Jet Aircraft Propulsion
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Lecture No. # 18
Elements of Centrifugal Compressor

Hello and welcome to lecture number eighteen of this lecture series on jet aircraft propulsion. We have been talking about jet aircraft propulsion systems, and off late we have also been discussing about axial compressors.

So, we have started taking up the components for discussion one by one. And one of the first components that we have decided to analyze was compressor. And as I mentioned there are different types of compressors. And primarily there are two types of compressors, which are used for aircraft propulsion; one of them is known as the axial flow compressor probably the more commonly used compressor these days, especially for larger sized engines.

The other type of compressor that is also used for aviation purposes is the centrifugal compressors. And so that is what we shall be discussing in today's lecture, we will have some discussion on details of centrifugal compressor. And how we can analyze in very simple terms, the performance of centrifugal compressors, and why is it that centrifugal compressors are not really used in larger engines. So, these are some of the topics that we are going to discuss in this lecture as well as we will continue to the discussion in the next lecture.

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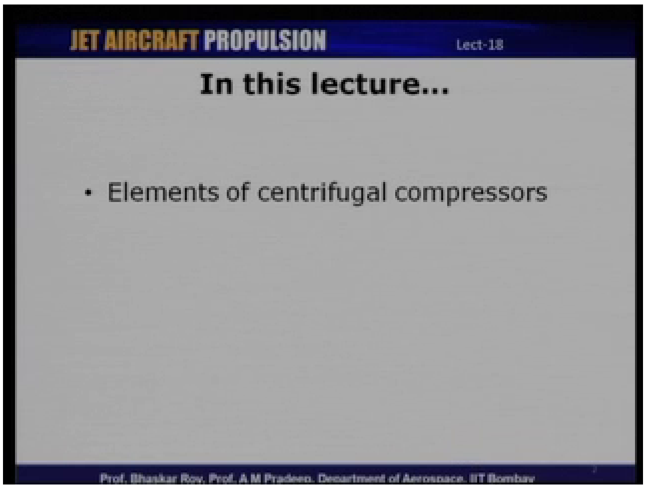

So today's lecture we will have discussion on elements of centrifugal compressor. We will be we will basically be talking about what constitutes a centrifugal compressor, what are the different components and so on.

Now, it is interesting to know that though centrifugal compressors are not very commonly used now. it is of course, used in many of the aircraft but most of the modern day commercial as well as military aircraft primarily use axial flow compressors, but interestingly the first jet engines that flew as you probably know by there are they were two independent developments one was in u k, where sir frank whittle had developed the first jet engine, which was demonstrated.

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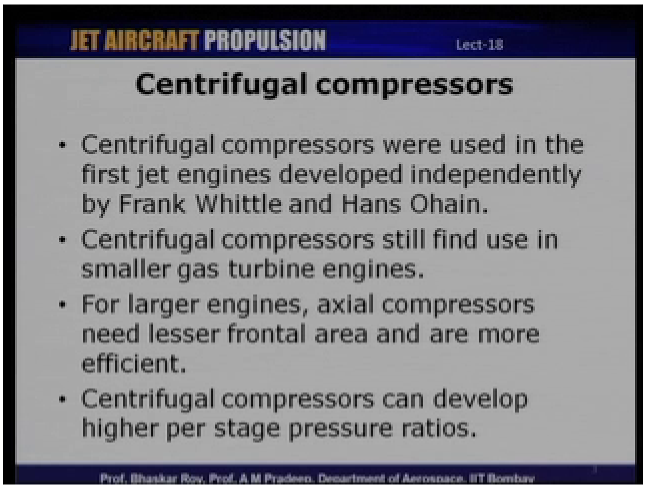

And the other development was in Germany by hans ohain, where he too developed and demonstrated a jet engine, so both these engines had centrifugal compressors in one way or the other. And so, centrifugal compressors still find some utility in modern day aircraft engines but they are usually limited to smaller sized engines. And the reason is that a centrifugal compressors have a larger frontal area that is, if you have to use centrifugal compressor for generating thrust in a large sized engine then the frontal area can become prohibitively very high, which means that for an aircraft engine, the drag of the engine would be quite high and that is something that we would aircraft engineers would not definitely want to have and therefore, they are usually limited to smaller sized engines.

And the other difference between centrifugal and axial compressors being that, for larger sized engines, axial compressors have slightly better efficiency than centrifugal compressors. And that is why centrifugal compressors are not really used in larger sized engines.

And the one advantage that centrifugal compressors have over axial compressors, is that centrifugal compressors can develop higher pressure ratio per stage that is for one stage of an axial compressor, you might not be able to generate too much pressure ratio, and which means that centrifugal compressors can develop per stage pressure ratios, which are much higher than what axial compressors can do.

And so, that is one significant advantage which centrifugal compressors have, which means that, if you look at a smaller sized engine, then if you use let us say one or two stages of centrifugal compressor, it will be possible for us to develop pressure ratios, which would have required five six stages of an axial compressor and that therefore, it obviously means there is a great saving in terms of a weight but of course, that comes with certain penalties and especially, if you want to use the same concept for a larger sized engine, the diameter of the compressor can become quite high and therefore, obviously the drag of such an aircraft would be very high. And that is why they are not used in larger sized engines.

So, let us take a look at a schematic of a typical centrifugal compressor. And what it looks like, so you already, we already discussed about axial compressors, so you know by now, how axial compressors look like. Axial compressors stage consists of a rotor followed by a stator. And these stages repeat as we move from the inlet to the exit of the compressor.

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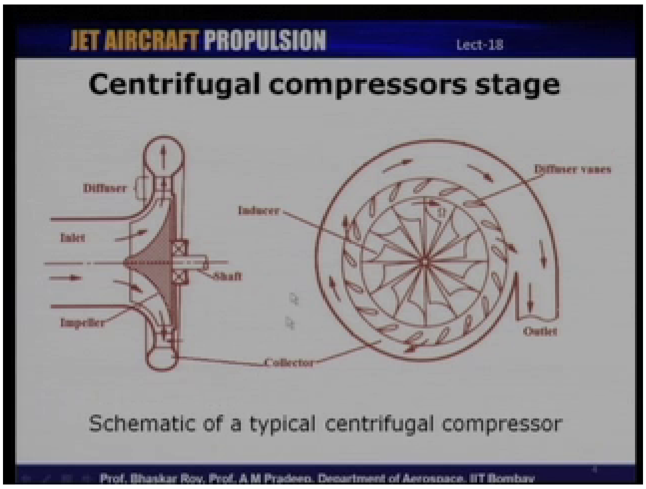

A centrifugal compressor is it looks entirely different as compared to axial compressors. Let us take a look at what they look like, so what I have shown here is a typical a centrifugal compressor just a schematic of one of them, so there are numerous designs of centrifugal compressors, this is just one of them. And there are two views of the same compressor that I have shown one is the side view and this is the front view.

So, what typically happens in a centrifugal compressor is that air comes in axially and it leaves the compressor radially, unlike an axial compressor, where the inlet and the exit are both axial here. The inlet is axial and exit is radial.

So, the incoming air as you can see is guided through a set of a avanes here, which are known as the impeller, so impeller is basically the rotor of a centrifugal compressor and then impeller diverts the flow into a collector or a volute through diffuser vanes, so we will of course, discuss about vane diffuser vanes in detail little latter from the front view this is how it looks like. We have the impeller, so this part of the compressor is known as the impeller and that is why this rotates.

So, impeller is the rotor of a centrifugal compressor from the exit of the impeller. The air the working fluid leads or is guided through a set of vanes, which are known as diffuser vanes and then it goes into a collector and it goes out through the outlet.

