IC Engines and Gas Turbines

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Lecture – 43
Introduction and Flow Analysis of Centrifugal Compressors

So, now as what in last class we have seen that there is a fundamental derivation for the Euler turbine pump equation or Turbo machinery equation where we have seen that the three effects are clubbed together where first effect is impulse effect where absolute kinetic energy changes and second effect is centrifugal effect, where radius would change and third effect is the reaction effect where relative velocity would change. Having said these three effects and entering into the part of the parts of the gas turbines gas turbine power plant.

Now in today's class we are going to see what do we mean by centrifugal compressor or objective are here is to id to identify different parts of centrifugal compressor, then understand the flow through those parts in the centrifugal compressor and then draw the T-s diagram for the centrifugal compressor. Then one of the objectives is to draw velocity triangles and then interpret the velocity triangle in perspective of the Euler equation and then consider it for further temperature and pressure wise. So, these are the thoughts which we would have to process for the present lecture. So, in view of this we will start with this centrifugal compressor.

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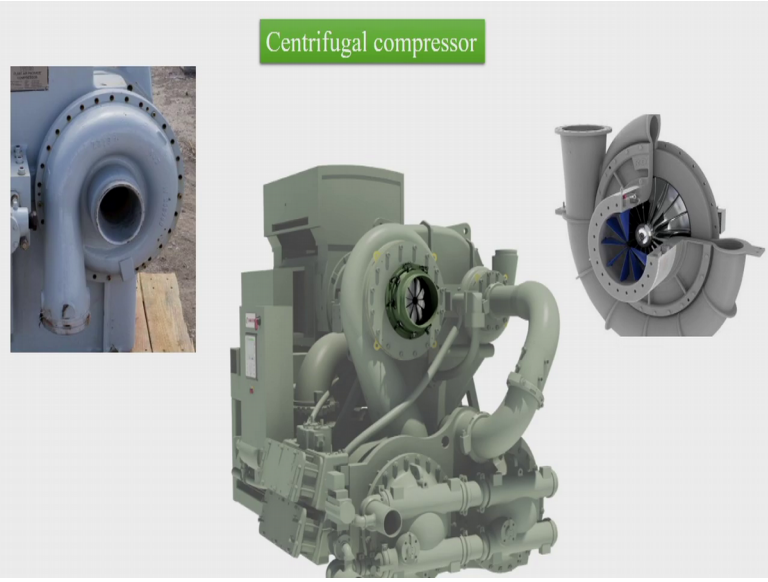

Here in the centrifugal compressor we always have seen this kind of objects in around our vicinity. So, these objects whenever they are seeing we term them as centrifugal compressors, practically their appearance is very special due to the volute casing. The volute casing or the cover of the compressor is a special cover for this kind of compressor, so these kind of compressor can be really identified when we are seeing them in our vicinity.

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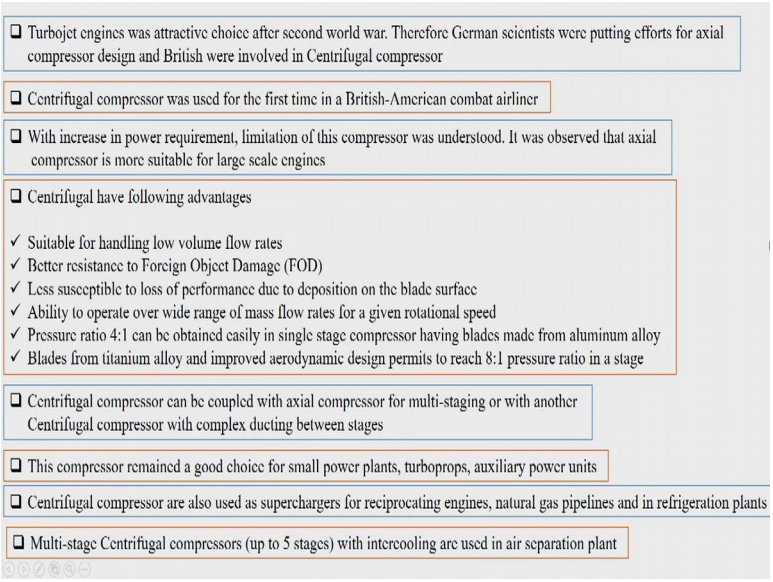

Then how does the centrifugal compressor process of development proceed? Basically turbojet engines were attractive choices after the Second World War when the turbo machines where they are getting developed and then we knew that we had seen that there were first turbo jet engines which were developed in the same period in that period turbojet machines were taught to be developed. But in the turbojet machine as we know there is one of the components as compressor.

