# Turbomachinery Aerodynamics

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## Lecture No. # 20
## Axial Flow Turbines: Turbine Blade 2-D (Cascade) Analysis

Hello and welcome to lecture number 20 of this lecture series on Turbomachinery Aerodynamics. We have we have probably half way through this course, and I guess you must have had some good idea about what in, what is involved in turbomachinery analysis, and what is involved in design of different types of turbo machines, especially the compressors. Now, starting the last lecture onwards, we are now looking at the axial turbines, and of course subsequently we were also in talking about the radial turbines and so on.

So, I think in the last class, you must have had got some introduction to what axial turbines are, and what constitutes axial turbines and so on. So, let us take that discussion little bit further, in today's class where we will we will be talking about two-dimensional analysis of axial compressors, well axial turbines. In a very similar fashion to what we had discussed for axial compressors. If you remember during one of the initial lectures probably the lecture - the second lecture or the third lecture, we had been talking about axial compressors, and how one can analyze axial compressors in a two-dimensional sense. So, we will we will carry out the similar analysis and discussion in today's class about how the same thing can be carried out for turbines, axial turbines in particular.

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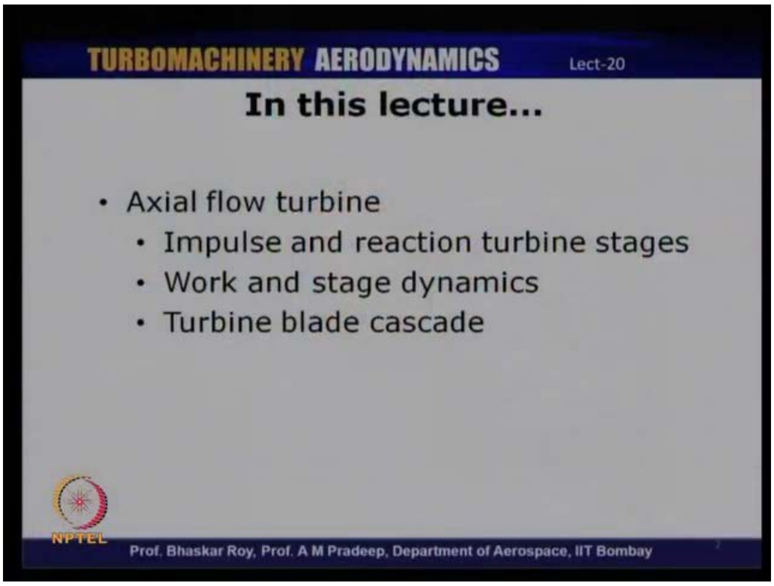


In today's class we basically being going to talk about the following topics. We will initially discuss, have some introduction to axial turbines, turbines in general. We will talk about impulse and reaction turbine stages which are the two basic types of axial turbines. We will then talk about the work and stage dynamics, how you can calculate work done by a turbine, and how is it different for impulse and reaction turbines. We will then spend some time on discussion about turbine blade cascade.

We will assume that the nomenclature we had used in the case of compressors, will still be valid, but of course we will just highlight some simple differences between a compressor cascade, and a turbine cascade, but the nomenclature remains the same in the sense that what we had called as camber or stagger or incidence all that remains the same for a turbine. So, I will probably spend lesser time discussing about those and take up some more topics on cascade analysis which we had not really covered in detail in compressors.

Now, when we talk about turbines, you must have had some discussion, some introduction to some the different types of turbines. As we know the different types of compressors like axial and centrifugal; similarly, we have different types of turbines as well. Now, in a turbine just like in a compressor, we have different components. In a compressor, we know that we have rotor followed by a stator. In the case of turbines we have a nozzle or a stator which pre-seals a rotor. So, a nozzle or a stator guides and accelerates the flow into the into a rotor, and of course, the work extraction takes place in the rotor. And which is unlike in a compressor, where it is the rotor which comes first and drives the flow, and then that goes into a stator which again turns it back to the acceleration and so on, diffusion takes place in both the rotor and the stator.

In a turbine, as well you could have differential amounts of acceleration or pressure drop taking place in the rotor and the stator. And there are certain types of turbines where the entire pressure drop takes place only in the stator, this rotor does not contribute to any pressure drop, it simply deflects the flow, these are called impulse turbines. We will discuss that in little more detail in some of these later slides.

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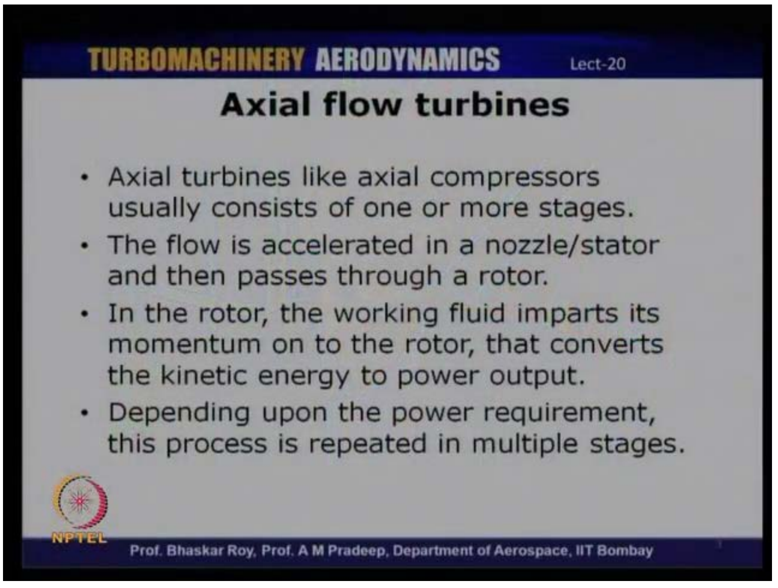


So, basically the flow in a turbine is accelerated in nozzle or a stator. And it then passes through a rotor. In a rotor, the working fluid basically imparts momentum to the rotor, and basically that converts the kinetic energy to power output. Now, depending upon the power requirement, this process obviously is repeated in multiple stages, you would have number of stages which will generate the required work output, which is also similar to what you have in a compressor, where you might have multiple stages which basically are meant to give you the required pressure rise in typical axial compressor.

Now, we have seen this aspect in compressors as well that due to the motion of the rotor blades, you have basically two distinct components or types of velocities. One is the absolute component or type of velocity and the other is relative component or relative velocity. This was also discussed in detail in compressors, and so you would in in a turbine the analysis that we will do in by analyzing the velocity triangle. You will see that there are these two distinct components which will become obvious, when we take up the velocity triangles, and this is very similar to what you had discussed in compressors. So, if you have understood velocity triangle construction for an axial compressor, it is pretty much the same in the case of a turbine as well. So, that will that is probably the reason why it will make it simpler for you to understand the construction of the velocity triangle.

Now, the fundamental difference between compressor and the turbine is the fact that the compressor is required to generate a certain pressure rise, there is a work input into the compressor, which is what is used in increasing the pressure across the compressor. Compressor operates in an adverse pressure gradient mode; that is the flow always sees an increasing the pressure downstream. In the case of a turbine, it is not that case, it is the other way round that the flow always sees a favorable pressure gradient, because there is a pressure drop taking place in a turbine which leads to a which is how the turbine extracts work from the flow. That is it converts part of the kinetic energy which the flow has into work output.

And therefore, in a turbine the flow always sees a favorable pressure gradient, and that is one fundamental difference between a turbine and a compressor. Now, because you have a favorable pressure gradient, the the problems that we have seen in the case of compressor like, flow separation and blade stall and seers and all that does not really effect turbine, because a turbine the flows always in a accelerating mode, and so the problem of flow separation does not really limit the performance of a turbine. So, it is possible that we can extract lot more work per stage in a turbine as compare to that of a compressor. And therefore, you would if you have noticed schematic of typical modern day jet engine you will find that there are numerous stages of compressor may be 15 or 20, which are actually given by may be 2 or 3 stages of turbine.

So, each stage of a turbine can actually give you much greater pressure drop, then what we can achieve or the kind of pressure rise we can achieve in one stage of a compressor, which is why a single stage of a turbine can drive multiple stages of compressors. So, that is the very important aspect that you need to understand, because the fundamental reason for this being the fact that turbines operate in a favorable pressure gradient, compressors operate in an adverse pressure gradient.

So, there are limitations in a compressor, which will prevent us from having very high values of pressure rise per stage; that is not a limitation in a turbine; and that is why you have much greater pressure drop taking place in a turbine as compared to that of the pressure rise, that you get from one stage of a compressor. So, turbines like compressors can be of different types; the compressors we have seen can be either axial or centrifugal. In the case of turbines, you get in fact in the some literatures also says we could also have mixed type of compressors axial and centrifugal mixed.

