrifugal compressor comes as the first component that we would see for the gas turbine power plant. We know that air enters into the compressor first so, compressor remains the first part, so we have some options for the compressor and centrifugal of compressor is one such option for that.

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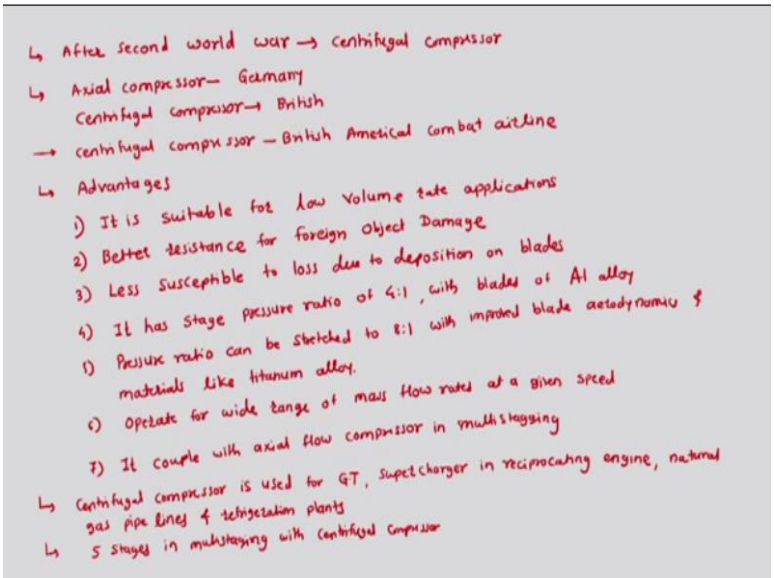

So, we will see, what are the advantages and how a centrifugal compression system has evolved. So, centrifugal compressor was first used and thought for the aircraft applications, so it was first used after Second World War, centrifugal compressor was used actually, different compressors were thought for the use of gas turbine and then among that one competition was with axial compressor.

And axial compressor was getting developed in Germany and at the same time, centrifugal compressor was developed in Britain, so it was developed by British, so centrifugal compressor and the axial compressor were contemporary, hence centrifugal compressor was first used in British American airline; combat airline. This centrifugal compressor actually has some advantages, so we will see what are the advantages of centrifugal compressor.

First advantage is it is suitable for low mass, low volume flow rate applications, second it is having better resistance for foreign object damage, third it is less susceptible loss due to deposition on blade, fourth advantage is it has stage pressure ratio of 4:1, these general rough stage pressure ratio with blades of aluminium alloy, this pressure ratio can be stretched to 8:1 with improvement, with improved blade aerodynamics.

And materials like titanium alloy, this compressor can operate for wide range of mass flow rates at a given speed; it can couple with axial flow compressor in multistage. In applications, centrifugal compressor is used for gas turbine; it has also used for supercharger in reciprocating engine, natural gas pipelines and refrigeration plants. We can go up to 5 stages in multi staging with centrifugal compressor.

So, this is rough idea about a centrifugal compressor and as it is told a centrifugal compressor is developed in parallel with the axial flow compressor and in case of axial flow compressor, it was found that it is more suitable for the higher mass flow rate applications, so it is not then developed centrifugal compressors development is seized or it went on the slow pace since it is not found suitable for higher volume flow rate or mass flow rate applications.

But this centrifugal compressor is found very encouraging in case of foreign object damage, in case of low mass flow rate application, in case of higher stage; single stage pressurize, so these are the advantages of centrifugal compressor. So, we will see, what are the parts of a centrifugal compressor, so a centrifugal compressor can have multiple intakes.