So, that compression can be either of axial type or of centrifugal type. So, within that German scientists were taking effort for the axial compressor design and development while British were involved in the design of undevelopment of centrifugal compressor. First centrifugal compressor was used for the British American combat airliner in the same period. So, this is how centrifugal compressor came into existence, but there is a problem with centrifugal compressor and due to that problem whenever there is a increased power requirement or high power requirement is existing or required, then centrifugal compressor is understood to have limitation so it is not further proceeded with.

So, it was observed that axial compressor is more suitable in such cases when we have a requirement of large power produced by the power plant. Obviously, so in that case axial compressors were from more suitable, but still centrifugal compressors have certain advantages. First is it is suitable for handling low volume (Refer Time: 04:09) basically that turns out to be in the above point that turned out to be disadvantage.

But the point is it is efficient if we are trying to handle low mass flow rate or low volume flow rate then centrifugal compressor handles it efficiently, then it has good protection against foreign object damage which is FOD. So, it has better resistance and good protection for the foreign object damage, it has less susceptibility to loss in performing due to deposition on the blade surface.

Basically this is one more advantage for this centrifugal compressor. It can operate for wide range of mass flow rate for a given rotational speed, whatever it had chosen for within the low volume flow rate range and then in 1 stage we can go for the pressure rise of 4 as to 1. In the centrifugal compressor where we have seen that the axial compressor will lead to very small pressure rise and then these pressure rise can be simply attained if we use aluminum as the material for the blade fabrication.

However, the blade material if it is titanium alloy then this pressurize can be increased from 4 as to 1 to 8 as to 1. So, there is there is a stress developed on the blades and due to rotation and then that stress is going to lead to a failure. If we try to increase it to raise the pressure then in that case we have to have some different material for higher pressure rise applications.

So, for that all sake when titanium alloys used then we can go with higher pressure rise centrifugal compressors can be coupled with axial compressors for multi staging or with another centrifugal compressor when we need to connect two compressors for the power plant. This compressor turned out to be a better choice for power plants which are small power plants This is also useful in the turboprop applications or some auxiliary power of generation applications.

So, this is thought as a good candidate in these applications, centrifugal compressors are also found prominently in super chargers for reciprocating engines natural gas pipelines and refrigeration plants. What we see in IC engine we know that for an IC engine we can use a supercharger which will supply the high pressure air to the or high temperature air to the intake of the engine.

So, for that supply we can use centrifugal compressor and that centrifugal compressor is prominently so used in refrigeration applications and reciprocating applications supercharges centrifugal compressors can be used in five stages with the intercooling arrangement. We have seen that intercooling leads to lesser work input constraint for us it would help us to have lesser input of work from the compressor side. So, for a intercooling is preferred and then we can use multiple compressor as it was told in one of the points that we can club it with other centrifugal compressor or with axial compressor, but then we can as well connect it with intercooler and go with 5 stages.

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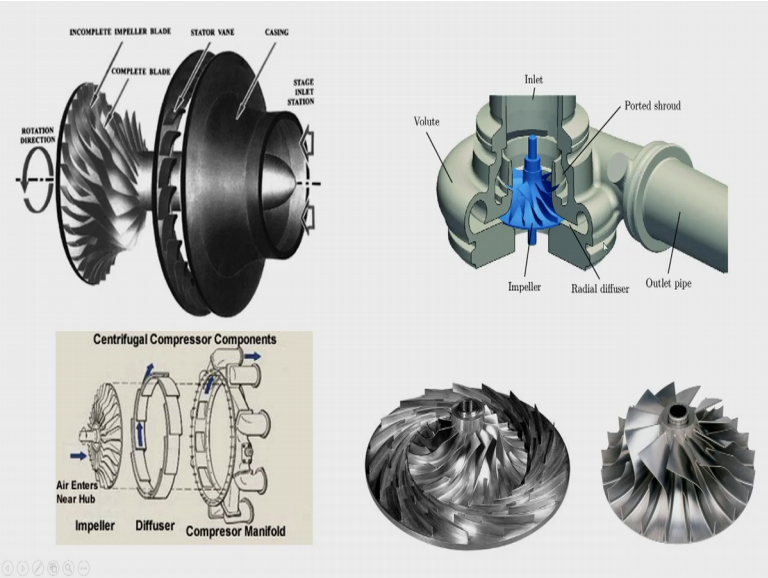