So, you can see that the incoming air enters the compressor axially and it leaves radially. In what way you will see shortly is that the pressure ratio per stage very much depends upon this diameter of the impeller, which means that, if you need to generate larger pressure ratio per stage, you obviously would need a larger sized centrifugal compressor.

And which means that this is the cross sectional area that will be required to develop a certain pressure ratio and higher the pressure ratio larger the cross section area and therefore, that is a limitation of application of centrifugal compressors to aircraft engines in modern day aircraft larger sized engines.

And there is another component, which is shown here, which is known as the inducer. We will discuss about inducer also in detail little, later inducer is one component or one part of an impeller, basically it is meant to drive or divert the flow smoothly into the impeller, in the absence of an inducer, the flow might enter the impeller with an abrupt change of direction leading to noise and efficiency loss, so that is the purpose of an impeller.

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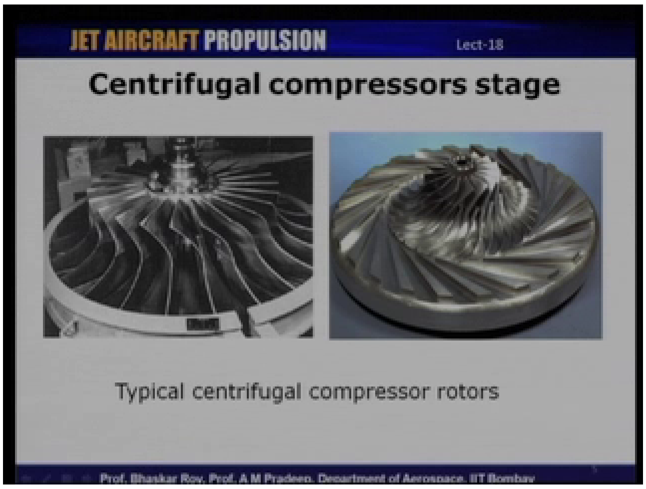

So, this is a schematic. I will now show you two typical centrifugal compressor rotor photographs of two different types of centrifugal compressors. So these are two centrifugal compressor rotors, one of them is a very old generation design of a centrifugal compressor, this is inducer as I had just discussed, and these are the impeller vanes; you can see that these vanes are straight

So, in earlier generation and of course, these are still used. The centrifugal compressor impellers were having straight blades. And what is shown here is a modern a day centrifugal compressor design much more complicated as you can immediately see here. These are the inducer vanes, and then you can see that even the impeller vanes are curved. They are not straight as you can see it here impeller vanes are straight in the older ones. Modern day designs have curved impeller vanes.

And at the exit of the impeller, we have the diffuser this is known as a piped diffuser and air here enters axially, it is guided through the inducer. And then it leaves the impeller and enters into the diffuser before exiting the rotor.

So, these are two typical designs of centrifugal compressor rotors. And though the concept is still the same there have been tremendous developments in terms of design and materials, which are used in centrifugal compressor rotors. And that is why the modern one, which I had shown, has a much more sophisticated design. And which means that these compressors will be able to generate higher pressure ratio with a better efficiency as compared to what we were able to achieve in the earlier days of design of a centrifugal compressors.

So, having understood some of the basic aspects of centrifugal compressors, so what we will do now is to see, if we can analyze a centrifugal compressor rotor or in some way we have already done this for an axial compressor rotor, so we can try to analyze the performance characteristics of centrifugal compressors. And let us see how we can do that based on the geometric parameters like the blade speed and radius and so on.

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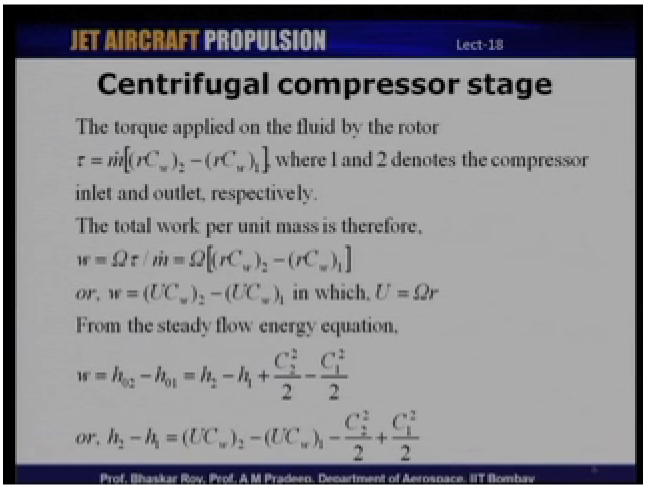

So, the first thing that we will do is to relate the enthalpy raise across a centrifugal compressor to the geometric and velocity parameters. So we know that the torque that is required to generate the pressure ratio or the torque applied by the rotor on the fluid is a function of the mass flow rate, and the difference in the tangential velocity.

So, here we have mass flow rate and the tangential velocities at the inlet and exit. So here are C w is the product of the radius and the tangential velocity at the outlet of the compressor, and similarly r times C w 1 is a correspondingly the product of the radius and the tangential velocity at the inlet.

Therefore, we can now calculate the work done per unit mass, which would be equal to the torque into the rotational speed or angular velocity divided by mass flow rate. And so we divide this by m dot and multiply it by omega. So we get omega times r C w at the outlet minus r C w one at the inlet and omega times r is the blade speed that is angular velocity times the radius obviously it is the blade speed or the peripheral velocity. So work done per unit mass id U times C w at outlet minus U times C w at one where U is equal to omega r.

Now, from the steady flow energy equation, we know that the work done per unit mass is basically equal to the enthalpy rise across the impeller or across the compressor. So that is h 0 2 minus h 0 1 is equal to h 2 minus h 1 plus C 2 square by 2 minus C 1 square by 2, where C 2 and C 1 are the absolute velocities at the outlet and inlet of the rotor respectively.

Now, h 0 2 minus h 0 1 is already known that is U times C w at outlet minus U times C w at inlet therefore, h 2 minus h 1 is U C w at 2 minus U C w at 1 minus C 2 square by 2 plus C 1 square by 2.

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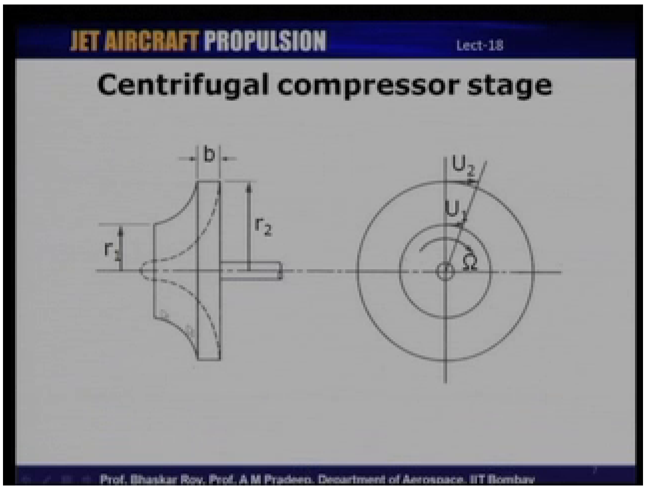

So, this is the static enthalpy rise across the compressor rotor across the compressor. So if you look at a schematic, which I have already shown earlier, I have simplified that this is the inlet of the impeller or the rotor. And this is the outlet, so that is the flow enters the rotor in this direction and leaves the rotor in this direction, which means that the inlet and exit are at two different radii, which is why we have two different peripheral velocities at the inlet we have

U 1, which corresponds to the rotational speed multiplied by r 1 omega times r 1 and U 2 is omega times r 2.