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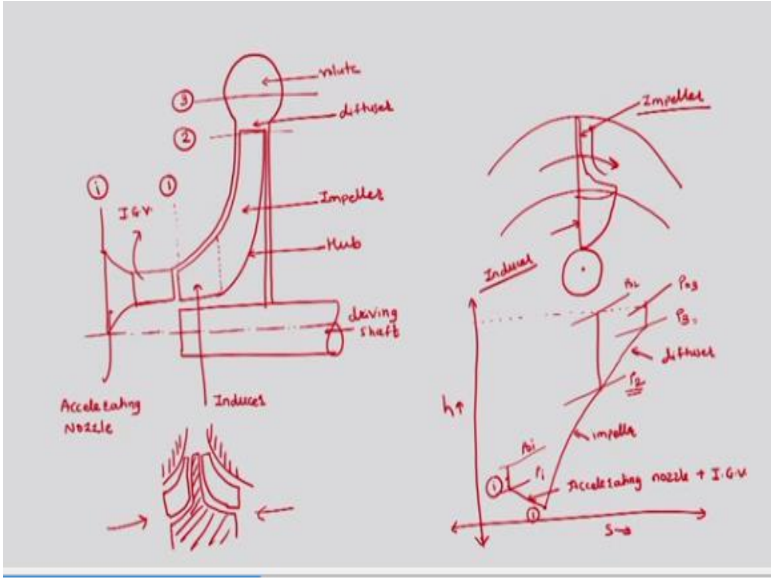

But if we have a single intake kind of centrifugal compressor, then it might have an accelerating nozzle which will accelerate the air and then it will go towards inlet guide vanes and after inlet guide vanes, there will be impeller, so this is general construction of a centrifugal compressor, this shaft is rotating. In this case, we will have this as accelerating nozzle, this is inlet guide vanes, this is inducer, this is impeller, this is volute and this is diffuser, this is hub and this is driving shaft.

So, these are different parts of a centrifugal compressor here for us, we will consider this as station i, then for us, this station at the entry to the inducer is 1, then at the exit we have 2 for the impeller and then we have 3 in the volute, so these are the 4 stations for us for discussing the thermodynamic of this centrifugal compressor. Now, this impeller is casted on the one side of a disc such that that side of the disc upon rotation will take the air or the gas from the accelerating nozzle and would pass it to the diffuser.

And then to the volute casing but it is possible that we will have this impeller casted on 2 sides and then in such case, we have a double sided impeller, in case of a double sided impeller, we will have a situation like this where we have 1 impeller on one side and other impeller on other side of a disc, so this would give us double sided impeller for a 2 side intake; intake will be from either side for the centrifugal compressor.

This centrifugal compressor we can sketch them using thermodynamic relations but before that let us make one more sketch here, we will have this is the centrifugal compressor which we are trying to plot on the front flight, this is side view, this is the front view of the centrifugal compressor. Here, this part is the impeller, this is an impeller and this we call it as the inducer and this would rotate in this direction, air would come axially to start with.

And then, air will come axially and then it will move in radial outward direction, having said this, we can plot thermodynamically the process of compression on hs diagram for this centrifugal compressor. So, hs diagram would be first were at station i, at station i this is Pi, so if we isentropically compress it, then we will reach P0i, this is the pressure but from i station due to the accelerating nozzle, we will have first decrement in enthalpy.

So, this is the reach to station 1, this is station i, then from 1, we would go to station 2 where we would reach pressure P2 and then we would go to station 3, where you would reach pressure P3, so this is at the exit of the impeller, this is at the exit of the diffuser but if we would have isentropically compressed, we would have got to P02 but if we would have compressed isentropically for the same, the diffuser exit, then we would reach the same total temperature.

But we would have lower total pressure as P03, so this is in case of impeller, this is in case of diffuser and this is for the accelerating nozzle and guide vane plus inlet guide vane, it is not compulsory to have inlet guide vane for a centrifugal compressor.

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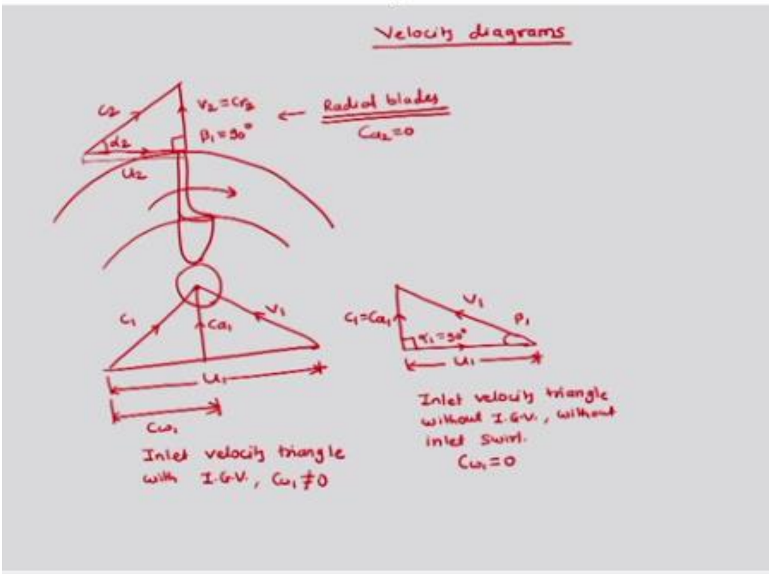