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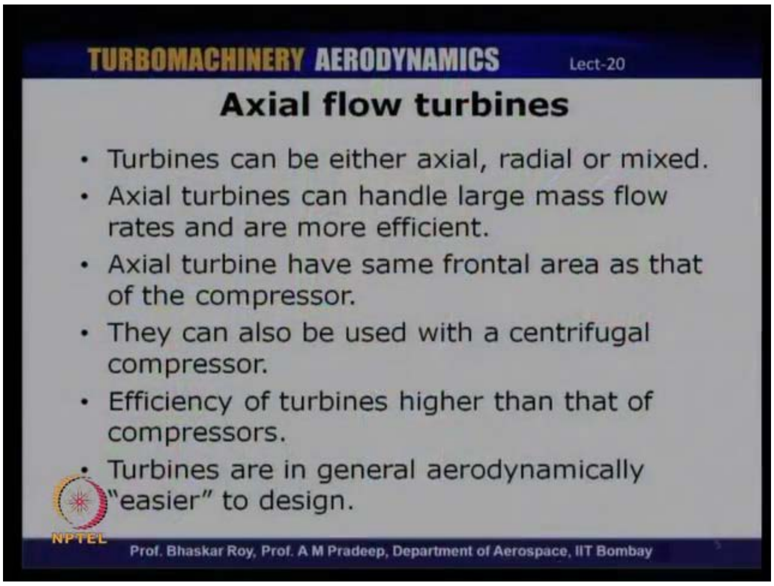


Similar thing is also there in the case of turbine, you could have an axial turbine or a radial turbine or a mixture or combination of the two called mixed flow turbines. Axial turbines obviously can handle large mass flows, and obviously are more efficient as very similar analogy we can take from compressors, which have larger mass flow and are obviously more efficient. And axial turbine main advantage is that it has the same frontal area of that of a compressor. And also it is possible that we can use an axial turbine with that of a centrifugal compressor. So, that is also an advantage.

And what is also seen is that efficiency of turbines are usually higher than that of compressors. The basic reason again is related to the common timer earlier that turbines operate in a favorable pressure gradient, and so the problems that flows sees in an adverse pressure gradients is not seen; there are no problems of flow separation except in some rare cases. And this also means that theoretically come turbines are easier to design, well easier is in-cord and un-cord, well in the sense that you know compressors require little more care in terms of aerodynamic design, but of course turbines have a different problem, because of high temperatures and so turbine blade cooling and associated problems; that is an entirely different problem altogether.

So, aerodynamically if you have to design a compressor and a turbine, turbines would be as easier to design than compressors, just because of the fact that. You do not to really worry about the chances of flow separation across a turbine, because it is always an accelerating flow. In the case of compressors that is not the case and there is always a risk that a compressor might enter into stall. So, let us now take a look at. Now, that I have spoken lot about types of turbines and there functions and so on, let us take look at a typical axial turbine stage.

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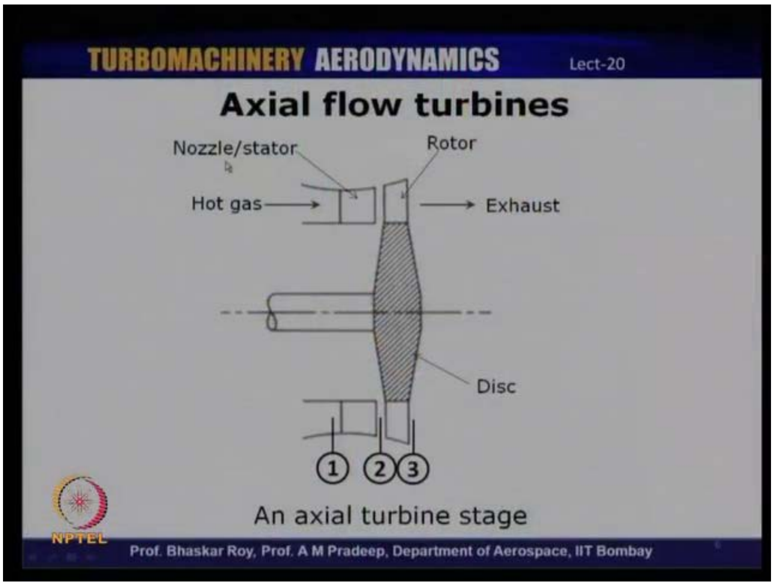


So, what is shown here is a simple schematic of an axial turbine stage. So, an axial turbine stage consists of as I mentioned nozzle or a stator followed by a rotor. So, this is just representing a nozzle through which hot gasses from the combustion chamber are expanded and then that passes through a rotor which is what gives us the power output. Rotor is mounted on what is known as disc, and of course, the flow from the rotor is exhausted into either a next stage or through the component downstream which could be a nozzle in the case of a air craft engine.

So, usually we would be denoting the stator inlet as station1, stator exit as station2 and rotor exit exist as station3. In some of the earlier generation turbines, the disc was a separate entity, rotor was mounted on slots which were provided on the disc, and so those separation separate mechanism for mounting rotor blades on the disc. Some of the modern day… So, it was very soon realized that having a separate disc and different blades in obviously will increase in the number of parts. So, the part count will increase tremendously.

So, but with modern day manufacturing capabilities in terms of 5 axis and 7 axis, numerical machines called CNC machine, computer guided machines. It is possible for us to make them out of a single piece. And this is done in smaller sized engines now, and some of the companies have their own names for that, for example, GE called such a disc which is combination of disc and the blade as blisc. Blisc means blade and disc together machined out of a single piece of metal. And similarly, their competitors also have their own terminologies like paternity called Integrated Blade Rotor or IBR; where there is no distinct root fixture for a blade, because blade and a disc are a single component.

The main advantage being that you have reduced significantly the number of parts. Whereas you would have let us say, typical turbine blade may have something like 70 to 80 blades or even more of course, mounted on a disc. So, that is like 80 to 90 parts for one stage of a rotor. Now, if you have a blisc, you have just a one component, because all the blades have been mounted on one disc. That is the tremendous advantage for in terms of maintenance aspect.

But at the same time, the primary disadvantage is the fact that - if there is one blade which gets damaged, in the earlier scenario you have just to replace the blade, here it becomes impossible to replace the blade, and so then of course, you will have to do rebalancing of the disc, and if the damage is severe then the whole disc as to be replaced. Of course, there are (( )) of having integrated blade rotor concept and of course there are lot of disadvantages and advantages. But for at least smaller engines economically that is in the long run that seems to be an advantage that you have a combination of the blade and the the disc.

So, having understood some of the fundamentals of turbines, let us move on to the more important aspect of analysis - the two dimensional analysis; that is to do with velocity triangles. I think we spent quite some time discussing velocity triangles for compressors. So, I will assume that you have understood the fundamentals of velocity triangles and try to kind of move on to constructing the velocity triangles just like that, unlike in compressors where I had done it step by step. The process is exactly the same as what you have done for a compressor. But of course it being a turbine there are certain differences which you need to understand.

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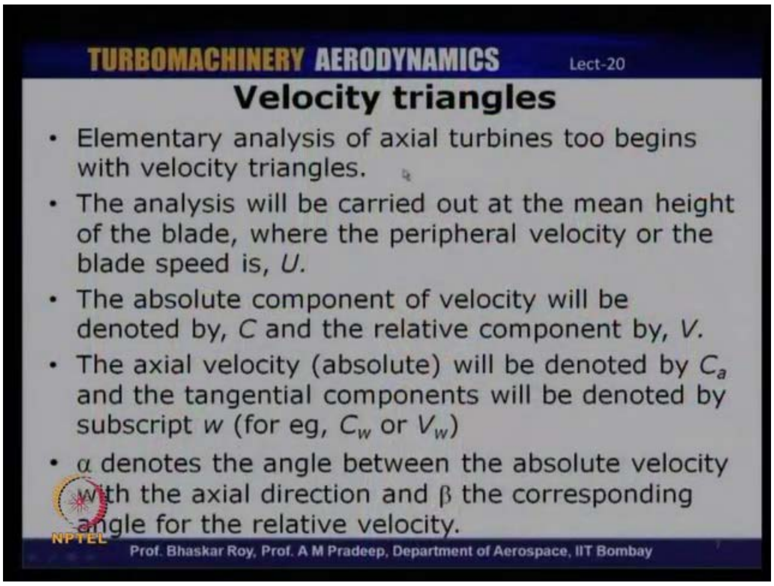


Now, velocity triangle analysis is an elementary analysis, and this is elementary to axial turbines as well, just like in the case of compressors. Now, the usual procedure for analysis is to carry out this analysis at the mean blade height, and we will have blade speed at that height assuming to be U capital U. Absolute component of velocity will be denote by C and relative component we will denote by V. And the axial velocity the absolute component of that is of denoted by C subscript a, just like in compressors, tangential components will be denoted by a subscript w. So, C w is of absolute component of tangential velocity, V w is the relative component in the tangential direction.