Then there are different parts of centrifugal compressor. We can see on screen that the centrifugal compressor can be shown in different figures is shown to other in different figures. So, if we see the topmost left figure in that case first left hand entities called as the impeller disk of the compressor and then we have stator vanes then we have casing. These are the three parts mainly for the compressor. We have seen that there are mainly two parts what we saw that there is rotor and there is stator in the compressor and then stator comes latter and rotor comes first.

So, we first had the flow entering into the rotor and then flow will go to the stator so same thing here as well flow will first enter since this is a centrifugal compressor, so here idea is to take the flow axially in and radially out.

So, we have flow in this figure which is coming axially in and it will go radially out like this or it will come from here and then it will go out from here and then it will pass into the stator vanes and then it would enter into the; it would enter into the volute casing. So, this would be the construction of centrifugal compressor. So, this is again we are having in the diagram below it we are having impeller and then we are having diffuser and then we are having manifold further this diagram is more clear if we see in the right hand side top part.

So, right hand side bottom we can see that there are two types of figures we are we are seeing that the those are impeller discs. So, these are also shown in this slide, there is one

more entity which is called a shroud and we are going to see that shroud is mainly used to avoid the flow between the high pressure side of the blade to the low pressure side of the blade.

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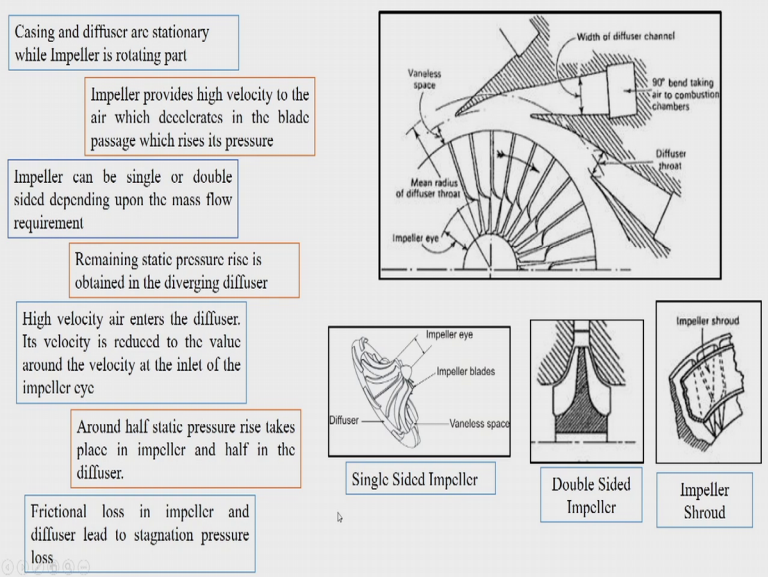

So, what would happen in the centrifugal compressor is this we will have flow which is coming in the eye of the impeller first and then I have the impeller has a curved part that is called as an inducer. So, if we go back if we go back then this curved part this curved part is called as inducer this curved part is called as inducer and here this curved part is called as inducer.

So, having said this we are having this in this figure the curved part is inducer this complete is impeller. So, the bottom of the inducer to the top of the inducer is called as the impeller eye from where flow will try to enter into the blades, then it will come radially and then it will go out radially and then it will enter into the diffuser passage. So, this is how the flow will move and then the flow since it is happening there is basically the rotation given to the blade from the applied electrical energy due to which the rotor is rotating, then rotor is rotating here in the clockwise direction and flow is going radially outwards.

So, these are the flow path lines or streamlines in case of the centrifugal comparison, so casing and diffuser are the two stationary parts while the impeller is rotating part of this centrifugal compressor. Here impeller job is to provide the high velocity to the air which

further would be utilized to decelerate either partially on the impeller itself or partially or fully in the diffuser, so this is how the working principle of the impeller or disc is.

Then impeller can be single hand or double sided depending upon the mass flow rate, here we mean that the impeller till time whatever seen disc we were seen they were having vanes on the only on one side we will see down the line there can be impeller on either side. So, partially some static pressure rise would expect would expect really taken place in the impeller blade and some pressurize will take place into the diffuser air with high velocity enters in to the diffuser and then the value of the velocity of the air gets reduced from the inlet to the outlet this is what it would happen into the centrifugal compressor.

