Turbomachinery Aerodynamics

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Lecture No. # 22

Axial Flow Turbines:

Blade and Axial Flow passages, Exit Flow Matching with Nozzle

Hello and welcome to lecture number 22 of this lecture series on Turbo machinery aerodynamics. The last few lectures, we have been talking about axial flow turbines, we started off with an introduction to axial flow turbines, and then subsequently we spend about of lecture on discussion basically towards the two-dimensional flow in axial flow turbines and to do with cascade analysis with axial turbines. We also had some discussion on the performance of the axial flow turbines.

And in today's lecture, we are going to basically talk about the performance characteristics of axial flow turbines. In the last class, we had the discussed about the performance parameters, which are used in analysis and understanding of axial flow turbines. And we will use some of those parameters in today's lecture to look at how the performance of an axial flow turbine can be characterized; and we will also spend some time to look at the different types of the blade shapes, and the flow characteristics through turbine blade passages, and we will also towards end of the lecture have some preliminary discussion on matching of the turbine exit flow with downstream component let us say nozzle; and so, these are some of the topics that we shall be discussing in today's class.

So, we will begin with discussion on axial flow turbine performance characteristics. If we recall some few lectures earlier on and when we are talking about axial flow compressors, we had spend quite some time in understanding the performance characteristics of axial flow compressors, and we will, so in today's lecture follow very similar approach towards understanding of the performance characteristics of axial turbines, but as was what we going to see very soon the performance characteristics of compressors - axial compressor and turbines are entirely different. Even though the parameters based on which there are accessed are very much same, basically the pressure ratio, the mass flow rate, non-dimensionless and efficiency; and so, though the parameters are the same the way this two components behave are quite different, and that is the very much to do with the fundamental nature of flow in axial flow compressors and turbines; the sense that in compressor the flow has to undergo and adverse pressure gradient, scenario, whereas, in turbine the pressure gradient is always favorable and that primarily relates to lot of difference in the performance characteristics.

When we discussing about axial flow compressors and the performance characteristics of compressors, we had carried out kind of analysis to look at and understand what are the non-dimensional parameters which could be used for gagging the performance of axial flow compressors. So, from the dimensional analysis we had identified few distinct non-dimensional groups, which can which basically have significant defect on the performance of axial flow compressors. So, the very same performance parameters are going to be used for judging the performance of turbines as well.

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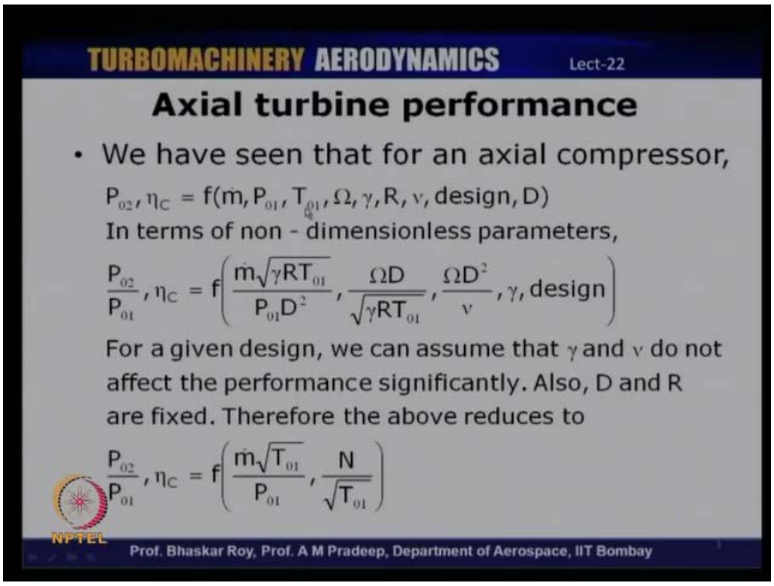

And so, in the case of axial flow compressor what we had seen was the exit pressure of the compressor and the efficiency or functions of variety of parameters like, mass flow rate and the inlet conditions like the inlet stagnation pressure, inlet stagnation temperature, the rotational speed, the ratio of the specific heats, the universal gas constant, the viscosity design, and the diameter and so on. So, this we reduced by dimensional analysis, and we arrived at this expression, which relates the pressure ratio in the compressors and efficiency to these different non- dimensional parameters; the first one that you see here is a function of mass flow and set of other parameters, the second one is function of the rotational speed and there of course, few other parameters.