Therefore U 2 and U 1 are not the same. In an axial compressor, we were carrying out analysis at the same mean diameter, where U 1 and U 2 exit of the rotor and inlet of the rotor, the blade speeds were same, but in this case we cannot assume that the blades speeds are same, because obviously they are going to be different.

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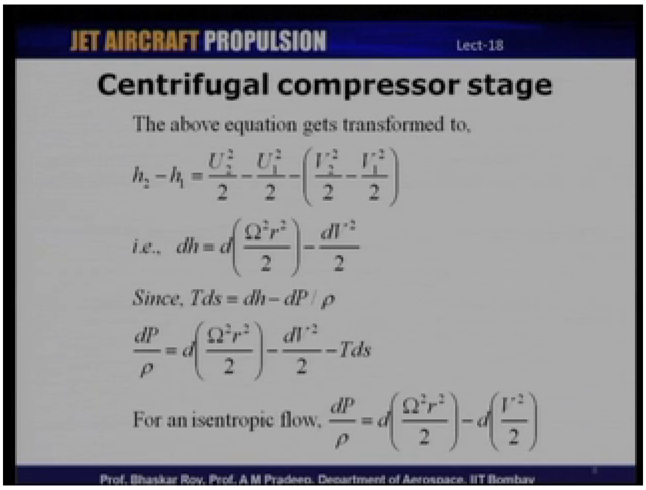

So, if we if we have that in mind then we can simplify the static enthalpy raise h 2 minus h 1 is equal to U 2 square by 2 minus U 1 square by 2 minus V 2 square by 2 minus V 1 square by 2.

That is d h which is h 2 minus h 1 is d times U square by 2, which is omega square r square by 2 minus d V square by 2, and from our Maxwell's relations we have T d s is equal to d h minus d P by rho, therefore we substitute V h here that is d P by rho is equal to d into omega square r square by 2 minus d V square by 2 minus T d s and for simplicity, if we assume that the flow is isentropic, then we have d P by rho is equal to d into omega square r square by 2 minus d V square by 2.

So, this is a very important expression that we have just now derived that d P by rho is equal to d into omega square r square by 2 minus d into V square by 2. Let us try to analyze this expression, which we have derived for a centrifugal compressor, and then we will get to know what exactly this means.

Now, for an axial compressor, we know that we have, we carry out the analysis for the same radius, which means that d of omega square r square by 2 is equal to 0. So far an axial compressor, this equation will reduce to d P by rho is equal to minus d into V square by 2. And what does that mean d P by rho is equal to minus d P square by 2 basically means that in an axial compressor, we get a pressure raise, which is only because of deceleration of the flow that is pressure raise in an axial compressor is primarily because in fact it is only because of deceleration of the flow that is, if you reduce velocity that is if d V is negative that is when you will have a positive d P so for a positive value of d P by rho for an axial compressor, we need to have negative value of d V because we have d of minus d of V square by 2 there.

So, an axial compressor pressure raise is primarily, because of deceleration of flow. So this is not obviously true for a centrifugal compressor, because we have just now derived an equation for centrifugal compressor, where we where we have just derived that d P by rho is d of omega square r square by 2 minus d of V square by 2.

So for a centrifugal compressor the pressure rise depends on two parameters that is one is the omega square r square, which is not 0 for sure for centrifugal compressor. It is not 0 because omega is always has a rotational speed there was always a change in radius. And so omega square r square is not equal to 0 which means that even if the second term is 0 that is if d of V square by 2 is still is 0 even then we can achieve substantial pressure raise in a centrifugal compressor.

So that is tremendous benefit that we have or that is one advantage that centrifugal compressors have in the sense that the mechanism of pressure rise in centrifugal compressor is entirely different from the pressure raise mechanism in an axial compressor.

In an axial compressor, the pressure rise is just because of deceleration of flow, which is why, in an axial compressor, the per stage pressure rise is very much limited because if you try to decelerate the flow too much, then the flow is operating against extreme adverse pressure gradients and there is a likely hood that the flow will separate.

And so, we can only decelerate up to a certain level in one stage, in a centrifugal compressor that is no longer a really a limitation, that is you can generate very high pressure ratio simply by increasing the diameter because r square is increased, and if you rotate the rotor at very high speeds omega square r square is also very high. And so it is possible that we can achieve a substantial pressure raise in a in one stage of a centrifugal compressor simply because of the mechanism of pressure rise, which is different from that of an axial compressor.

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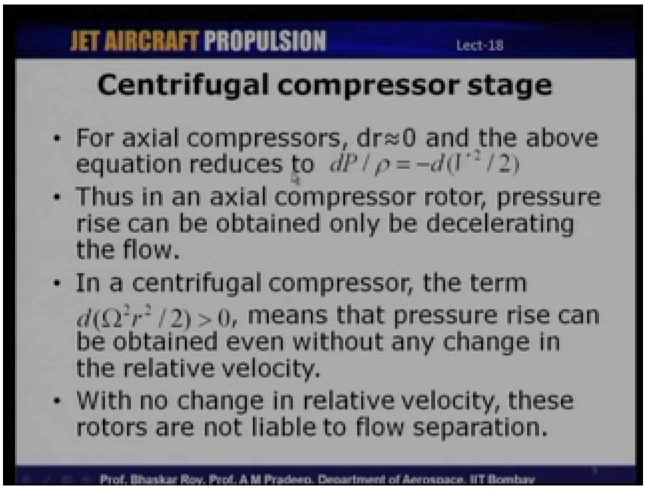

So, let us look at that equation once again. So we have d P by rho is d omega square r square by 2 minus d V square by 2 for an axial compressor, the radius change of radius is 0, because we consider for the same mean diameter or any other circumferential location.

So for axial compressors d r is equal to 0, which means that d P by rho is minus d V square by 2. So in an axial compressor rotor pressure rise is basically because of deceleration in a centrifugal compressor. The first term is always greater than 0, which means that pressure rise can be obtained even without any change in relative velocity.

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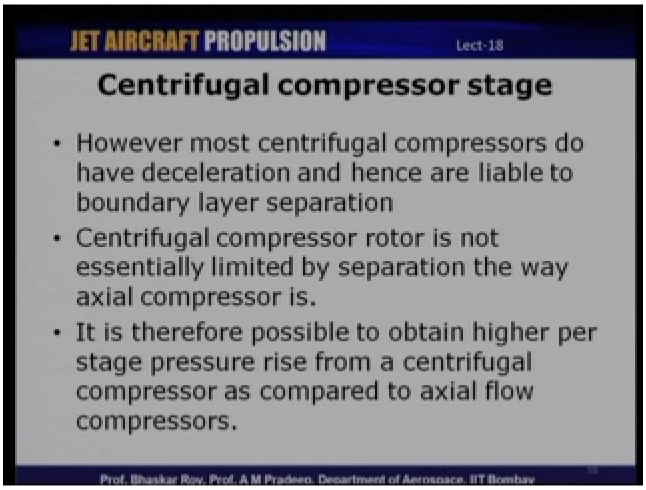

So, with no change in relative velocities it means that centrifugal compressors are not really subject to issues of flow separation, but most of the modern day centrifugal compressors also have certain amount of deceleration taking place. And which means that there are also liable to separation in some sense or the other.

But the essence of this is that centrifugal compressor rotor is not limited by flow separation to the extent that axial compressor rotors are; axial compressor rotors suffer heavily because of flow separation issues whereas, centrifugal compressor rotors really do not have that problem.