Around half static pressure is expected to rise into the impeller itself and then further half pressure rise is expected to take place in the diffuser. This is a single sided impeller and then this is double sided impeller where we will have flow coming from both the sides and then flow will go radially out from both the slides, so this helps us in the improving mass flow rate. Then there is chance if we can see this, then there is a high pressure on one side of the blade and a low pressure on the other side of the blade then due to the pressure difference and having the open passage between the high pressure and low pressure then there is a chance that air will flow from high pressure to the low pressure side.

So, as to avoid this pressure avoid this flow we can close this passage as possible as we can use in a shroud which is called as impeller shroud. But due to manufacturing difficulties it is difficult to close completely, however it would lead to some friction and that is called so called as windage loss in the compressor.

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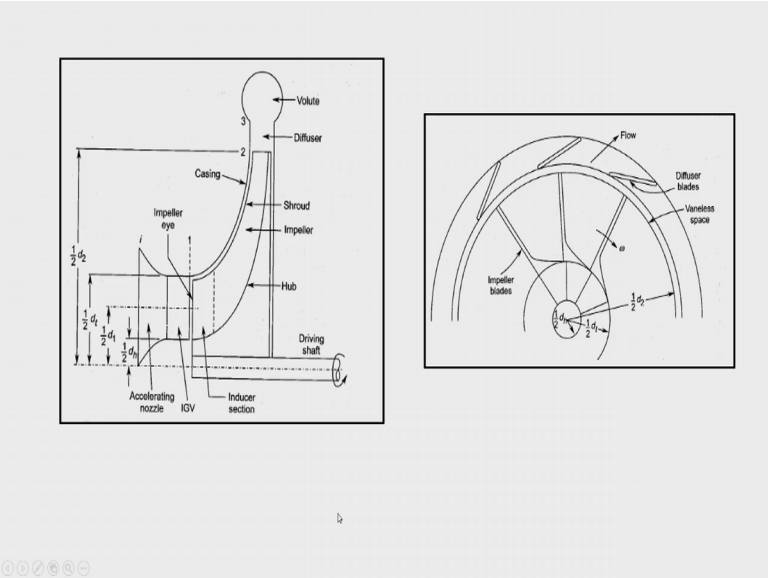

So, practically if in a in a sophisticated compressor or in a complete compressor rather what we would have is an accelerating nozzle and then we will have inlet guide vanes then we will have inducer then we will have impeller then we will have diffuser and then we will have in volute casing. So, this is what the complete construction of a centrifugal compressor.

So, there may be inlet guide vane or may not be there may be accelerating nozzle or may not be, but rest of the components are existing for a centrifugal compressor. So, we will see now what is going to happen when we are having a centrifugal compressor with all these entities. So, this is again an diagram for centrifugal compressor with it is range which are radially outward, so fluid come into the centrifugal compressor impeller inducer and then it would go radially out and then it would go out from the diffusion blades, so this is how the flow passage in case of the centrifugal compressor is. Now we will see what are the velocity triangles for the impeller or for the centrifugal compressor in general, then in this case let us see first case that we are having first as only the inducer.

But then, there is no inlet guide vane inducers idea over here in case of centrifugal compressor is to smoothly have entry of the air into the radial vanes. So, that is what the inducer is having curved portion inducer is curved for that particular reason basically

when we on the compressor rotations would start, so there is a chance that air is going to come in random direction from everywhere.

But we know that centrifugal compressor is radial machine where flow has to go radially, so axial entry will be there radial outlet will be there or axial entry within that the flow can come from any direction towards the axis of this centrifugal compressor, but it has to go radially outward. Then so as to channelize the flow and have smooth entry to the flow the inducer is curved in case of this centrifugal compressor.