So, for compressors, we have seen that for a given design, we can assume that this gamma and nu does not change or does not affect the performance significantly. Similarly, the diameter and the gas constant fixed. If that is the case the set of parameter would now simply find reduce to the pressure ratio and efficiency being functions of m dot mass flow rate multiplied by the inlet stagnation temperature divided by the inlet stagnation pressure and the rotational speed divided by the square root of T 01. So, this is what we have derived for an axial compressors, and what we will see the exact same logic can also we applied for a turbine, and so, we will use similar parameters for plotting the performance characteristics of axial turbines.

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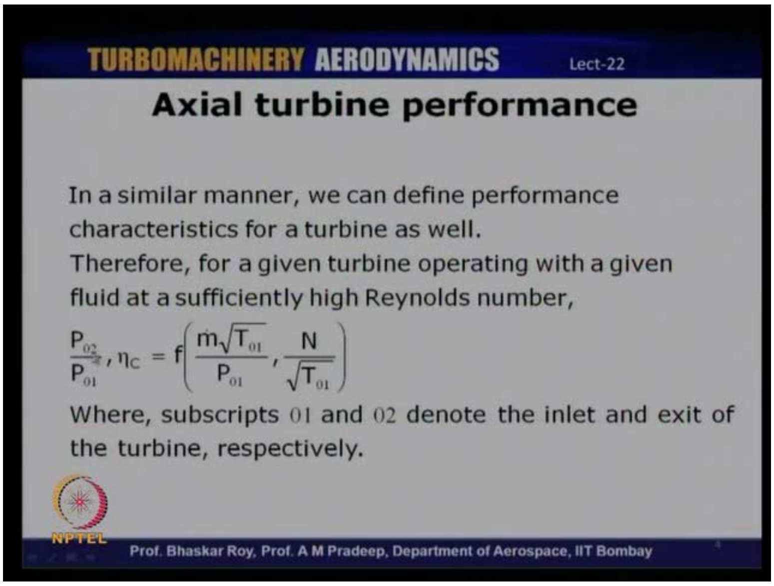

So, in the case of turbines, what we will see is the the exits the pressure ratio rather of the turbine and the efficiency or again functions of similar parameters mass flow rate time stagnation temperature divided by the stagnation pressure and the speeds and by root T 01. So, we will use these parameters of for characterizing the performance of axial flow turbines as well. So, in the case of turbines, just like we done for the compressor, we will first take a look at the pressure ratio versus mass flow rate and subsequently, has a function of very non-dimensional speed and subsequently, we will also look at this variation of efficiency.

Now, the interesting thing to observe in the case of turbine that we will very soon see is that unlike in a compressor where we had the performance characteristics, which was rather elaborate a set of characteristics, lines and you also certain line and choking line and in operating line and so on. In the case of turbines, the performance characteristics are much more simpler; in the sense that there is only one primarily one limiting line as you could call. In the case of turbine, since we have the performance which is limited by choking at one end, and there is nothing like turbines surge or instabilities and so on; and that is one distinct difference between a turbine performance as compare to the compressor performance.

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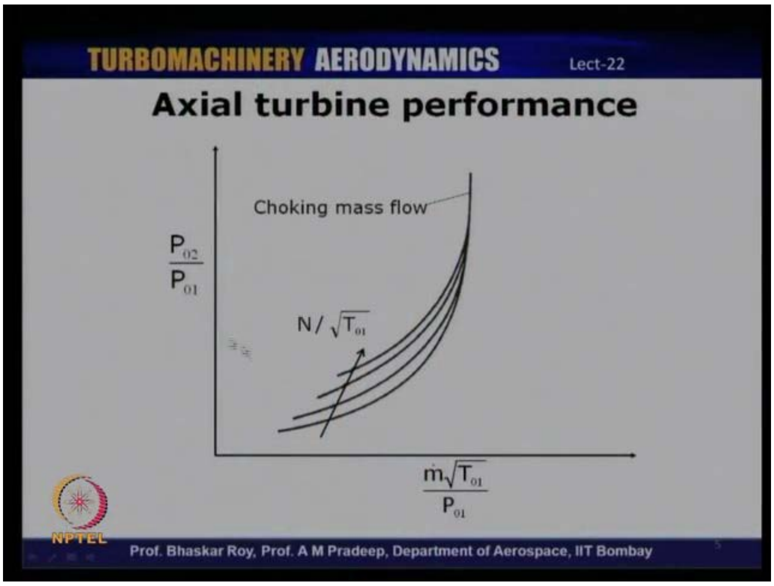