And regarding angles, alpha will denote the angle between the absolute velocity and the axial direction, and beta denotes the corresponding angle for relative velocity. So, these are the terminologies, nomenclature that we have used, even in a compressor we will follow exactly the same nomenclature in the case of turbine as well. So, let us move directly to a velocity triangle of a typical turbine stage.

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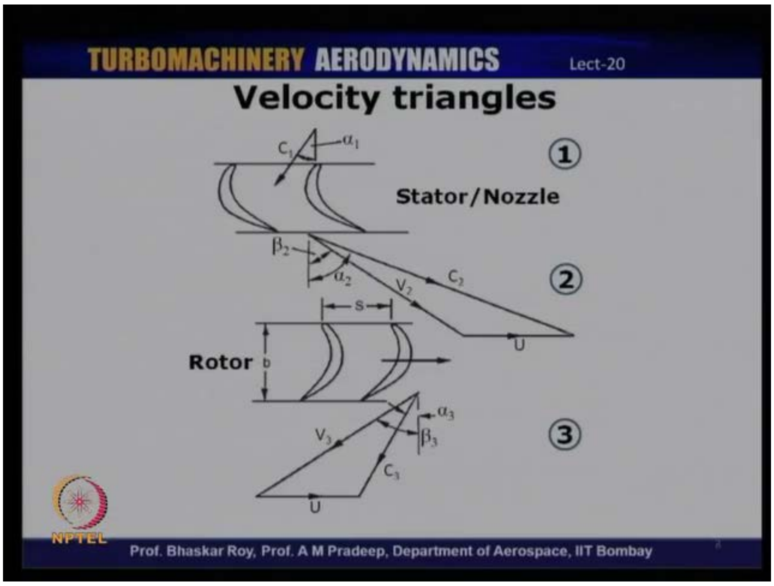


So, turbine stage as we have already seen consists of a rotor, well a stator or a nozzle. It is usually refer to as nozzle in the case of turbine, because the flow is accelerated in in an stator of a turbine, and that is why it is called an nozzle, and then you have a rotor which follows a stator or a nozzle. Now, inlet to stator is denoted as station 1, exit is denoted as station 2, exit of the rotor is station 3. So, let us say there is an inlet velocity which is given by C 1 which is absolute velocity entering at an angle alpha 1, it exists the stator or nozzle with a highly accelerated flow which is C 2, you can see that C 2 is much higher than C 1, and that is exactly the reason why this is called a nozzle.

Now, at the rotor entry, we also have a blade speed U; please note that the direction of this vector U is from the pressure surface to the section surface, unlike in compressor where it was other way round. Here the flow drives the blades and that is why you have the blade speed which is in this direction. This is the absolute velocity entering the rotor and relative velocity will be the vector some of these two or vector difference between these two and that is given by V 2. Alpha 2 is the angle which C 2 makes with the axial direction, beta 2 is the angle which V 2 makes with the axial direction. And just like we have seen in compressors V 2 enters the rotor at an angle which is tangential to the camber at the leading edge. This is to ensure that the flow, this is obviously when the incidence is close to 0 to ensure that the flow does not separate.

At the rotor exit, we have V 3.V 3 is less then V 2 as you can see, and of course, that also depends upon the type of the turbine, whether it is impulse or reaction, and you also have C 3 here and this is the blade speed U. Beta 3 is the angle which V 3 makes with the axial direction, alpha 3 is the angle which the absolute velocity C 3 makes with the axial direction. So, if you now come go back to the earlier slide is of lecture 2 or 3, where we had discussed about velocity triangles for an axial compressor, you can quite easily see the similarities as well as the differences. I would strongly urge you to compare both these velocities triangles by keeping them side by side.

So, you can understand the differences between a compressor and a turbine; at the same time, you can also try to figure out some similarities between these two components. And so it is very necessary that you have understand clearly both the differences as well as the similarities from a very fundamental aspect that is the velocity triangle point of view. So, this is a standard velocity triangle for a typical turbine stage. I am not really mentioned here, what kind of a turbine it is whether it is impulse or reaction, we will come to that classification very soon, and you will see that there are different ways, in which you can express the velocity triangle for both of these types of turbines.

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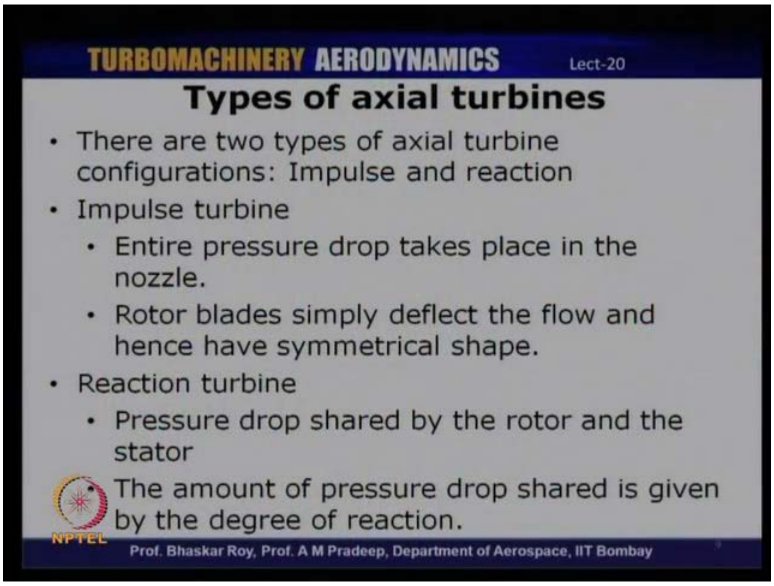

So, let us now try to take a look at the different types of turbines. I mentioned in the beginning that there are two different configurations of axial turbines that are possible, the impulse and the reaction turbine. In an impulse turbine, the entire pressure drop takes place in the nozzle, and the rotor blades would simply deflect the flow and would have a symmetrical shape. So, there is no acceleration or pressure drop taking place in the rotor in an impulse turbine. So, the the rotor blades would simply deflect the flow and guided to the next nozzle if there is one present.

In a reaction turbine on the other hand, the pressure drop is shared by the rotor as well as the stator. And the amount of pressure drop that is shared is defined by the degree of reaction, which we will discuss in detail in the next lecture. Now, which means that the degree of reaction of an impulse turbine would be 0, because the entire pressure drop as already taken place in the stator, the rotor does not contribute to any pressure drop, and so the degree of reaction for an impulse turbine should be 0. So, these are two different configurations of axial turbines which are possible. And what will do is that we will take a look at their velocity triangles also, but before that we need to understand the basic mechanism by which work is done by a turbine.

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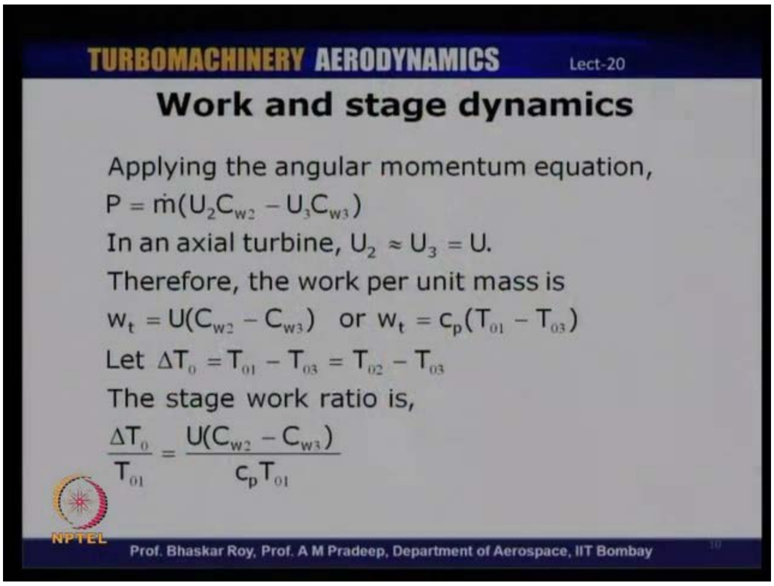


Now, if you were to apply angular momentum equation for an axial turbine, what you will notice is that power generated by a turbine is a function of well three parameters; one is of course a mass flow rate, the other parameters are the blade speed and the tangential component of velocity - the absolute velocity. So, if you apply angular momentum at the inlet and exit of the rotor, then the power generated by the turbine is equal to mass flow rate multiplied by U 2 into C w2 which is the product of the blade speed and the tangential velocity absolute at the inlet of the rotor, minus U 3 times C w3 which is again blade speed at rotor exit, and multiplied by the tangential component of the absolute velocity at the rotor exit.