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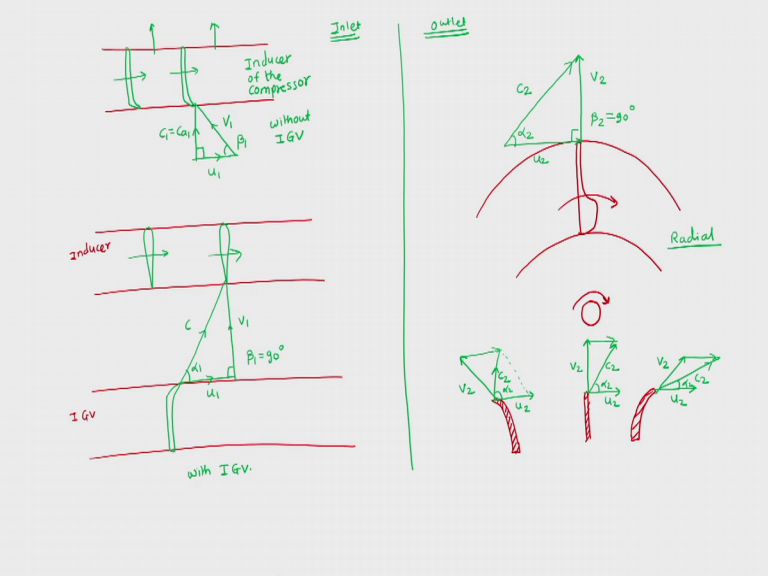

So for that all sake if we have inducer and then there is no inlet guide vanes, then in that case what we will have is velocity triangle as we know we are naming c as the velocity for the absolute velocity and u is the velocity for the rotation velocity and then c and u and then we are having v velocity which is for the relative velocity. So, these are the 3 velocities what we have denoted, then further c velocity has three components one is axial component one is whirling component and third is our radial component there are 3 components of the velocity which is absolute velocity and the absolute velocity submission of two vectors which is relative velocity vector and tangential velocity vector.

So, flow is expected to come from bottom and it is going to go from the top, so here further what would happen is flow would come then enter tangentially into the inducer this is inducer of the compressor. So, this is inducer of the compressor and then we are

having velocity entering tangentially to it. So, we will say it as v 1 but inducer is rotating, so this is basically the rotational speed u 1 in this direction if you remember and if you go back then we can see here that this is the direction of rotation as it is shown over here for the impeller and this is the inducer. That the plane in which we are drawing this velocity triangle is the plane which is tangential which is rather horizontal plane which is passing through the inducer or mid height of the inducer.

So, this is where we are trying to plot this velocity triangle, so that is where we are saying that it is used with the tangential velocity. But since we are not having an inlet guide vane we expect that flow will come axially, so c 1 is equal to ca 1.

So, this is what the velocity triangle it would look like, we will here onwards you should remember that for us we will use beta is the angle for the relative velocity and alpha is the angle for the absolute velocity. So, we have a completely absolute velocity at the intake of the inducer and then we have partially u velocity, but then there is no whirl velocity and here we are since drawing the velocity triangle on the horizontal plane in there is no radial velocity as well in case of this intake inlet velocity triangle.

Further if we consider a case that know now we are having some inlet guide vane, then if we are having inlet guide vane then we will have the velocity triangle along with the inlet guide vane. So, far that all sake let us draw the inducer and then inlet guide vane, so this is inlet guide vane and this is inducer. Then we will have to draw those configurations, now in this case this for us this is inducer and then this is this is inlet guide vane in this case we expect the velocity c 1 to be approaching in this direction. But relatively it will enter in this direction and then this would turn out to be the velocity which is where we will have alpha 1 as the angle of the absolute velocity, but in this case beta 1 is equal to 90 degree.

So, here if you remember then it is rotating in this direction. So, inducer is rotating in this direction and then velocity is coming axially in, but in between we have inlet guide vane. So, inlet guide vanes job is to let it enter smoothly into the blades. So, having said this as velocity triangles now we have to draw velocity triangle for the rotor. So, this is the inlet velocity triangle with inlet guide vane or with the out inlet guide vane this case is without inlet guide vane without inlet guide vane and this is with inlet guide vane. Now we will have to draw the velocity triangle for the rotor.

So, in the rotor case, there are three options for us within that we will choose first an option where we are having radially entry of the blade or where we are having radially outward blade for the centrifugal compressor, then let us draw a sample blade for the centrifugal compressor and then we will draw the velocity triangle for that case. So, here we are having a centrifugal compressor vane and then it is rotating in this direction. This is inducer and then this is impeller disc and flow is coming axially in here this is the shaft which is rotating like this, so this is incoming in this direction and then it is going out in the radial direction.