So, if we look at a performance characteristic of a typical axial flow turbine. So, here we have the pressure ratio and mass flow rate as a function of the varying speed. As speed change the performance characteristics also time to change, and what you see here as you keep changing a speed non-dimensional speed. All these characteristics would kind of one and merge to words single line, and that is choking mass flow; so, that is the certain limiting mass flow that kind of affects the performance of an axial turbine, and that is limited by choking.

So, this is very much unlike the case of axial compressor where we had seen a distinct variation in performance with non-dimensional speed, and there was also limiting line on the left hand side of the compressor characteristic, which was to do with the onset of instabilities and that was refer to as surge lines. So we do not really see this kind of limiting parameter in the case of axial turbines. So, from the performance map of turbine, which is basically, the pressure ratio versus mass flow rate for different non-dimensional speeds; as speeds change, you can see that towards the certain mass flow all of them kind of merge and you have limiting mass flow that is the choking mass flow.

So, compressibility in the case of turbine, limits the performance; and that is one of the limiting performance parameters in the case of turbine. So, we will also look at some of the other limiting parameters like the stresses and temperature, which also limit the performance of axial turbines. So, the other parameters that we would be interested in in the case of turbine is the efficiency of a turbine, and how the efficiency of a turbine is affected by variation of let us say the pressure ratio, and what is the effect of pressure ratio on the efficiency of an axial turbine. Now, in the case of efficiency, we have plotted efficiency again as function of the speed; as speed changes what really happens to efficiency. So, if we look at efficiency characteristics here.

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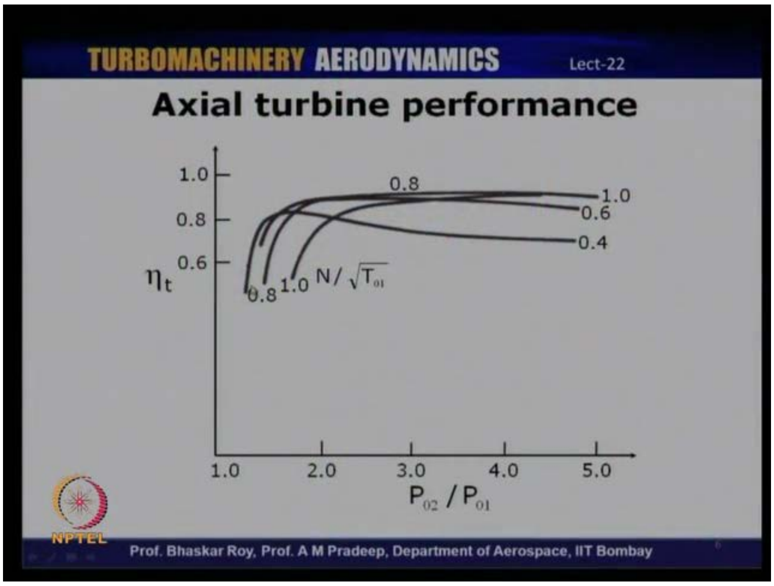

So, here we have the turbine efficiency as function of the speeds, and on the x axis we have the pressure ratio. You can immediately see that the pressure ratio in the case of turbines can be substantially higher than that of a compressor for stage, which we have also discussed in the last lecture that single stage of the turbine can actually derive the multiple stages of compressor, because pressure drop that a single stage of turbine can handle is much larger than the pressure raise that can be achieved through a single stage of an axial compressor. Now, if we look at the efficiency characteristics, you can also see that the efficiency is quite flat, in the sense that the variation of the efficiency is very is rather insignificant over a wide range of pressure ratios as well as mass flow rate.