Now, we would normally assume that the blade speed is does not change from at a given radial plane, and therefore U 2 can be assume to be equal to U 3, and therefore the work done per unit mass would now be equal to blade speed that is U multiplied by C w2 minus C w3 or which is also equal to the from the thermodynamics point of view, there is a stagnation pressure, stagnation temperature drop taking place in a turbine, because the turbine expands the flow, and work is extracted from the turbine, and therefore there has to be a stagnation temperature drop taking place in a turbine.

Therefore the enthalpy difference between the inlet and exit of the turbine would basically equal to the work done by or work developed by this particular turbine. So, work done per unit mass is also equal to C p time T 01 minus T 03, where this is basically the enthalpy difference; C p T 01 is enthalpy at inlet of the turbine, C p T 03 is the enthalpy at the exit of the turbine. Let us now denote delta T 0 which basically refers to the stagnation temperature. The net change in the stagnation temperature in the turbine delta T naught is equal to T 01 minus T 03 which is also equal to T 02 minus T 03, because 1 to 2 is the stator and there cannot be any change in stagnation temperature in the stator. Therefore, T 01 minus T 03 is equal to T 02 minus T 03.

So, we now define what is known as the stage work ratio, which is basically delta T naught by T 01 and that is equal to U times C w2 minus C w3 divided by C p times T 01. So, this is basically follows from these two equations here which correspond to the work done per unit mass; one is in terms of the velocities and other is in terms of stagnation temperatures. So, a similar analysis was also carried out when we were discussing about axial compressors, and were also we had a kind of equated the work that the flow does on well work done by the compressor on the flow as compared to the stagnation temperature rise taking place in a compressor as a result of the work done on the flow. So, there are also we have defined the pressure rise or pressure ratio per stage in terms of the temperature rise across that particular stage, and the velocity components which come from the velocity triangles.

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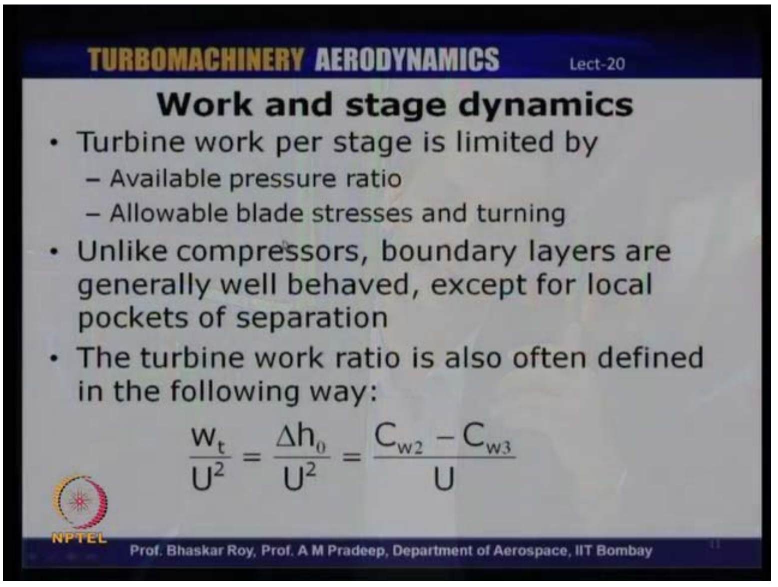


Now, what you can see here is that - the turbine work per stage would basically be limited by two parameters; one is the pressure ratio that is available for expansion, and of course the other aspect is the allowable the amount of blade stress and turning that is physically possible for one to achieve in in the case of a particular turbines. So, there are two parameters; one being the available pressure ratio and other is allowable blade stress and turning. That one can achieve in a particular turbine configuration.

So, in unlike in a compressor where we also had the issue of boundary layer behavior, because the flow was always operating in an adverse pressure gradient mode in compressors, in a turbine the pressure gradient is favorable. So, boundary layer behavior is generally something that can be controlled, and there are normally not much issues related to boundary layer boundary layer separation or growth of boundary layer and so on. Of course, there are certain operating conditions, and which under which certain the stages of turbine may undergo, local flow separation, but that is for only short durations.

In general in a favorable pressure gradient boundary layers generally, tend to be well behaved. Now, the turbine work ratio that we had seen in the previous slide is also often defined in and as a ratio between the work done per unit mass divided by the square of the blade speed. Therefore, W t by u square which is also equal to the enthalpy rise or rather enthalpy drop in the case of turbine divided by U square, which is basically equal to delta C w divided by U or net change in the tangential velocity absolute divided by the blade speed.

Now, this is an important parameter, because based on this we can understand or the differences between an impulse turbine and a reaction turbine, which is what we are going to next to take a look at what are the fundamental differences, besides of course, the fact that in an impulse turbine, flow is the entire pressure drop takes place only in the nozzle and in reaction turbine that is shared between the nozzle and the rotor. Let us take up an impulse turbine first and we will take look at the velocity triangles for an impulse turbine, and then try to find out the work ratio per stage of an impulse turbine, and related to some parameters which we can get from the velocity triangles.

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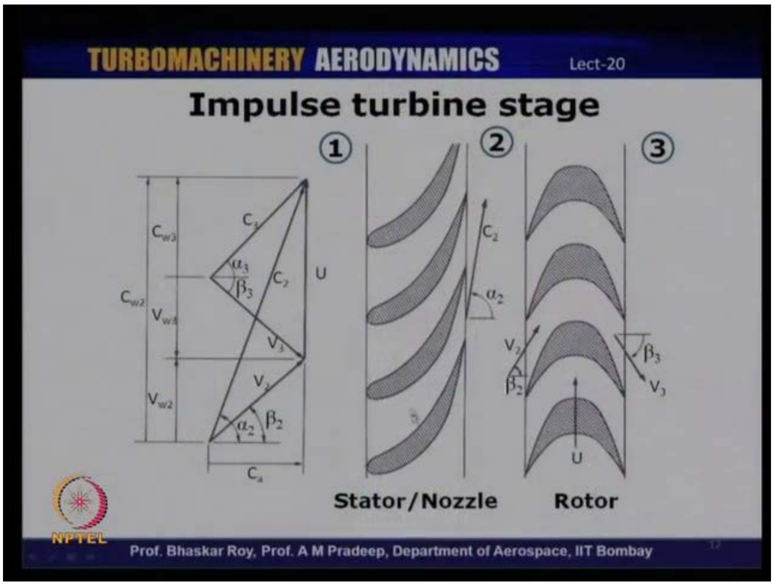


So, here we have a typical impulse turbine stage, a set of a row of nozzle blades followed by a row rotor of the blades. And… So, flow is accelerated in the nozzle, and so the velocity that reaches the rotor. The absolute component is C 2, and at an angle of alpha 2 with the acceleration and as the result of the blade speed U, the relative velocity which enters the rotor is V 2 which is at an angle of beta 2 with the acceleration. And in an impulse turbine, I mentioned that the rotor simply deflects the flow and there is no pressure drop taking place in the rotor, and therefore, at the exit of the rotor we have V 3 which is at an angle of beta 3 by virtue of the symmetry of the blades, we will have beta 2 is equal to minus beta 3, and velocity in magnitude v 2 would be equal to v 3.

So, which we can also see from the velocity triangle shown here; C 2 is the absolute velocity and entering the rotor, V 2 is the relative velocity and the corresponding angles here alpha 2 and beta 2. Now, in the rotor we have V 3 which is equal to V 2 in magnitude, but at an angle which is different from the inlet, that is beta 3 will be negative of beta 2 in the other direction. Absolute velocity leaving the blade is C 3. Now, if you look at the other components of a velocities like this is the actual component of the absolute velocities C a, and the corresponding tangential components of the relative velocity which are obviously equal and are opposite in direction like V w2 and V w3; you can see that these are equal in magnitude, but of course the that directions are opposite, because V 2 and V 3 are in opposite directions. And C w2 is the absolute component of well tangential component of the absolute velocity are inlet, C w3 that at the exit of the rotor.