So, having said this we will have velocity triangle since we are saying that flow is expected to go radially out velocity triangle at the inlet is already drawn, but for the outlet we will draw the velocity triangle. Now velocity triangle at the outlet is expected like this velocity of the flow will go radially out and then this velocity is v 2 which is going radially outward, but at this point we know that there is a tangential velocity in this direction which is u 2.

So, relatively flue will go in absolute velocity of the flow this is c 2. So, practically we will have this is alpha 2 and then beta 2 is equal to 90 degree. So, this is the velocity triangle for the outlet, so if we see then this part is for inlet and this part is for outlet. So, this is outlet velocity triangle in case of the radial vanes, but vanes need not be radial in case of a centrifugal compressor they can be of different types they can be either backward curve or forward curve.

So, in case of back ward curve or this is radial vane practically speaking this is radial, in case of backward curve for we have will draw for backward curve velocity triangle will be different at the outlet. But the inlet velocity triangle would be same, so in case of backward curve we will have blades which are not radial but they are backward curve and then in case of radial we have blades which are radially outward and in forward curve we have blades which are forward curve so these are blades ok.

So, we will have velocities accordingly in the outlet, so first we will draw for backward curve everywhere let us consider that u is the velocity which is tangential and is of same magnitude, then here since blades are backward curve. We will have this is u 2; this is u 2 this is u 2 and this is v 2 then this is v 2 and then this is v 2 this is v 2.

Now in this case, these two vectors would add and we can know that this vectors would lead to this as absolute velocity c 2 and this will lead to absolute velocity c 2. This would lead to absolute velocity c 2 in this direction. So, what we will have is this angle as alpha 2 and then we will have this angle as alpha 2 this angle as alpha 2 ok, then accordingly we can decompose it into whirling component and radial component for the absolute velocity. So, in that case we can draw the velocity triangle or the blades of the impeller.

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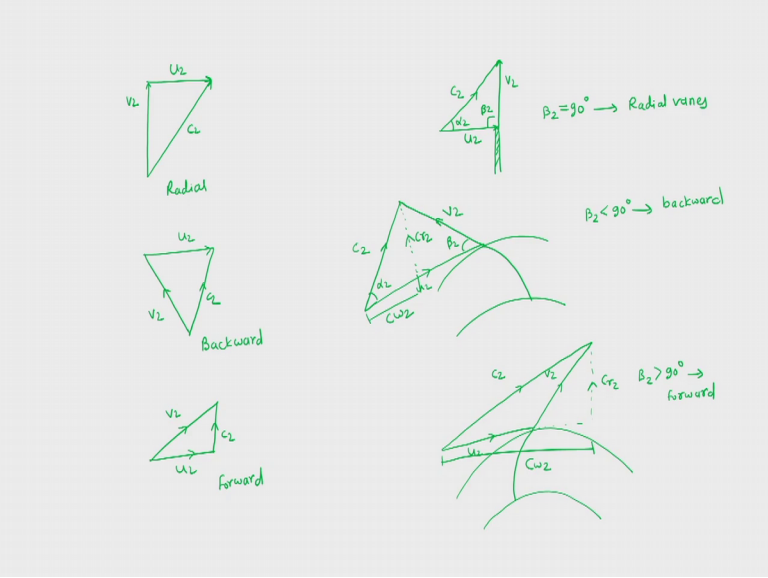

So, in such a case let us draw the velocity triangle for the radial blade for the radial blade what we have is this as v 2 and this is u 2 and then we will have we will have c 2 as the velocity which is this is c 2 this is u 2 and then this is for radial as what we had drawn earlier. In case of backward facing, we have this as v 2 this as u 2 and then this is c 2 this is backward and in case of forward we are having this as v 2; this is u 2, then this is c 2 so this is Forward. So, this is how we will have velocity triangles for the 3 blades which are of different type so Radial Backward and forward type.

But here what is important to note that we have to draw the angles and those angles would be for the those angles would be for the absolute and relative velocity ok. So, in this case we will again show that if this is the blade tip then this is the v 2 this is u 2 and then this is c 2. So, we have this as alpha 2 this as beta 2, so far as beta 2 equal to 90 degree is the case of radial vanes and for now backward facing blades. So, let us draw a backward typical backward facing blade.