So, let us plot the velocity diagram which is an important discussion point for a centrifugal compressor, so we will plot velocity diagram. So, in the first instance we will plot velocity diagram, if we have a case where we have this as the impeller which is rotating in this direction, which is taking air in axial direction, so if we try to plot the velocity triangle in axial plane or the plane containing axis of the shaft, then we have this as ca1 which is axial velocity by which air is entering.

But this would be the absolute velocities even by which air would be entering and then this would be v1 and then this all would be u1, where this would remain as cw1, which is the whirl velocity at the intake, so this is velocity triangle; inlet velocity triangle with inlet guide vanes, since we have cw1 not equal to 0 but if we consider the same situation without inlet guide vanes, then we would have the velocity triangle looking in this fashion.

So, we will have cw1 to be 0 and then in that case, we have a complete velocity which is axial which is entering and this is v1 velocity, then this is u1, here this is again inlet velocity triangle but it is without inlet guide vanes, it is also called as without inlets swirl. Inlet guide vanes bring in inlets swirl, so it is since it is without inlet swirl, we have cw1 it is equal to 0.

So, this is how air would be entering into the impeller i and then while it is leaving, it would leave with from the tip of the impeller which has velocity u2 which is tangential velocity and then since this is a radial kind of situation, where air would try to go radially which is v2 = cr2 and then this induces absolute velocity c2 which is angle alpha 2, where alpha 1 is 90 degree, this is beta 1, this is beta 1 is equal to 90 degree.

And this is a special case for radial exit or radial blades, these are called as radial blades, here we will have axial velocity to be completely converted into radial and then axial velocity is 0 at the outlet. Having said this, we will move ahead and then decompose the same situation where we are supposed to fail that we are at the impeller i and then at this inducer of the impeller, we will try to plot, this is the inducer of the impeller.

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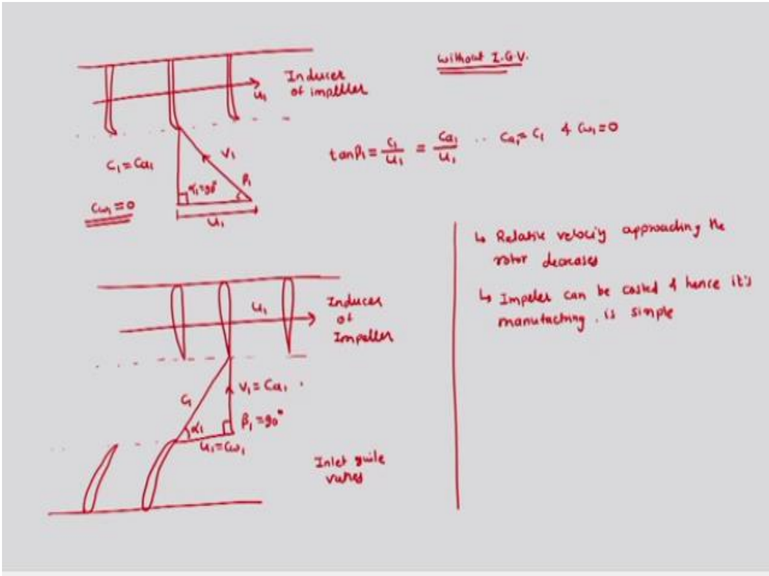

And this is the complete impeller, so we will try how the situation is different, if we are having IGV and without IGV, so this is one impeller, this is other impeller, these are the inducers which we are seeing from the front view and then this is the third impeller, we are plotting inducer of impeller and they are rotating in this direction, we are seeing from the top and then in this case, we do not have any guide vane.