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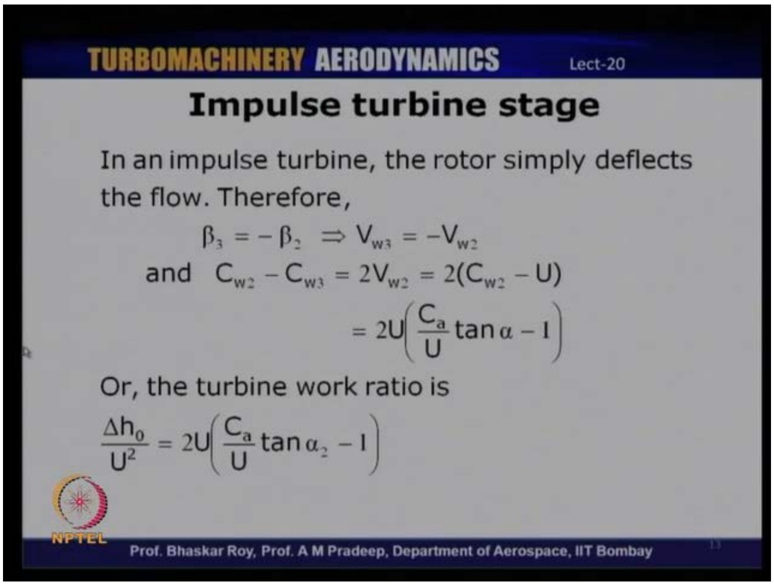


So, this is typical velocity triangle of of an impulse turbine stage. And if if you take a closure look at the velocity triangles, I have mentioned that the angles beta 3 and beta 2 are equal in magnitude, but they are different by their orientations. So, beta 3 is equal to minus beta 2 which means that we have V w3 is equal to minus V w2. And the difference in the tangential component of the absolute velocities C w2 minus C w3 will be equal to twice of V w2. So, let us take a look at the velocity triangle again C w2 is this minus C w3 is equal to the sum of V w2 and Vw3, and since they are equal we have that is equal to twice of V w2, which is also equal to 2 into C w2 minus U or this is equal to 2 U into C a by tan alpha 2 minus 1.

So, that is again coming from the velocity triangles, you can see that C a tan alpha 2 is this component minus U is equal to twice of this. So, the difference between the tangential component of the absolute velocity C w2 and C w3 that is delta C w for an impulse turbine equal to 2 U into C a by U tan alpha 2 minus 1. Therefore, the work ratio that we have defined earlier, for an impulse turbine that is delta h naught by U square is equal to 2 U into C a by U tan alpha 2 minus 1. We will now, take a look at what happens in the case of an of a reaction turbine and calculate the work ratio as applicable for a reaction turbine, and see the is there a difference fundamentally in the work ratio of an impulse turbine and a reaction turbine.

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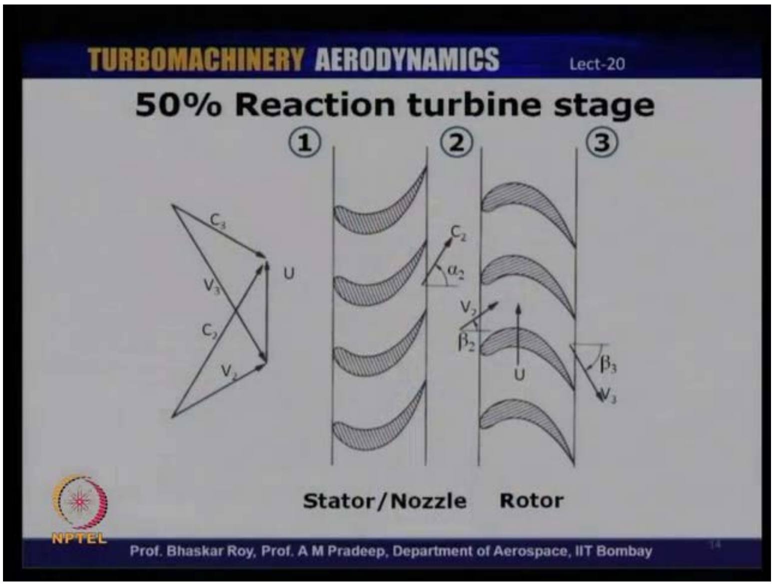


Now, let us take a look at a typical 50 percent reaction turbine, just for simplicity. The reason why we took up a 50 percent reaction turbine is, because in a 50 percent reaction turbine the pressure drop is shared equally between the nozzle and the rotor. And therefore, the velocity triangles as you can see are mirror images of one another; the velocity triangle at the inlet of the rotor is this, where this is C 2 the absolute velocity coming in from the rotor from the nozzle; V 2 is a relative velocity and this is the blade speed.

And since they are mirror images and the exit of the rotor, you have V 3 and C 3. And therefore, you can clearly see that C 2 will be equal to V 3 and V 2 will be equal to C 3, corresponding the angles alpha 2 will be equal to beta 3, and beta 2 will be equal to alpha 3. For this is true for only 50 percent reaction turbine, for any other reaction stages of course, the velocity triangles need not necessarily be symmetrical, and this is also assuming that the axial velocity is does not change across the rotor and the nozzle. Now, for this kind of a reaction turbine which is having a degree of reaction of 0.5; since the velocity of triangles are mirror images are symmetrically. If we assume constant axial velocity, we have C w3 is equal to minus C a tan alpha 2 minus U. And therefore, the turbine work ratio would basically be equal to twice into twice of C a by U tan alpha 2 minus 1.

This we can compare with that of the impulse turbine where it was 2 U multiplied by C a by U tan alpha 2 minus 1. So, you can immediately see that there is fundamental difference between the work ratio as compared to a turbine which is impulse or in this case of course example was for a 50 percent reaction of turbine. So, there is a fundamental difference between the work ratio as applicable for an impulse turbine as compared to that of a 50 percent reaction turbine, and in general for any reaction turbine as well.

Now, this was as per as the different types of turbine configurations were concerned and how one can analyze these turbine configurations. And what are the fundamental differences between let see an impulse turbine and a reaction turbine, and how one can from the velocity triangle estimate the work ratio that or the work done by these kind of turbine stages. So, what I was suggesting right of the beginning was that you can clearly see differences between the compressor and turbines by looking at the velocity triangle for these two different cases, and comparing them to understand the fundamental working of compressors and turbines and what makes them two different components.

What we can take up next for discussion is something we have discussed in detail for compressors as well; that is to do with a cascade. And as you have already seen a cascade is a simplified version of rotating machine, and you could have different versions of cascade, you could have a linear cascade or an annular cascade. And basically a cascade would have a set of blades which are arranged; set of similar blades which are all arranged in certain fashion, and at a certain angle which we have referred to as the straggler angle. And cascade analysis forms a very fundamental analysis of design of turbo machines whether it is compressors or turbines.

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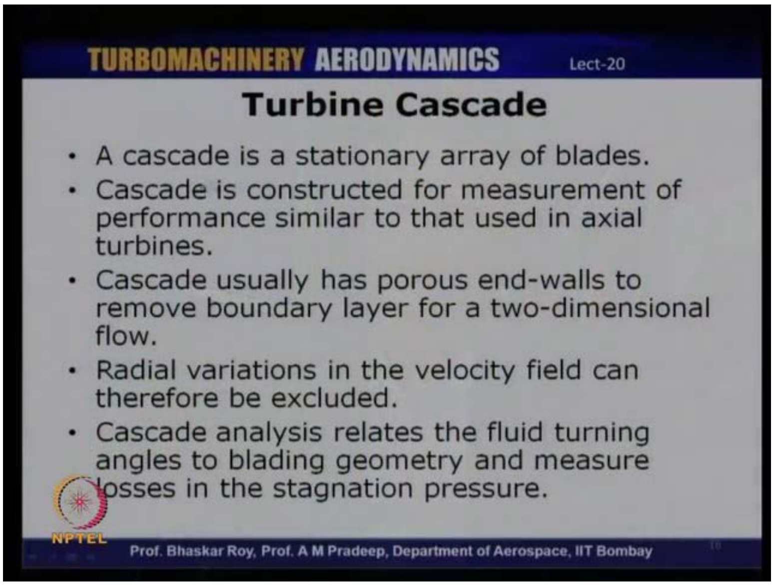


So, cascade basically consists of an array of stationary blades. And constructed basically from measurement of performance parameters, and what is usually done is that we would like to eliminate any three-dimensional effects which are likely to come up in a cascade. And one of the sources of three dimensionality is the presence of boundary layer .So, one would like to remove boundary layer from the end walls of the cascade, and so that is the standard practice one would have porous end walls through which boundary layer fluid can be removed; to ensure two dimensionality of the flow entering into a cascade. Now, it is also a standard assumption that radial variations in velocity field can be kind of eliminated or ignored. And cascade analysis is primarily meant to give us some idea about the amount of blade loading that a particular configuration can give us, as well as the losses in total pressure that one can measure from a cascade analysis.