So, efficiency, as speeds change, efficiency characteristics are relatively flatter; as compare to the compressor, which we had seen is likely to have very sharp change in a efficiency unlike the case of turbines; and it is also known that typically the turbines are operated much higher efficiency than compressors, and turbine efficiencies are usually slightly on the higher side as compared to compressor which is operating under the same pressure ratio range. Now, So there are few aspects that one would… One can derive from these performance characteristics of a turbine, and one of the important aspects that I just mentioned is that the fact that efficiency, variation of efficiency is rather… The amount of change in efficiency that you see in the case of turbine is very insignificant for wider range of mass flow rates and pressure ratios.

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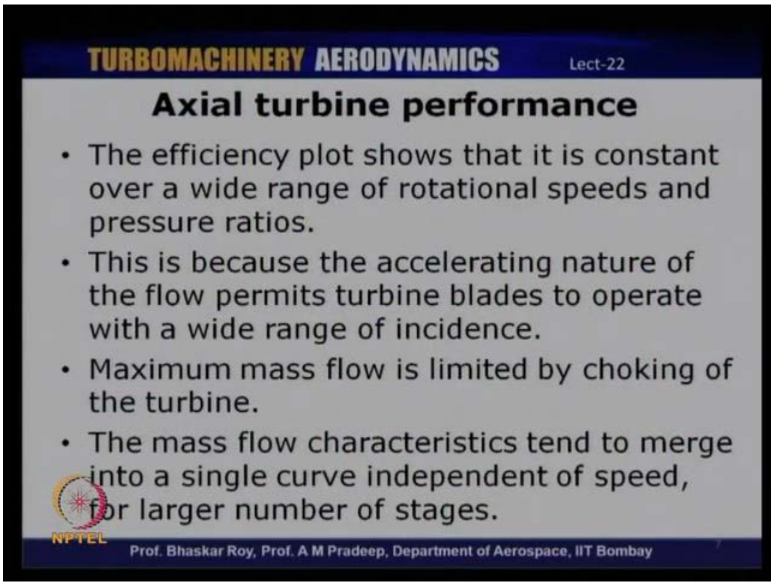

So, efficiency plot basically shows us that the efficiency tends to remain constant over a wide range of rotational speeds and pressure ratios. The main reason for this being the fact that in the case of turbines, the flow is basically operated in favorable pressure gradient, unlike the case of compressors where there are lot of limitations is which the flow would encounter, because its operating in an adverse pressure gradient; and that is the one of the reason, why turbines generally tend to have better efficiency; and at the same time the pressure ratio that one can achieve is much higher in turbine as compared to that in the compressor.

Now the other aspect that we also notice from the mass flow characteristics is that the choking point or choking line in the case of turbine, limits the performance of a turbine in that sort of becomes the limiting line in the case of axial turbines; and whereas in compressor, you also had a surge line on one side, which is limiting the performance of axial flow compressors and what we will also see that the mass flow characteristics would kind of merge into the single line or a single curve as we keeping increasing the rotational speed, we had seen that higher mass flows all these individual characteristics lines merge and form a single line, it eventually become the choking limit or choking line for the axial turbine. Now, few more aspects that we need to understand here that is when an axial turbine is operating very close to the design point that is at low incidence levels.

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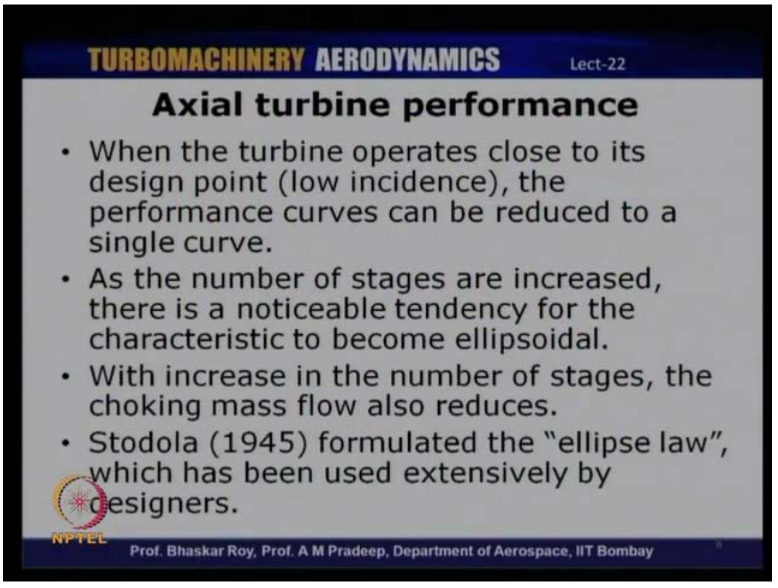