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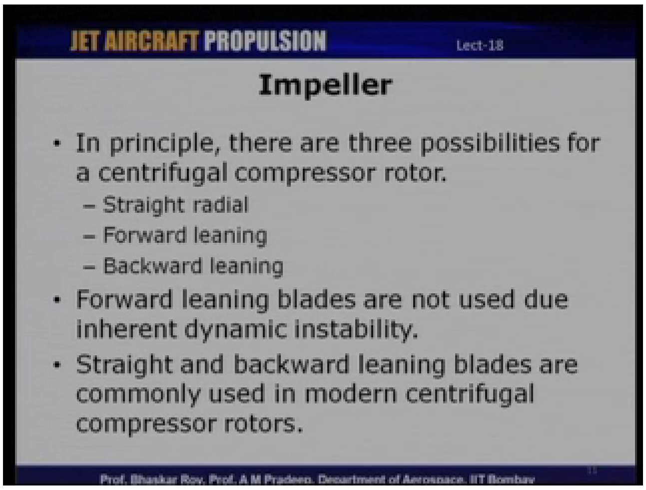

So, what we will discuss next is about one of the components of a centrifugal compressor. When I showed you the schematic, you had seen that there are different components of a centrifugal compressor. We have inlet duct then there is an impeller. And one constituent of an impeller is inducer, which I will discuss a little later. Impeller is the main section of a diffuser of a centrifugal compressor. It is a rotor of a centrifugal compressor.

Following the impeller we have a diffuser. We in fact diffuser again consists of two different sections. We will discuss that also. One section is a vane less diffuser and the other is the vane diffuser and then out out of the diffuser the flow exceeds and goes into a collector or a volute, which is basically the discharge of the compressor.

So, let us look at the impeller of the centrifugal compressor first, and see what is basically the function of an impeller, so impeller as I mentioned, is the rotor of a centrifugal compressor and the based on the design. It is possible to have three different types of impellers. The simplest of them is the straight radial impeller and it could either be forward leaning or backward leaning.

Now, forward leaning blades are inherently dynamically instable that is they have instability problems because of the very fact that they have a forward leaning geometry whereas, the other two straight and backward leaning do not really have that problem and these are the type of vanes, which are used in most of the modern centrifugal compressor rotors in fact earlier days of centrifugal compressor rotors only had straight radial rotors basically because they were simple to design fabricate backward leaning blades on the other hand require more intricate fabrication. And the rotors are subject to very high levels of stress, which in those days it was not possible with the materials they had and manufacturing techniques that were available, which is why are the two pictures that I had shown one of them consisted of a straight radial blade, the older one and the modern one had backward leaning blades.

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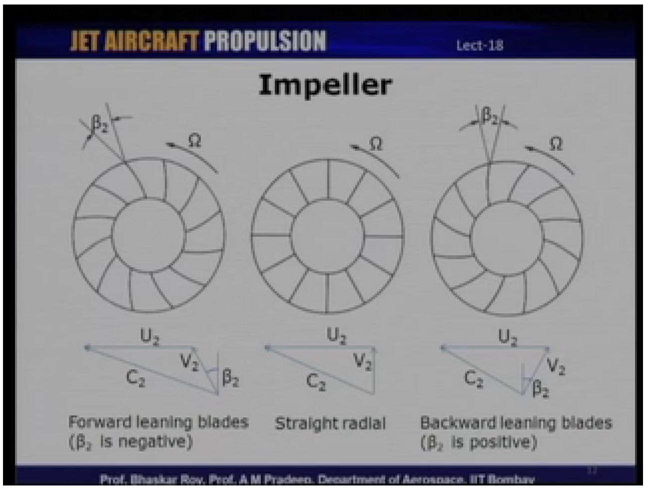

So, these are the three different geometries of impellers which are possible they have just been shown schematically here, and the first one that you see here is the forward leaning then we have a straight radial and the backward leaning.

So, let us look at the straight radial first because that is the simplest one. So this impeller consists of blades or vanes, which are straight and in the radial direction, so if this is the direction of rotation then at the outlet of the impeller, the flow leaves relative velocity leaves the blade in a radial direction.

So, you can see that V 2 is radial in this direction and correspondingly the C 2 is we can complete that from the velocity triangle U plus C is a u plus V is equal to C, so U 2 is corresponds to the blade speed at the impeller exit, V 2 is the relative velocity at the exit, and C 2 is the absolute velocity at the exit.

So, if we look at the forward leaning blade geometry we will see that the velocity triangles will have a a geometry as what you can see here that is V 2 will obviously be tangential to the blade at the tip of the impeller, which is why we have V 2; which is leaning at an angle of beta two here, beta two is negative when it is measured in this direction, so negative beta 2 V 2 lives the blade radially, and then we can complete the velocity triangle in the same fashion as we did for the straight radial.

Backward leaning blades on the other hand we have the backward leaning blades here, these are backward leaning, and this is direction of rotation of the rotor, so here V 2 lives in this direction that is why you see a V 2 here, beta 2 that is the blade angle at the tip at the exit of the impeller is positive, and that is why we have a blade angle like this, so V 2 in this direction C 2 and U 2.

So, these are the three different types of impeller geometries, which are possible or designs; which are possible and as I said these are the two ones; which are commonly used straight radial and backward leaning blades.

Forward leaning blades are inherently unstable and therefore, these blades are not used because of the very fact that they are instable whereas, the other two are the ones which are preferred radial blades are easier to design, but backward leaning blades are in terms of efficiency they are they perform better and therefore, some of the modern day centrifugal impeller have backward leaning blades.

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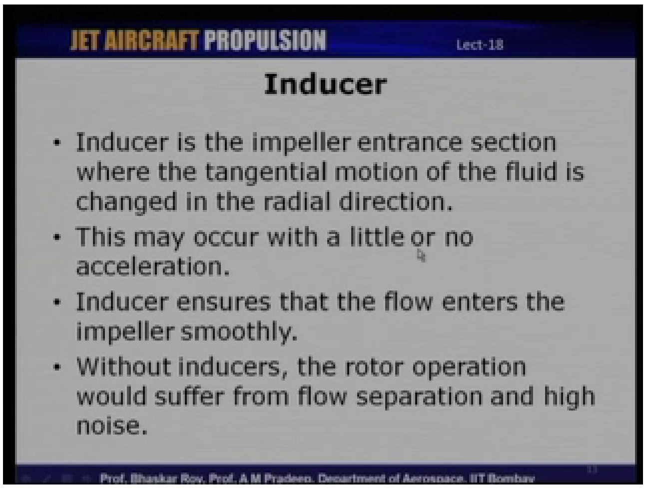

Now, the other component now impeller is as I said the main component heart of a centrifugal compressor that is the rotor, the other component that is of interest to us is the initial part of the impeller that is known as an inducer I have already shown you some pictures of the inducer. Inducer is the initial part of an impeller, wherein the flow is guided smoothly into the impeller because I mentioned that the axial flow which is entering into the compressor becomes radial through the impeller.

So, there has to be some way and because there the impeller itself is rotating at a certain speed there is a relative velocity there so, which means that is there is no inducer or if there is no other component to guide the flow into the blades it means that the flow will enter into the impeller at very high incidence angles, and this could not only lead to risk of flow separation within the impeller. It will also lead to lot of noise and loss of efficiency.

So, inducer is a component, which basically guides the flow into the impeller. Inducer has a function very similar to that of guide vanes, inlet guide vanes in an axial compressor axial compressor rotors often at least the first stage of an axial compressor often have inlet guide vanes they basically guide the flow into the rotor.