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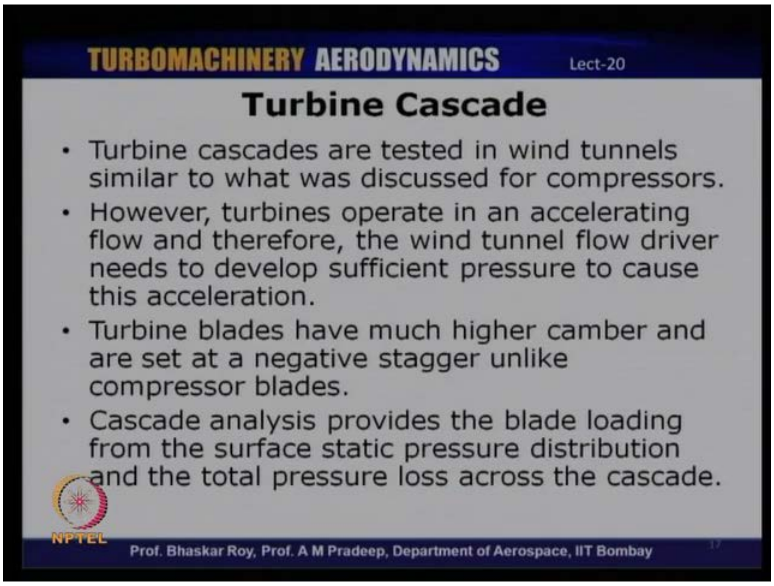


So, and in turbine cascades testing also involves wind tunnels which are very similar to what we have discussed for compressors. I had shown you cascade wind tunnels, when we are discussing about a cascades in the context of compressors. In turbine cascades are also tested in similar wind tunnels. And just that in a case of turbines, since they are operating in an accelerating flow. There there is a requirement of a certain pressure drop across a turbine. So therefore, the wind tunnel is required to generate sufficient pressure which can be expanded through a turbine cascade. Now, turbine blades has are probably aware would are likely to have much higher camber, than compressor cascades or compressor blades. And turbine cascades are set at a negative stagger unlike in compressor blades; something I will explain when we take up a cascade, schematic in in detail.

Now, cascade analysis will basically give us as I mentioned two parameters besides the sets of other parameters, like boundary line thickness and all and losses, etcetera. The most fundamental parameter we would like to look at from the cascade analysis is this surface static pressure distribution or CP distribution, which is related to the loading of the blade, and the second aspect of the is the total pressure loss across the cascade, which is yet another parameter that one would like to infer from the cascade analysis.

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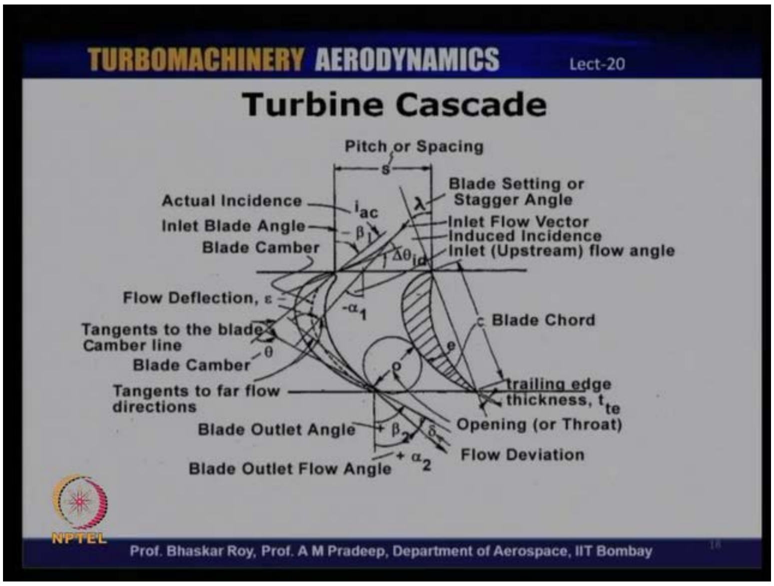


Now, let us take a look at a typical cascade, turbine cascade nomenclature. I think I mentioned in the beginning that all the terms that we have used for compressors will it is the same nomenclature that we apply for a turbine as well. Just that that the way the blades are set, so the blade geometry they are quiet different between compressors and turbines.

So, if we look at a typical compressor cascade, these are the blades you can immediately see that these blades have much higher turning for camber than compressor blades. So, it is a set of these blades which are arranged either linearly or in an annular fashion which constitute a cascade. So, these blades are set apart by a certain distance, which is as you can see denoted by pitch or spacing. And these blades are set at a certain angle, which is called the blade setting or the stagger angle. So, you can see this lambda which you see here refers to the blade setting or stagger angle. The blades have a certain camber which is basically the angle subtended between the tangent to the camber line at the leading edge and that at the trailing edge. So, the difference between that gives us the a blade camber.

Now, the flow enters the cascade at a certain angle, you can see that inlet blade angle is given here as beta 1 and the blade outlet angle is beta 2. Now, so if there is a difference between the blade angle and the flow angle at the inlet; that basically the incidence which is denoted by i here .So, this is the incidence angle. Similarly, a difference between the blade outlet angle and the outflow angle is the deviation which is denoted by delta. So, at the exit you may have flow deviation and the inlet one may have an incidence.

And if you draw a normal rect normal to the tangent at the trailing edge and take it to the next adjacent blade, the section surface of the adjacent blade. So, this distance that you see here is basically refer to as the throat or opening at the turbine exit, and that is here denoted by a symbol o. The blade called as you already know is denoted by C. And then the blades also would have a certain finite thickness at the trailing edge. So, that is denoted here by the trailing edge thickness. So, the blades practically will have a certain amount of finite thickness and that is what is denoted here as the thickness at the trailing edge.

So, these are the fundamental nomenclatures nomenclatures that used in turbine very similar aspect was also used in compressor, where we had defined all these different parameters like incidence, deflection, deviation and blade angle, the camber, the pitch, stagger all of them defined. Difference is, of course, the way the blades are set, this is set at a negative stagger as you can see, the compressor cascade if you go back you will see that the way the blades are set is opposite to what you see in the case of a turbine. That is basically to ensure that the flow passage gives you the required amount of flow turning, and also the flow acceleration in the case of turbine cascades, and in in compressor cascade, the setting is to ensure that you get a defilation in a compressor.

So, having understood the fundamental nomenclature of a turbine cascade; we would now take a closer look at the different aspects of flow through a cascade and I would be deriving well not really a detailed derivation. But I would just give you some idea about how one calculates the lift developed by a certain cascade turbine cascade. In two different cases, one is if you do not assume any losses or if it is inviscid analysis, and followed by an viscous analysis one of course would also get a drag in the case of viscous analysis, how one calculate the lift and of course that is basically related to loading of the blades eventually.

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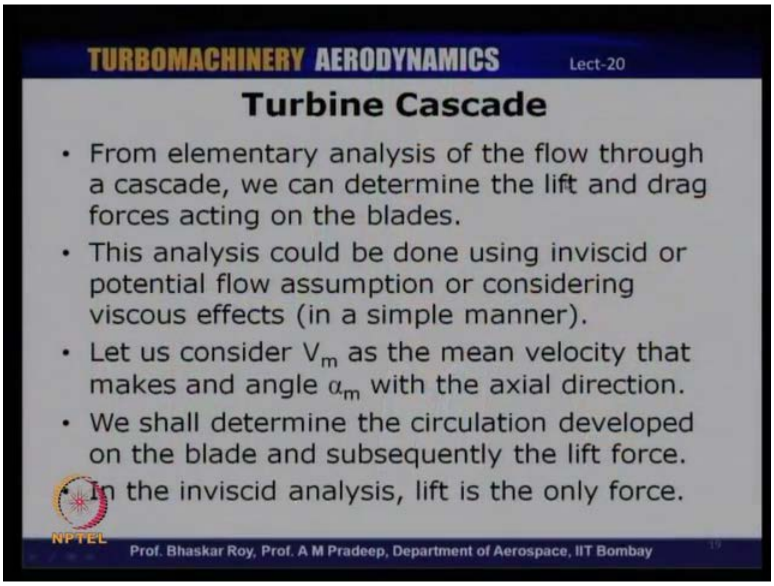


So, the basic idea of cascade analysis is that just like in case of an airfoil, because cascade is in some sense in airfoil analysis, we can determine the lift and drag forces acting on the blades. And this analysis, as I mention can be carried out using both these assumptions potential flow or inviscid analysis or by considering viscous effect in a rather simplistic manner. So, we will assume that the mean velocity which we going to denote as V subscript m, makes an angle of alpha subscript m with axial the direction. What we will do is to determine the circulation developed on the blades, and subsequently the lift force. In the inviscid analysis obviously there is no drag and there is only a lift force, which lift is only force acting on the blade. In the case of an inviscid analysis, when you take up a viscous analysis there are two components of a force and resultant force, they will lift and they drag.