The performance characteristics as one would notice, would kind of merge and reduced to a single curve; what is also seen is that as the number of stages are increased, there is a noticeable change tendency for these characteristics to become ellipsoidal; and this was kind of formulated in play back in 1940s by Stodola, who formulated known as the ellipse law; and which was for long time being used by lot of designers. Basically what ellipsoidal law tells us is that as you keep increasing the number of stages, the mass flow characteristics kind sort of resembles ellipsoidal. So, that can be you know theoretically or empirically correlated, and so that was sort of used as a thumb rule by designers for long time, just as said starting point for the designer.

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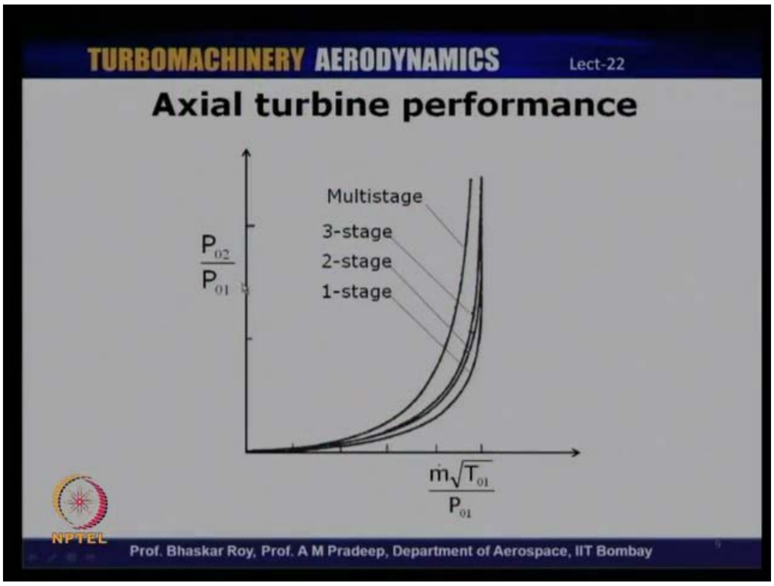

So, what is basically being employed here is that as we, let us take a look at the performance characteristics once again; now, this is pressure ratio verses mass flow characteristics, and we have seen that we have already seen the performance characteristics, which was limited by choking on one one end. So, as you keeping increasing in number of stages, let us say we are increasing number of stages from 1, 2, 3 and tending towards multistage turbine, the performance characteristics as you can see changes, and eventually becomes or resembles an ellipsoid; and that is, something that was empirically correlated in Stodola ellipse law, and which basically relates the mass flow versus with the pressure ratio of through an empirical correlation; and so for a long time that was lot of used as thumb rule in the design preliminary design axial turbines, and so these are some of the aspects that one can observed from the performance characteristics mass flow versus the the pressure ratio, and efficiency versus pressure ratio of mass flow.

So, here I mentioned that there are few aspects that limit the performance of turbine and so, we can identify three distinct aspects, which limit the turbine performance. One of them is compressibility and that we are already seen in the performance characteristics that the mass flow is limited by choking mass flow, and so that affect of the compressibility. Besides compressibility there are two other aspects or parameters that limit the performance. The other parameter is the stress that these blades would need to undergo, while operating under extremely high temperature as well as rotational speeds.

So, stress is other limiting parameter and the third parameter of course, is the inlet temperature. So, we… If we have…If we recall during your course on, let say propulsion, basic propulsion code that assume you have carried out cycle analysis of jet engines you must have noticed that an engine performance is very sensitive to the turbine at temperature, which is maximum temperature in a (( )) cycle, and so higher the temperature, better is the performance of the cycle; and so, one would always want to use higher and higher temperature at the turbine entry. So that performance of engine can be improved.

And therefore, turbine is it is always desire us that we use a higher temperature on the turbine relate for better performance of the whole engine, but as we know that material limitation would prevent us from using extremely high temperatures in the turbine; and so inlet temperature also limits the performance of turbine; in the sense that though aerodynamically, it would be possible for use to higher temperature, it is mechanical limitation, because the material that currently available have certain amount for temperature limits that would prevents us from using very high temperatures in the turbine.