So, we are plotting without IGV or without inlets whirl, so for this case air would enter as v1, then this was the inlet velocity triangle, so we have ca = ca1 and alpha 1 = 90 degree and beta 1 is actually, angle made by the axial velocity with tangential velocity here, we have cw1 = 0. From this figure, we can obviously write tan beta 1 = c1 upon u1 or it is also = ca2 upon u1.

Since, we have ca1 = c1 and cw1 = 0, but if we have inlet guide vanes, then the same situation would get differently managed, then we have one blade of impeller like this, it is rotating in this fashion, this is again inducer of impeller and then we have flow coming from the inlet guide vanes, so inlet guide vane is trying to send the flow, so we have flow which is approaching in this direction which is v1 = ca1 for this case.

But relatively, it is entering like this, where we have this velocity is u1, this velocity can be depicted over here, this is absolute velocity c1 and c1 is making alpha 1, this is beta 1 is equal to 90 degree, so this case is with u1 is equal to cw1 and again, we are having inlet guide vanes but we are making an arrangement here, there is no difference between u1 and cw1, since we have u1 is equal to cw1.

Having said this, we will mention what are the things related to inlet guide vane, then due to the inlet guide vane, we have relative velocity approaching the rotor decreases as what we can see here, we have inducer and impeller blades as straight, so it is easy to manufacture, so these are the things related to impeller and inlet guide vane. So, impeller can be casted and hence its manufacturing is simple.

So, these are some facts related to the impeller or inlet guide vanes for this centrifugal compressor. We will move on and then plot for the different case of the centrifugal compressor.

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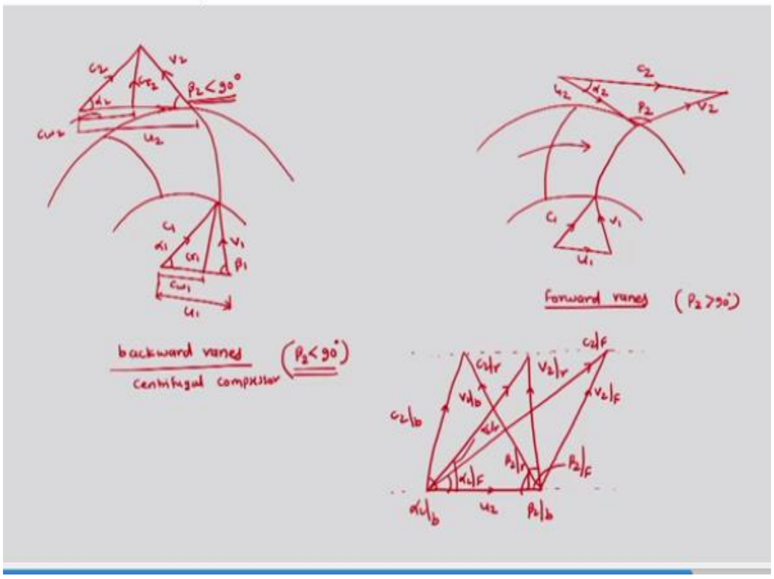

Let us say that now, the blades are not radial, if the blades are not radial, then they can be backward, curved or forward curve, so this is the case where we have backward vanes and in this case, we have velocity triangle and inlet, which is this V_1 velocity and then we have this as radial velocity and so, this is absolute velocity, so we have Cr_1, V_1, C_1, so C_1 will make alpha 1 angle, this is complete u_1.

And then this is cw1, having said this, this is beta 1 angle, so this is the velocity triangle at the inlet and at the outlet, the velocity triangle will be this way where this tangentially would go out as v_2 velocity, this tangent to the circle will be the tangential velocity, which is u_2, so this complete is u_2, then we have this as Cr_2, then this smaller component of u is Cw_2.

And then this will become c2, so these are the decompositions of velocities for backward vanes, centrifugal compressor. Now, here we can see that this is beta 2, this is alpha 2 and beta is less than 90 degree and then this represents the central theme for backward facing vanes, where we have beta 2 less than 90 degree, if we go back and if we see here, then we can see in case of radial, we have beta 2, which is 90 degree.

So, beta 2 remains 90 degree when we are talking about radial vanes, if our vanes are backward facing or backward curve, then beta 2 is less than 90, having said this we will go ahead and plot for forward curved ends and then we have a different situation, where vanes are forward curve, here again rotation is in this direction and then curving is also in the same direction.