So, inducer has a very similar function that it can guide the flow into the impeller, so that the flow entering the impeller enters the impeller smoothly without any risk of separation or loss of efficiency as a result of separation.

So, inducer is a component, which is meant for that but inducer basically forms a component of impeller itself, so it means that it is also possible that there there are centrifugal compressors, which do not have an inducer.

So, there are in fact such centrifugal compressors also, where which do not really have an inducer because for the range of operation of that compressor probably a presence of an inducer is not really required, so and and also some of the modern day centrifugal compressor rotors have impellers, which are themselves curved and that sometimes does not require the the the presence of an inducer as such.

So, inducer is the entrance part of an impeller, where a tangential motion gets changed into a radial motion and this may or may not occur with acceleration or deceleration depends on the geometry of the inducer itself. Basic function of the inducer is that it should ensure that the flow enters the impeller smoothly and therefore, without inducers there could be flow separation and high noise, which might affect the performance of a rotor.

So, let us I will i will show you those pictures, which I had shown initially just to show you the inducer part of the impeller, so for this rotor, this part of the impeller is the inducer, so you can see that the flow, which is coming in axially will be guided smoothly into the impeller, so if if there is no inducer there is there are chances that the flow might enter the impeller at very high incidences and leading to separation and noise.

Similarly, for this rotor you can see this component, this part of the impeller basically constitutes the inducer. So this is the inducer part of this particular rotor and inducer is therefore, this as well.

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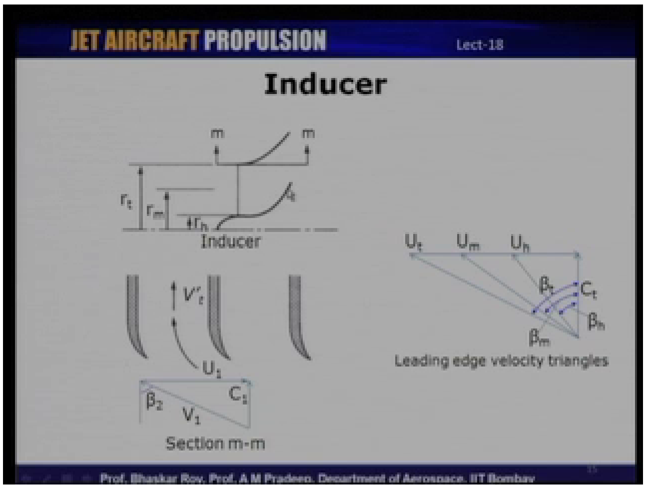

So, if we look at this schematically, so this if you were to take a cross section here, then this is how it would look like, so this is these are the this is basically the inducer part of the impeller, so we have taken a cross section here, so if we chop of the inducer at this section, which is section m m then this is what we will see and we can see that the incoming flow, the absolute velocity is C 1 as a result of the rotation of the impeller. We have a blade speed here and therefore, the relative velocity V 1.

So, in the absence of any inducer what would have happened is that this component would not have been there, so the flow would enter the impeller at an angle of beta 2, which means that without the presence of the inducer flow would have impinged on the rotor at very high incidence and obviously the flow vane separate leading to loss of performance.

So, from the hub to the tip of the rotor that is, if this is the hub section, which has a radius of r h and the mean section radius is r m, tip section radius is r t, the corresponding velocity triangles will get changed because the blade speed changes for each of these locations blade speed is different.

So, for the hub section we have a blade angle of beta h mid section, it is beta m and tip section, it is beta t, so the blade angles are different all the way from hub to the tip, which is true because the blade speed keeps changing which means that there should be a certain small inclination as you can see here there would be a slight inclination to the inducer from the hub to the tip and that is basically because we have to take into account the variation of blade speed from the hub to tip.

So, inducer is meant primarily for this purpose, so let us now look at how we can relate the velocity exiting the inducer or velocity of the flow relative velocity the flow entering the impeller as compared to the velocity actually entering into the inducer.

So, V t prime is the relative velocity entering exiting the inducer or entering into the impeller, so V t prime is basically equal to V 1 t cos beta 1 t that is it is a component of the incoming relative velocity multiplied by the cos component of the blade angle that is we can relate the velocity exiting the impeller, the inducer to the relative velocity at the inlet through the blade angle.

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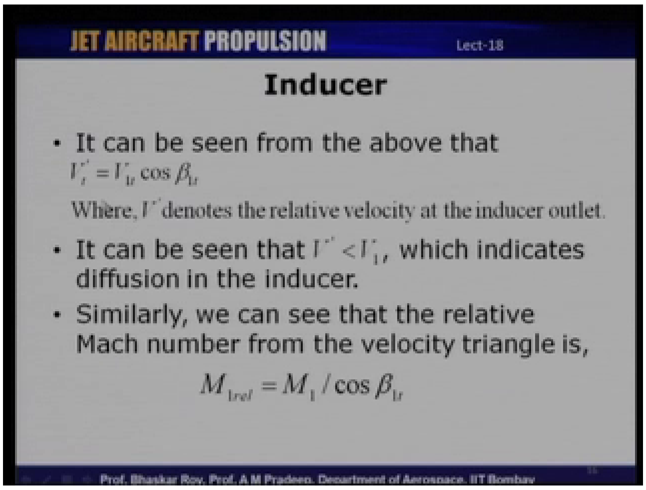

So, V 1 t V t prime, which is basically the velocity relative velocity leaving the inducer is basically a function of the inlet relative velocity multiplied by cos beta 1 t, so if we can see that for any positive value of beta the exit velocity will be less than the relative velocity entering, which means that there will be certain amount of diffusion taking place in the inducer itself because of its very geometry there will be a certain deceleration taking place within the inducer.

Now, the other parameter, which is the relative mach number can also be determined in the same way, which basically equal to the absolute mach number divided by cos of beta 1 t and we need to as we have done for an axial compressor the relative mach number is important because if we would like to keep the design subsonic. We need to ensure that these mach numbers are kept under control because as the mach numbers relative mach numbers exceed certain levels then the shock losses or losses due to the presence of shocks can severally affect the performance of these compressors, so we need to also keep this in mind.

So, we have I think in the initial part of the lecture; I mentioned when we were discussing about pressure raise in a centrifugal compressor, the mechanism of pressure raise in centrifugal compressor rotor is different from that in an axial compressor in the sense that in centrifugal compressor, it is possible that we get a pressure raise even if there is no deceleration of the flow, which is because of the displacement of the centrifugal flow force field in a centrifugal compressor rotor.

And therefore, we can also try to explain this using what is known as the coriolis acceleration, which is which also plays a significant role in performance of centrifugal compressor rotor.

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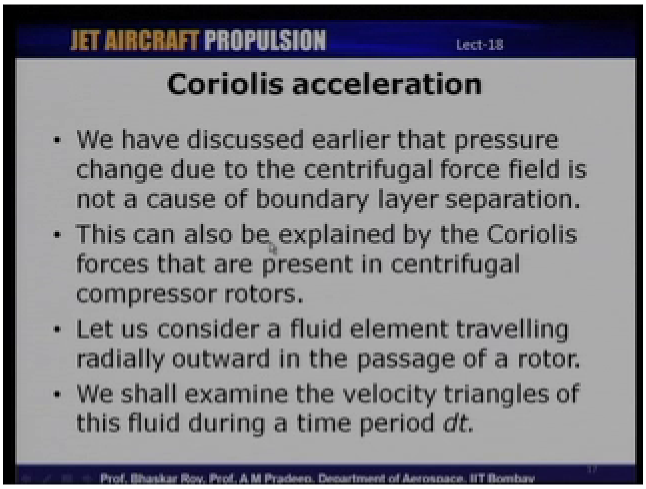

So, we will try to get some elementary idea of what this coriolis acceleration means and what it does to the performance of centrifugal compressor rotors. So in the case of centrifugal compressor rotor the pressure change in the case of centrifugal compressor rotors, the risk of boundary layer separation is probably lower than that of axial compressors because a pressure raise is primarily because of the centrifugal force field and not really because of the deceleration of flow.