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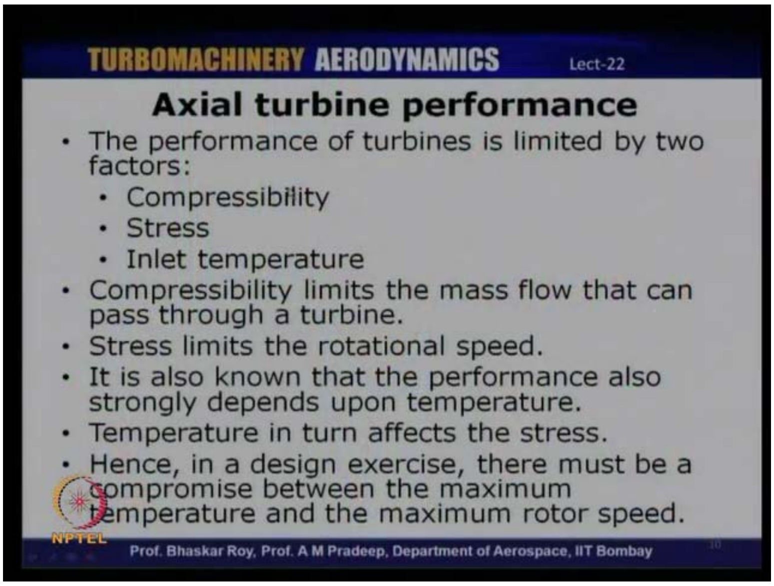

So, if we look at the performance of a turbine is limited by these three parameters compressibility, stress and the inlet temperature; and compressibility as a mentioned, limits the mass flow that can pass through a turbine; stress on the other hand, limits the rotational speed; and sense we know that turbine inlet temperature is also very significant aspect of performance, turbine into temperature also limits the performance. But, if we should look at the second and the third parameter which is stress and temperature they are quite related in the sense that temperature also affects the stress, because it induces thermal stress on the blades, and so temperature and stress are in somewhere limited; and so there is in typical design exercise, there is always lot of compromise that is used to at arrive at an optimum balance between the stress that a blade can sort of stand, which also limits rotational speed; and also the maximum temperature that one could used in a turbine, and that is why there are lot of technology which has come the recently soon use higher turbine temperature. Some of these are to do with using artificial cooling techniques to keep the blade cooler, and permit higher temperature that could be used; there are also lot of research going on to identify and develop newer materials, which can be standard higher temperature as well as stress; and so a turbine performance, which are which is basically limited by compressibility, stress and temperature. So, for a turbine designer, it is come like you have seen also compressor, there is certain amount of optimization that should be required to be carried out by the designer to arrive at set of parameters, which would gives us best performance, and at that same time would also enable the materials that are currently available to be used in current designs arrived.

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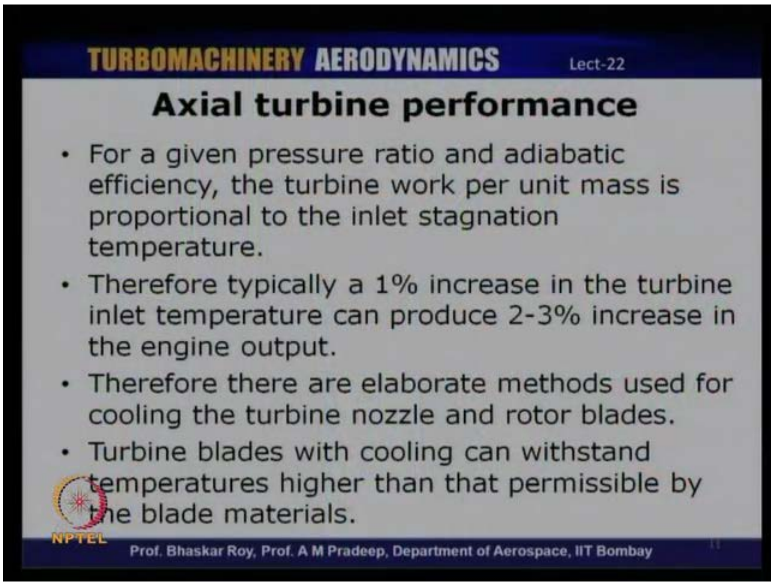