So, this is v1 which is tangential in and then this is c1 and then this is u1 and being the forward curve, this is v2, then we will have tangential velocity which is u2 and then we get absolute velocity which is c2 and then in this case, this is beta 2, this is alpha 2 and then we have this as forward vanes and in this case, we have beta 2 which is greater than 90 degree.

So, now for the same inlet velocity triangle, we have 3 options; one is radial forward curve and then backward curve, then we can have 3 velocity triangles which are possible for the same inlet triangle, so first velocity triangle and the outlet was like this and this is u2 and then this is v2 for radial, this is c2 for radial. Having said this, this is beta 2 for radial which is 90 degree.

Now, we will consider the same radial outlet velocity and then we have 3 options for the backward sweep, forward sweep and radial blades, so then for forward sweep, we have beta 2 more than 90, so this would be the option for us where we have this is v2 which is for forward, this is C2 which is for forward and then this is beta 2 or forward, this is alpha 2 for forward.

And earlier case, we had this as alpha 2 for radial, now we know we are talking about the backward sweep vanes and for backwards sweep vanes, beta 2 is less than 90, so this is the option for us for same u2, we have c2 or backward sweep, we have v2 or backward sweep and then this small up acute angle is beta 2 for backward sweep and this is alpha 2 for backward sweep.

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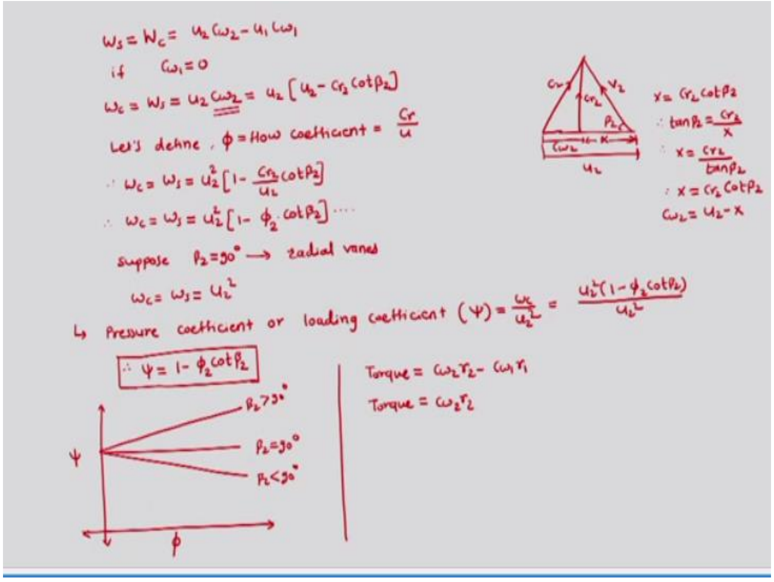

So, these are the 3 options for us for the same inlet velocity triangle and same u2 velocity, having said this we will continue and then we can use the Euler turbine equation turbo machinery equation to evaluate the compressor work or stage work; Ws stands for stage or Wc for the compressor if we have single staging, then the work input is

$$Wc = u_2Cw_2 - u_1Cw_1.$$

Now, let us take a special case where we have no inlets swirl that is cw10, so

$$Wc = Ws = u_2Cw_2.$$

And then this can be written as u_2Cw_2 can be written let us consider, the velocity triangle and from the velocity triangle, we can write down it as Cw_2 can be written as $u_2 - Cr_2 \cot\beta_2$. If we go back and see the velocity triangle now, consider the velocity triangle for the backward facing case, we will draw that velocity triangle for backward facings case this is velocity triangle for backward facing case, where we have this as v_2, this as C_2, this will be Cr_2, this is u_2 and then this for us will be Cw_2.

So, we want to represent Cw_2 and so, Cw_2 is u - this and this x, whatever it is so, this is x = Cr2 $\cot\beta_2$, since we know $\tan\beta_2 = Cr_2/x$ and this gives us $x = Cr_2 /\tan\beta_2$, so $x = cr_2$ cot of β_2, so you can use $Cw_2 = u_2 - x$ and then this x is basically $Cr_2 \cot\beta 2$, let us define φ as flow coefficient and this flow coefficient is actually Cr/u.