So, we can also explain that using the coriolis an forces, which are present in centrifugal compressor rotors, but of course, this will also be present in axial compressor rotor, but we have not taken that into consideration in our design because we were looking at just one radial location of an axial compressor rotor, where as in centrifugal compressor the presence of coriolis acceleration is much more significant than axial compressor.

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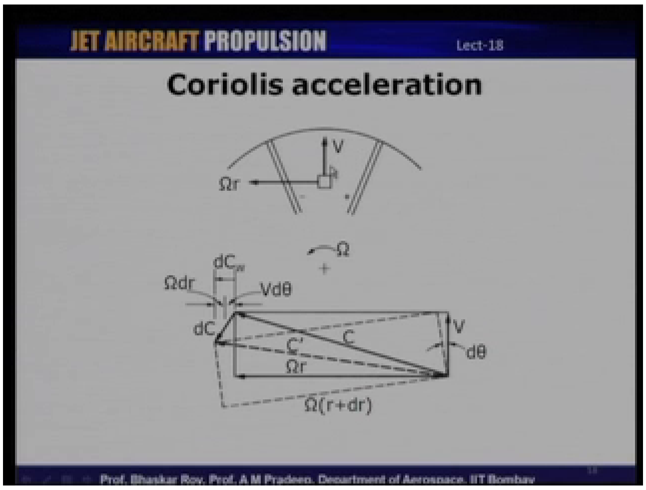

So, if we consider a fluid element, which is travelling radially outward in the passage of a rotor and then what we will see is what happens to the velocity triangles during a certain time period b t, so this is the fluid element, I was talking about there is a fluid element, which is travelling through the impeller, these are the impeller vanes, so I have we have chosen a straight radial impeller vane for simplicity, this is the relative velocity with which the fluid element moves, and this is the peripheral velocity, that is omega r.

So, at the exit of the impeller we have two velocity triangles shown here, the one in solid lines represent the velocity triangle at a certain at t 0, and the one in the dotted lines represent the velocity triangle after a certain instance of time.

So, what we see is that since it is a straight radial rotor the velocity lives the impeller in the radial direction, and this is the peripheral velocity omega r, C is the absolute velocity, so that completes the velocity triangle here after a certain instance of time what we see is that the velocity triangle gets distorted, so there is a slight distortion in the velocity component and therefore, the velocity components are slightly different from what they were earlier.

So, here the dotted line represents the new velocity triangle and what we see here is that there is this additional velocity component as a result of this distortion in the velocity triangles that gets induced and that is basically represented by this differential change in the absolute velocity, which is d C and it has different components; it has components due to the blade speed that is omega d r as well as the change in relative velocity times the the angular rotation that is b theta.

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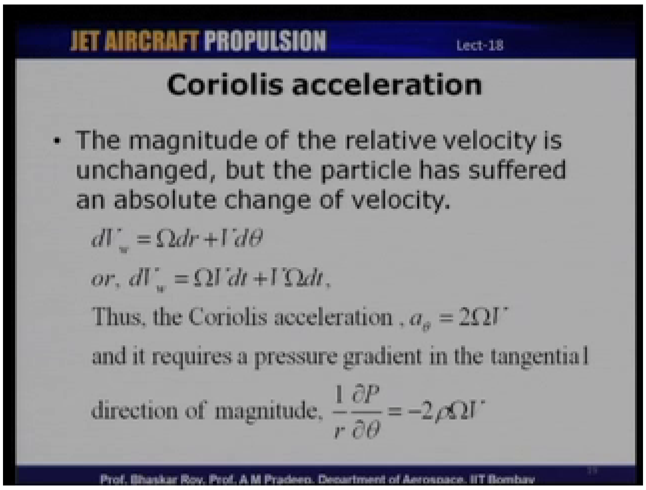

So, this velocity, which if we are assuming that the magnitude of relative velocity remains unchanged there is a slight change in the absolute velocity, which the particle undergoes that is basically given by this component that is d C, so this is assuming that relative velocity does not change much, which is what is clear from this velocity triangle we are not changing relative velocity much, but it does it definitely leads to a change in the absolute velocity.

So, the component of velocity that is d V w; that is the component in the tangential direction is basically equal to omega times d r plus V time d theta, so that is what is shown here omega times d r and V times d theta.

So, that is basically equal to omega times V d t plus V into omega d t therefore, the component of this, which contributes towards the coriolis acceleration is basically, which is represented by a subscript theta or a w is equal to two times omega into V that is coriolis acceleration is basically equal to it is a function of the rotational speed or the angular velocity and the relative velocity.

So, two times omega into V basically represents the coriolis acceleration here, so if we if you remember our expression, which we had derived earlier for pressure raise and we substitute for the coriolis acceleration there what we get is that the pressure gradient in the tangential direction that is del P by del theta one by r del P by del theta is equal to minus 2 into rho into omega into V.

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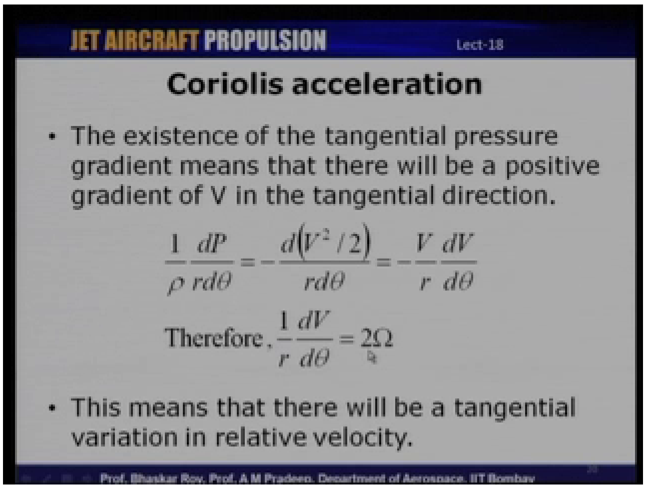

So, what this means is that as a result of this coriolis acceleration we have a certain a presence of a tangential pressure gradient a velocity gradient, so existence of this tangential pressure gradient will also result in the presence of a variation of a relative velocity in the tangential direction that is the previous equation if you were to simplify that what we get is one by rho d P by r d theta is equal to d of V square by 2 by r d theta which is minus V by r d V by d theta therefore, one by r d V by d theta is equal to two times omega because we have already seen d P by d theta, how it is a function of the coriolis acceleration.

So, one by r d V by d theta is equal to two times omega this means that there will always be a tangential variation in the relative velocity, which is a function of the radius as well as the peripheral as well as the tangential velocity, so d V by d theta represents the tangential variation of velocity as a result of the coriolis acceleration.

So, there is always a change in the tangential component of velocity, which is a function of the rotational speed and obviously the radius at which we are considering this as well.