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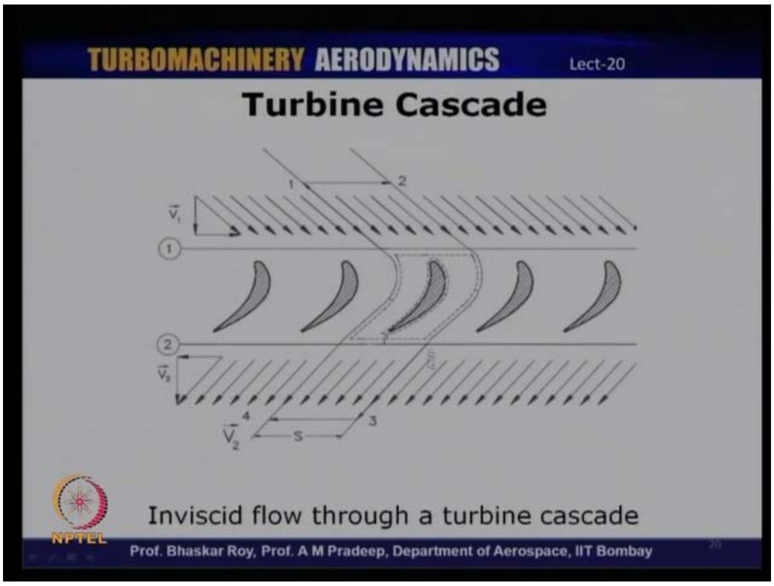


So, this is the geometry, we are considering for an inviscid flow through turbine cascade. If, you take a look at two different stream lines let us say, this is one stream line and another stream line which is bounding one particular blade, that is shown here these are the two different stream lines. What we are going to do is to find the circulation reduced over this particular airfoil which is currently an airfoil here, and then relate that to lift developed on this particular blade. So, the inlet flow the entering the cascade is V 1 and the flow exceeding the blade is V 2, and of course, we will assume mean velocity of V m which makes an angle alpha m with the acceleration.

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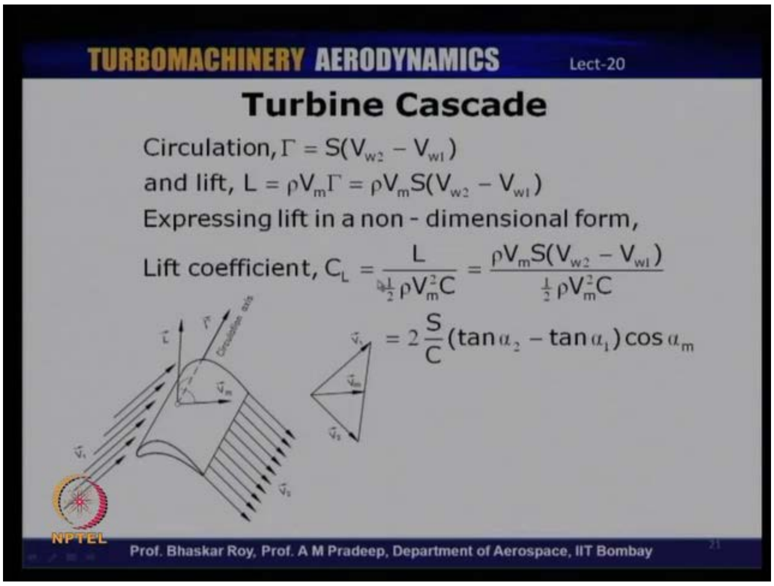

So, if this is the case and this is how you can take a look at this circulation axis; so, this is the axis along which we are calculating the circulation, and therefore, this is the lift acting on this particular blade. Since it is a turbine blade, you know that this is basically the direction in which the lift is going to act. So, the mean velocity that is showed here by vector V m acts in this direction, this is inflow velocity V 1, and this is the exit velocity V 2.

So, the circulation that is denoted by capital lambda here is equal to S multiplied by the difference in the tangential velocities V w2 minus V w1. And lift is related to the circulation which is product of density, times, the mean velocity and the circulation. Therefore, lift acting when there are no other effects considered like viscous affects, then the lift acting here would be simply the product of rho times V m into the circulation which S into V w2 minus V w1.

So, this is expressed in a non-dimensional form which we referred to as the lift coefficient. So, see l here lift divided by half rho V m square into C, and this is equal to rho into V m into S V w2 minus V w1 by half rho V m square into C. So, this can be related to the angles, the across, the cascade, and so we can simplify this lift coefficient as 2 into S by C into tan alpha 2 minus tan alpha 1 multiplied by cos alpha alpha m. So, this is the this is basically lift coefficient on a turbine blade, assuming that flow is in this inviscid.

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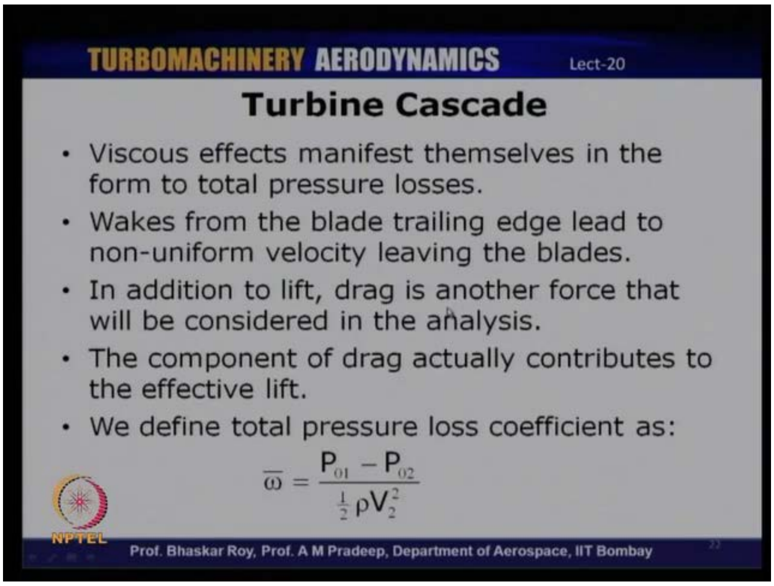

Now, what happens if there are viscous effects? The primary effect of viscous flow on the flow through a turbine cascade is the fact that viscous effects manifest themselves in the form of pressure losses - total pressure losses. And therefore, the wake from the blade trailing edge will lead to a non uniform velocity leaving the blades. In the previous analysis, we were assuming uniform velocity entering the blades and uniform velocity leaving the blades, because it is a potential flow.

So, here in the case of viscous analysis in addition to lift, one would also have a drag which we will also contribute to left in some where the other. So, the effecting force acting on the blade will be resultant of both the left as well as the drag acting on the blade. So, we now defined what is known as total pressure loss coefficient where defined a similar parameter for compressors as well. So, this is denoted by omega bar, because there is a total pressure loss taking place across the blades as a result of the viscous effects. So, omega bar is equal to P 01 minus P 02 divided by half rho V 2 square. This is the losing total pressure across the turbine cascade.

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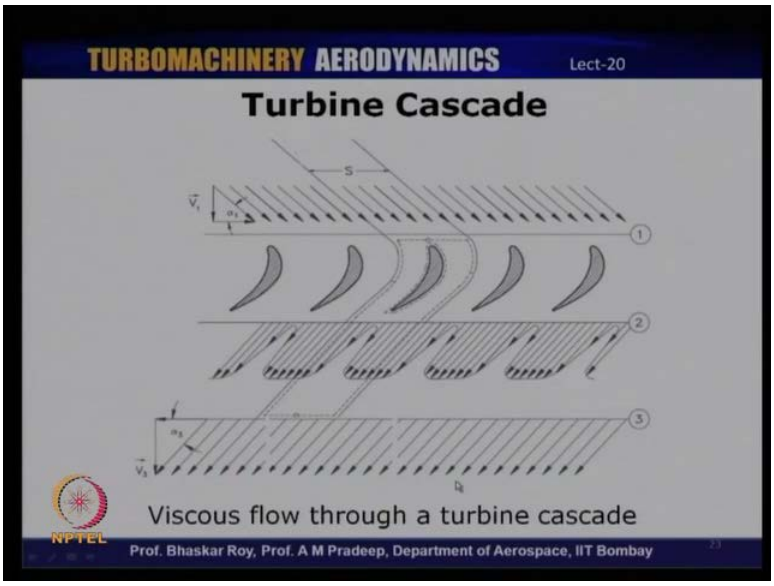


So, the schematic ahead shown earlier now gets modified, because you have a set of uniform stream lines entering turbine cascade, but as they leave the cascade you can see that they have became non uniform, basically at the trailing edge where there is a wake. So this, what is shown here schematically is the these are the different wakes of all these blades that are present here. So, there is difference in the forces acting on the blade as a result of this non uniformity in the velocity at the at the exit of the turbine cascade.