So, we have $Wc = Ws = u^2$, we can take common minus Cr_2u_2 into $\cot\beta_2$, so we have

$$Wc = Ws = u_2^2 (1 - \varphi 2 \times \cot \beta_2)$$

and in this case, we have β_2, suppose more than equal to 90, suppose equal to 90 degree that means, radial vanes, we have $Wc = Ws = u_2^2$, so let us define one more term which is pressure coefficient, our loading coefficient as Ψ and then this is

$$\Psi = Wc/u_2^2$$

So, having said this we will get

$$\Psi = \frac{u2^2(1 - \varphi 2\cot\beta 2)}{u2^2}$$

so pressure coefficient or loading coefficient is $1 - \varphi 2 \cot\beta 2$, we can use this for comparing different compressors which is on centrifugal compressors of different blades, different number of blades, different blade geometries, different pressure rises, different sweep angles.

And then if we plot this for a particular case, where we have Ψ versus φ, then we can get a graph which is for β2 is equal to 90 degree, this graph is for β2 greater than 90 degree and then this graph is β2 less than 90 degree, so this is how flow coefficient would alter the loading coefficient for a centrifugal compressor and from this we can get and compare different centrifugal compressors.

Similarly, as what we said for the work input, we can also say for torque and we know torque = Cw2r2 – Cw1r1 and for radial vanes,

$$\text{torque} = Cw_1Cw_2r_2,$$

so from here if we multiply an angular velocity, we were getting the compressor work. Now, in case of compressor or rather centrifugal compressor, we expect the flow to be going out which is radially.

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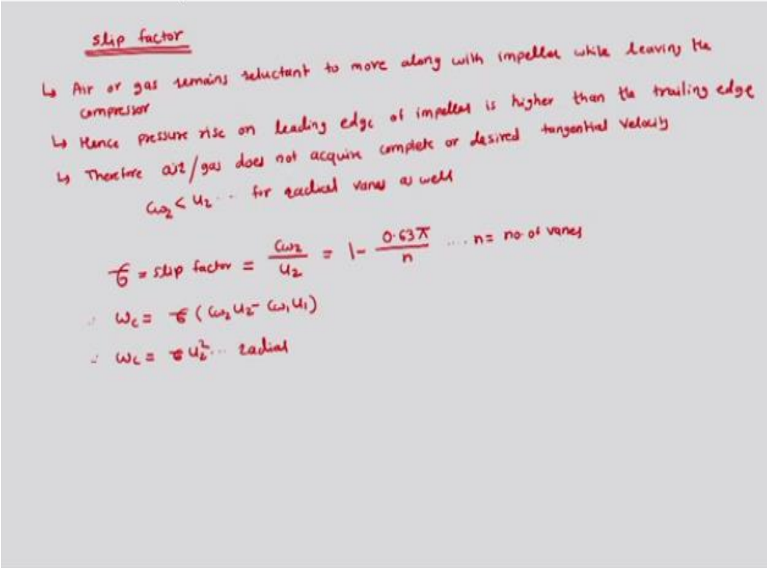

So, but it does not go, there is a term which is called as slip factor here actually, air or gas remains reluctant to move along with impeller while leaving the compressor, this reluctancy is what we are talking about is for the tangential velocity, hence pressurize on leading edge of impeller is higher than the trailing edge therefore, air or gas does not acquire complete or desired tangential velocity.

So, in practical sense Cw2 is less than u2, this is true for radial vanes as well, hence we have to define a slip factor which is defined like this, which is slip factor which is ratio of Cw2 divided by u2 and this can be related to a correlation which gives this with number of vanes or number of blades as 1 – 0.63 pi divided by n, where n is number of vanes and then we can write down due to this slip factor, there is a change in work input.

So, we can write down Wc which was earlier said as Cw2u2 – cw1u1, where it was expected that for radial case Cw2 = u2 but it is not going to come like this, so we have multiplied by sigma, so for radial case we have sigma u2 square, a special case for radial. So, slip factor is going to alter the work input to the compressor, use of the velocity triangle to find out different performance parameters of the compressor; centrifugal compressor will be discussed in the next class, thank you.