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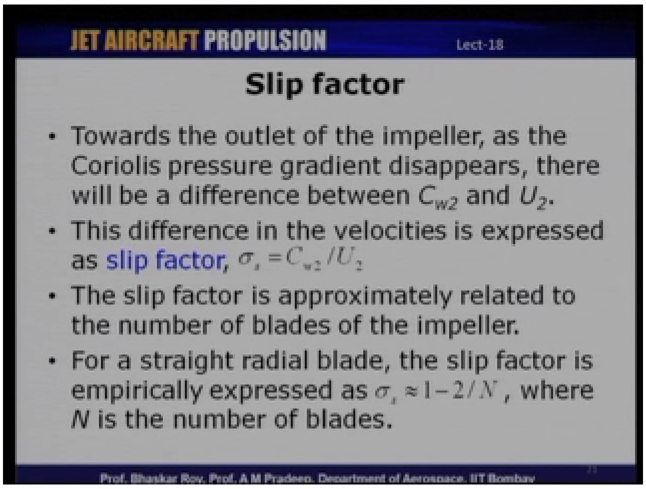

So, because of the presence of the coriolis acceleration we have seen there is a tangential variation in velocity and so, if if you were to look at the velocity triangles at the exit of the impeller, this variation is going to effect the velocity triangles at the exit, now that is as the fluid element lives the impeller there is going to be a slight variation in velocity triangles from what it should have been as per our earlier analysis.

So, this is basically because of the variation in tangential velocity, the tangential variation in velocity being a function of the rotational speed, so towards the outlet of the impeller as the coriolis pressure gradient will disappear, because at the exit there is no no more coriolis pressure gradient there as it disappears there will be a difference between the tangential velocity and the blade speed.

So, this difference is basically represented or is known as the slip factor ratio of this difference C w 2, which is the exit tangential velocity divided by U 2, which is the exit peripheral velocity of the impeller. And it is now known that the slip factor is is a related to the number of blades in the impeller that is as the number of blades changes the slip factor also can change in fact there is an empirical relation, which correlates the slip factor to the number of blades one of the empirical correlations is that slip factor is 1 minus 2 by N, where this is obviously of course, true for a straight radial blade here N is the number of blades, which means that as the number of blades increases the slip factor will approach one.

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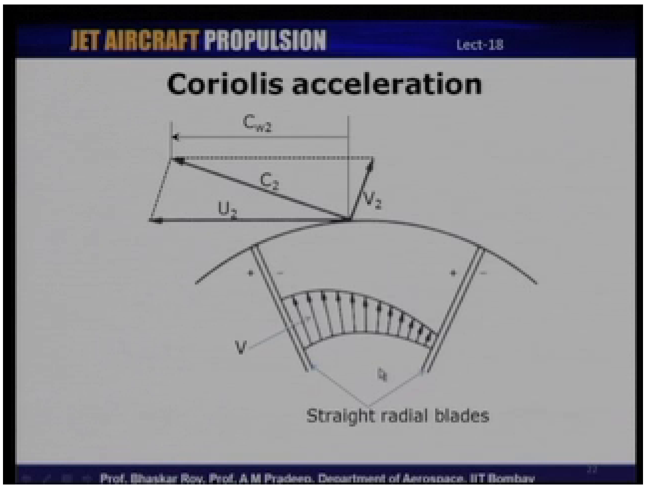

So, if you look at the velocity triangle at the exit, this is the variation in the velocity that I mentioned that there is a tangential variation in velocity at the outlet of the impeller. It means that there will be a difference that is since there is a tangential variation, the relative velocity that leaves the impeller is no longer radial, and there is a slight component that the relative velocity will take as it lives the impeller, because of the disappearance of coriolis pressure gradient here.

And as V 2 deviates from the radial direction it means that component of C 2, that is C w 2 will start becoming different from the blade speed that is peripheral velocity, so higher the deviation of V 2 from radial direction, the lower will be the slip factor.

So, if V 2 were to leave the blades radially then slip factor will be equal to 1 because C w 2 will then be equal to U 2, which is what we had seen earlier. Let me go to the velocity triangle I had shown initially, so if this is how the velocity triangle would have been that is the one shown in solid line that is relative velocity leaving the blades or impeller radially. C w 2 is equal to omega r or U, which is not really true and therefore, the presence of slip leads to a difference between the tangential component of the absolute velocity at the impeller exit as compared to the peripheral speed that is U 2.

So, slip factor is one minus is basically the ratio of C w 2 to the peripheral velocity that is U 2, so as the number of blades will increase what will happen is that if we have more number of blades between in in a rotor, then the tangential variation in velocity also reduces that is, because we the variation from this end of the blade to the other blade, if we have more number of blades obviously will be less. And that means that the slip factor will increase we will have a higher slip factor which approaches one as we increase the number of blades.

So, slip factor is a parameter, which directly depends on the number of blades empirically for straight radial blades. We have seen it is 1 minus 2 by N and as the number of blades increases slip factor will approach one, so we have now looked at three different components of a centrifugal compressor. We have discussed about inducer; we have discussed about the impeller and different types of impellers straight radial forward leaning backward leaning.

And, now we are going to discuss about the other component, which constitutes a centrifugal compressor that is the diffuser, so the flow as it lives the impeller enters into what is known as a diffuser and diffuser again usually consists of usually consists of two ha components. One part of the diffuser is known as the vaneless diffuser or vaneless pace, and then it is followed by vaned diffuser that that is if you have recall the schematic I had shown for centrifugal compressor rotor, there were air foil sections shown at the outlet of the impeller.

So, that is one type of diffuser that is possible it is a vaned diffuser, and some of the other types of diffusers are piped diffusers and so on, so the photograph of the modern day centrifugal compressor rotor I had shown had a pipe diffuser geometry, if you recall.

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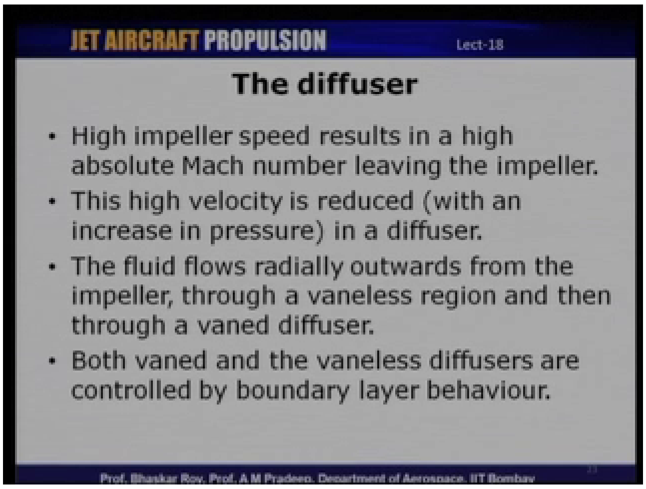

So, diffuser is a component, where in which is similar to a stator in an axial compressor in axial compressor as we know, we consists of a rotor followed by a stator. The diffuser has more or less the same function in centrifugal compressor and in a diffuser the other aspect is that if we at the periphery or a exit of the impeller usually we have a very high velocity and therefore, it might lead to very high mach numbers, which leave the impeller.

So, this can again be decelerated within an increase in pressure in the diffuser, so the fluid usually flows through a vaneless region and then through a vane diffuser and of course, the performance of the diffuser is highly a sensitive to the boundary layer behavior, which means that it can be affected substantially by a boundary layer separation.