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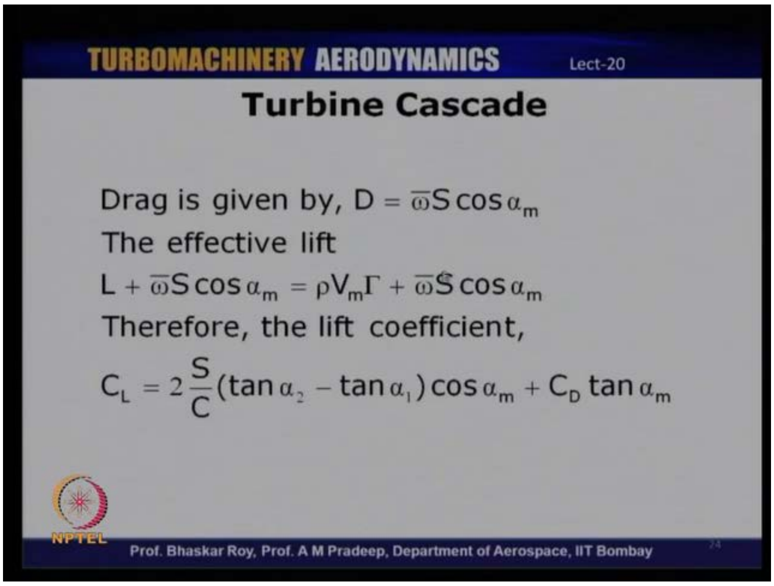


So, in this case, we can calculate drag as equal to the losses, we can relate the drag to the losses total pressure losses, omega bar into S into cos alpha m. And therefore, the effective lift will now be equal to the sum of the lift as well as the component of drag in that effective direction that is omega bar into S into cos alpha m. And lift we know is the product of density and the mean velocity and the circulation. So, that is rho V m into delta plus omega bar S cos alpha one alpha m. Therefore, the lift coefficient in this case will get modified as twice into S by C tan alpha 2 minus tan alpha 1 cos alpha m plus the drag components C D times tan alpha m. So, this is the manner in which we can calculate lift coefficient for both this cases; one is for case the without viscous effects and the second is if we consider the viscous effects.

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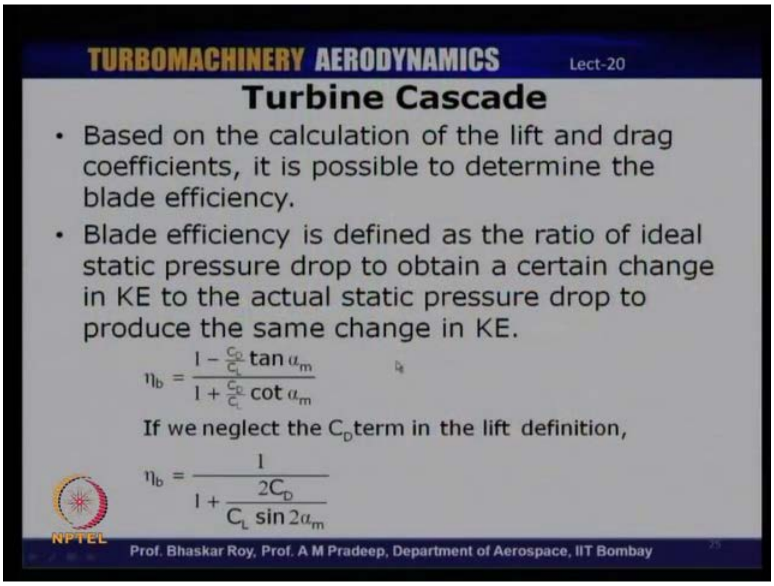


So, the basic idea for calculating these coefficients was to calculate, also calculate the blade efficiency. So, based on the calculation of the lift and drag coefficient, we can now calculate the blade efficiency, which is basically the ratio of ideal static pressure drop to obtain a certain degree of kinetic energy change to the actual static pressure drop which will produce the same change in kinetic energy. Therefore, the blade efficiency is in have of course skip the derivation of the blade efficiency. But it can be related to the lift and drag coefficient like blade efficiency is 1 minus C D by C L tan alpha m divided by 1 plus C D by C L cot alpha m. And if you want to neglect the drag term in the lift definition, because C D - the drag term is usually much smaller in comparison to the lift. The blade efficiency is simply 1 by 1 plus 2 into C D divided by C L sin into twice alpha m. So, this basic idea of calculating the lift drag and coefficient was also to calculate the blade efficiency, which is basically a function of C D C L have the mean angle alpha m.

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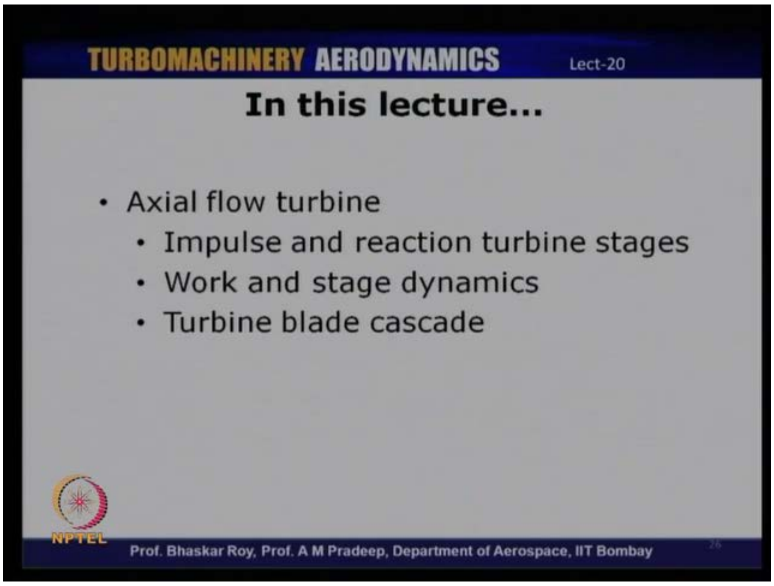


So, let me now quickly recap our discussion in today's class. We had taken up three distinct topics for discussion; one was the different types of turbine, configuration the axial turbine configuration, the impulse and the reaction turbine stages and we have done. We had a look at the velocity triangles and how we can calculate the work ratio for impulse and reaction turbine stages. We have also carried out the work and stage dynamic, we looked at these different components or configurations of axial turbines, and how we can go about determining the work ratio of these two configurations of axial turbine. And then we had some discussion on turbine cascades, and calculation of lift and drag for a typical turbine configuration, and how we can use that information to calculate the blade efficiency from simple turbine cascade testing. That is simple cascade testing can actually give us some idea about the blade efficiency that this kind of a blade configuration can give us. So, that bring us to end of this lecture.

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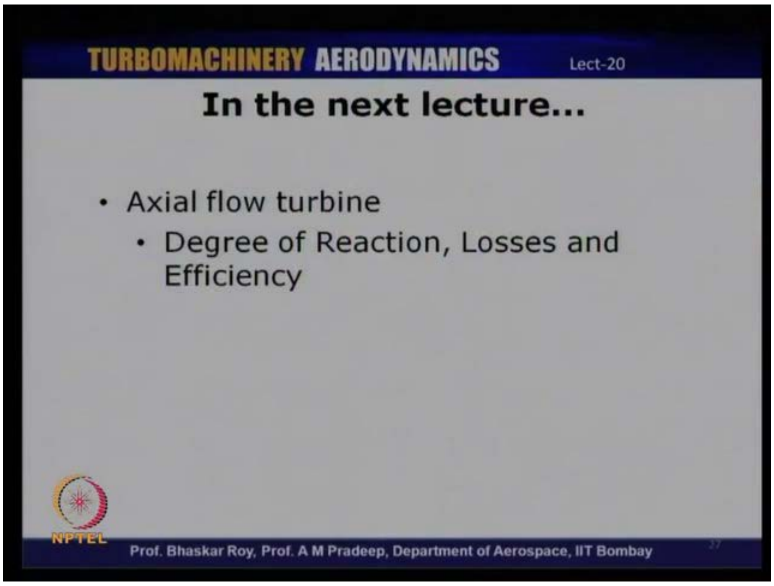


We will continue discussion on axial turbines in the next lecture as well, where we will primarily talking about the performance parameters, degree of reaction losses as well as efficiency of axial turbines. And were we also take up detailed discussion on whatever the different losses in a two-dimensional sense. And how we can define the efficiency and you will see that different ways of defining efficiency for a turbine. So, we will take up some of these topics for discussion in the next class.

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