So, here we will have this as our this as our v 2 which is v 2 and then this is the tangential velocity which is u 2. So, this would turn out to be the in this case this would turn out to be the c 2. So, for c 2 we have to decompose it so this is practically beta 2 this is practically the alpha 2, so we have beta 2 here is less than 90 degree and then we call it as backward facing vanes. But this c 2 can be decomposed into 2 components one component is c r 2 and other component is c w 2 and we had seen that this c w 2 appears which is a whirling component and c r is radial component and this whirling component appears in case of the work input formula for the compressor.

Now, if we will draw the case for forward facing vanes, then let us draw that; so this is forward facing vane. So, in this case we have v 2 here then we have u 2 we have u 2 here and then we have c 2 here we have c 2 here. So, accordingly we get c r 2 and then we will get complete this as c w 2, so this is how velocity components would get decomposed for beta 2 which is greater than 90 degree and that is for forward facing vanes.

Actually in principle practically people tried to use beta 2 is equal to 90 degree range radial range since it is impelled to fabricate, however we can see that later on that if we are having beta 2 greater than 90 then the pressure requirement pressurize which would happen will be higher for the given blade. So, there would be a problem of surging and then there is problem of the flow dynamics inside the compressor. So, generally blades with beta greater than ninety beta greater than 90 are not preferred, beta less than 90 are preferred or beta equal to 90 are preferred beta less than 90 blades would give us lesser stringent requirement for the pressure rise in a stage since it would have lesser work input.

So, lesser pressurize and then that is why we would have lesser work input for the beta less than 90 case. But simple to fabricate blades of radially out vanes which is beta 90 degree are generally preferred, after having this now we will go with certain things in the case of centrifugal compressor. So now, we know that there are certain things like w compressor or w shaft which is required and we know that it is equal to specific work.

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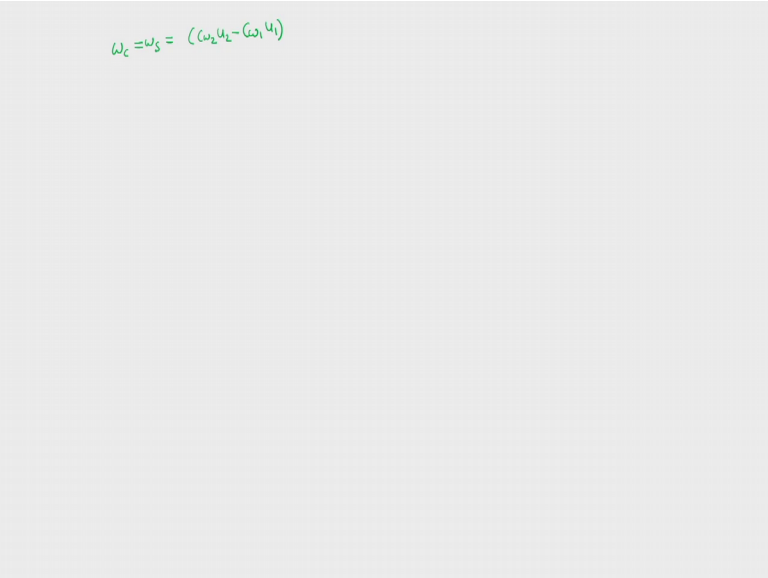

If we try to say that we will not have m dot here and then it will be c w to u 2 minus c w one u 1 and this work formula is obtained from the Euler turbine equation from derivation, here u is pi d n by 60 which is the tangential speed obtained for given omega and then here diameter d 2 is at the outlet or at the tip and diameter d 1 is at the impeller mid height of the impeller i or inducer mid height of the inducer. So, this is where pi d one and by 60 and then this is 1 pi d 2 n by sixty will give us the u o1 and u 2 then c w 2 is the whirling velocity at the outlet and c w 1 is the whirling velocity at the inlet. Now knowing these things we can find out the compressor work input in this case.

So, here we can see that if we are having higher radius component have a higher radius at the outlet then we can get more and more compressor work in a stage. So, that increases the frontal area of the compressor and due to which this compressor is not preferred since it would lead to more drag for the air crafting. So, this is the soul this is one of the major reasons why centrifugal compressors are not opted for aircraft engines since they lead to more drag.

Since for higher pressure requirement their surface area increases frontal area increases, now we can find out the c w 2 and c w 1 using the velocity triangles and then we can find out the pressure rise or temperature rise in case of the centrifugal compressor ok. So, this pressure rise temperature rise or what is the thermodynamic process in the flow for the compressor which is centrifugal compressor that thing we will see in the next class.

Thank you.