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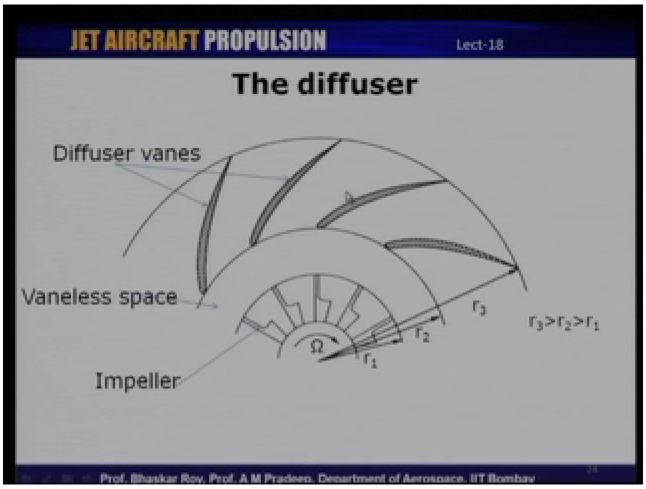

So, this is one geometry of a diffuser shown, and so the if if this if we say that this is the impeller of the compressor then the flow exits the impeller enters into what is known as a vaneless pace. So, there is some amount of diffusion in the vaneless pace and then the flow proceeds into the diffuser vanes, so diffuser section consists of these two, wherein the diffused the diffusion actually begins in the vaneless pace and then continuous in the vane diffusion section as well.

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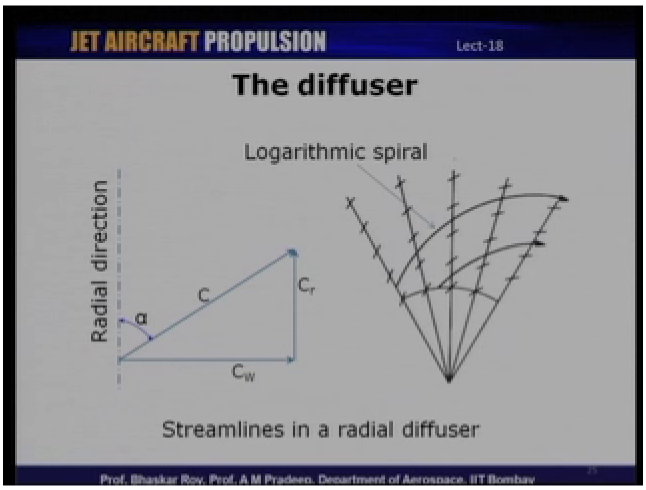

There are some centrifugal compressors, which do not really have a vaneless pace, but most of them do have a a small amount of space, which wherein diffusion is initiated and then it continuous in the vanes of the diffuser. And so if you look at the presence of or the velocity triangles as we look at the flow exiting the impeller, then if this is the absolute velocity that lives the impeller it has two components, one is the tangential component the other component of the absolute velocity is the radial component.

And, what we see is that as the flow lives the impeller, a fluid element takes up a path as shown here, which is very similar to a logarithmic spiral and that is basically, because of the presence of these velocity components that is it has a tangential component and the radial component and as a result of that the the fluid element takes a trajectory, which is like a logarithmic spiral.

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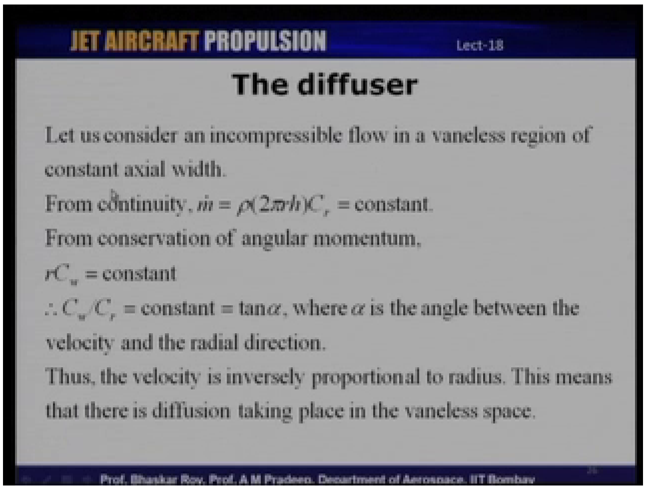

And so, if you look at for an incompressible flow at least the mass flow rate is basically density times the cross sectional area times the radial velocity, which is a constant and if we have to have if we look at the conservation of angular momentum then we have r times C omega, which is a C w; which is the tangential velocity is a constant that is from conservation of angular momentum.

So, if you take the ratio of these two, we have C w, which is tangential velocity divided by radial velocity is a constant and that angle is equal to the alpha, which is the angle between the velocity and the radial direction. So, this angle that if you see here is the angle, which the relative velocity makes with the radial direction; which is tan alpha is basically equal to the ratio of these two.

And so, tan alpha is C w that is tangential velocity divided by C r. And this means that the velocity is inversely proportional to radius, so you can see that both of them whether you can consider the relative the radial velocity or the tangential velocity. They are both inversely proportional to the radius, which means that as we as the fluid element moves from a lower radius to a higher radius; which is what happens as if this is the impeller outlet as the fluid element moves from this location to this, the radius is changing and as that changes since the velocity is inversely proportional to radius there will be diffusion taking place in the vaneless pace itself, which means that there is a diffusion, which is occurring right from the outlet of the impeller all the way upto the inlet of the diffuser vanes so diffusion begins from the impeller outlet and continuous in the vaneless pace and also in the diffuser vanes.

And and so the diffuser, which constitutes which is one of the components of the impeller of the centrifugal compressor as a whole is one component, where the flow exiting the impeller gets decelerated there is pressure raise associated with that. And of course, here the pressure rise mechanism is purely because of deceleration unlike their impeller, where there are two components or constituents of pressure rise one because of the centrifugal force field, and the other because of deceleration.

So, let me just quickly recap our discussion in today's class. We have discussed about elements of centrifugal compressor, so it is an overview of a centrifugal compressors as such we will continue this discussion of course, in the next lecture as well in today's class. We have looked at what constitutes a centrifugal compressor, and what are the simple differences between centrifugal compressor and an axial compressor and what are the typical applications of centrifugal compressors as compared to axial compressors.

We then discussed about what are the different constituents or components of a centrifugal compressor and then we had some preliminary discussion about these different components like the inducer, the impeller and the diffuser, which again had two components.

So, all these components put together constitute a centrifugal compressor and we have also seen how these components can be related to the counter parts of an axial compressor like the impeller is like the rotor of an axial compressor, the diffuser part is similar to that of a stator of an axial compressor.

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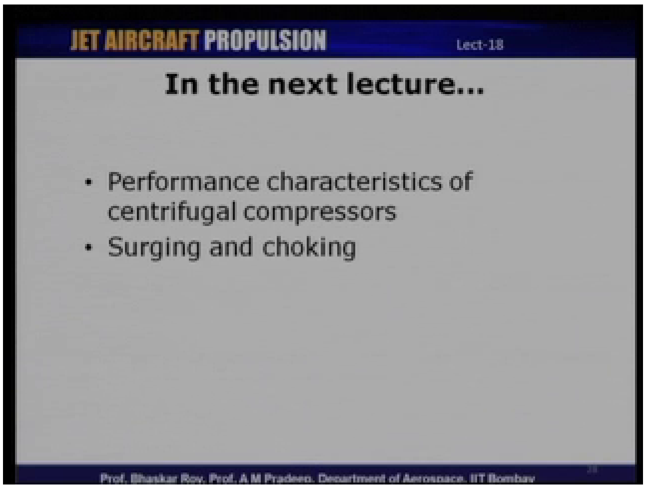

And so, in the next lecture what we will discuss about our we will take up this discussion further we will discuss about the performance characteristics of centrifugal compressors. We already had a similar discussion for axial compressors; we will now be discussing about performance characteristics of centrifugal compressors; we will also discuss about surging and chocking of a centrifugal compressors these are two limitations that basically limit the performance of centrifugal compressors, and so we will take up some of these topics for discussion during the next lecture.