Now so, it is a known fact that the turbine inlet temperature has significant affect on the engine output. So, it is known that if we look at just a thumb rule, 1 percent increase in the turbine inlet temperature can produce of 2 to 3 percent increase in the engine output, if we looking at the overall engine; and the therefore, it is necessary that we identify methods by which one can increase the turbine entry temperature to the extent possible, and which is why the elaborate mechanism, which are used for keeping the blade cooler than in fact, the turbine entry temperature, in most of the modern day engines have temperatures which are actually higher than what the materials can withstand, but it is possible for us to use these higher temperatures, because of the fact that we employ cooling technologies to keep the blade cooler at the blade surface protected from very high temperatures. We will of course, we are discussing about turbine blade cooling techniques in detail in some of the later lectures; and this is just to highlight significant of fact that the temperature; turbine entry temperature as significant effect or not just the turbine performance, but also on the engine as a whole. So, now that we have been talking about the turbine performance and its affect are the parameters which affect the turbine performance. Let us also discuss about the turbine blades in little more detail and what are different types of blade that are used; we are already discuss that there are two fundamental types of turbine axial turbines and one of them is called the impulse turbine and other is called is reaction turbine. So, let us now try to understand the the aerodynamic shape of these different types of blades; all these blades as we know are fundamentally airfoil sections, but let us also try to look at the different types of blades which are being used in various types of turbine sense. So, depending on the application, the very shape of the blades can change significantly and that is what I would like to explain in in the next few slides.

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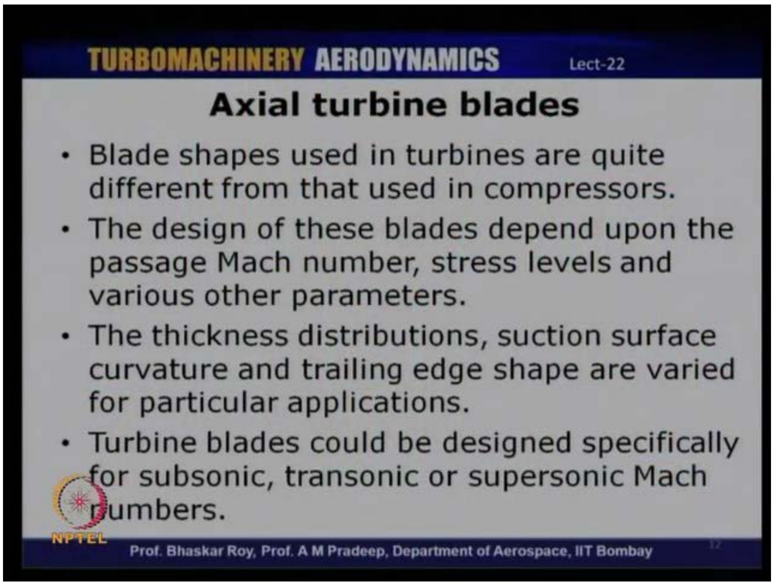

Now, the blades that used in to turbines can be quite different from those that are used in compressors, something that we we must realized by now, in the last few lectures that we are been discussing. There are varieties of parameters which affect the performance or the shape of these blades. Some of these parameters are to do with the the Mach number at which these blades have to operate these stress levels and host of parameters. Now, depending upon the application, the thickness distributions or the curvature of the blade, the trailing edge shape all these are varied, and these are strong functions of the application for which the turbines is to be used, and a turbine can also be use operated and are designed for a variety of Mach numbers ranging from subsonic to transonic or even supersonic. So turbines blade shapes can vary substantially as one changes the Mach number; this is something also seen for compressors for low speed compressor the blades shapes that are used the quite different from the blades stator used in little transonic axial compressor.

So, in the case of turbine as well these blades can be quite different; and there are various ways in which these blades shapes are profiles are derived are developed. Some of these are basically derived from agencies like NACA series; you must have seen NACA series, blades which was discussed during compressor discussions. So, there are series of blades which NACA had developed where back in the 1940s; and so, these blades are… These are of course, some of the source of blade profiles and there could be various other profiles that are used in the case of turbines.

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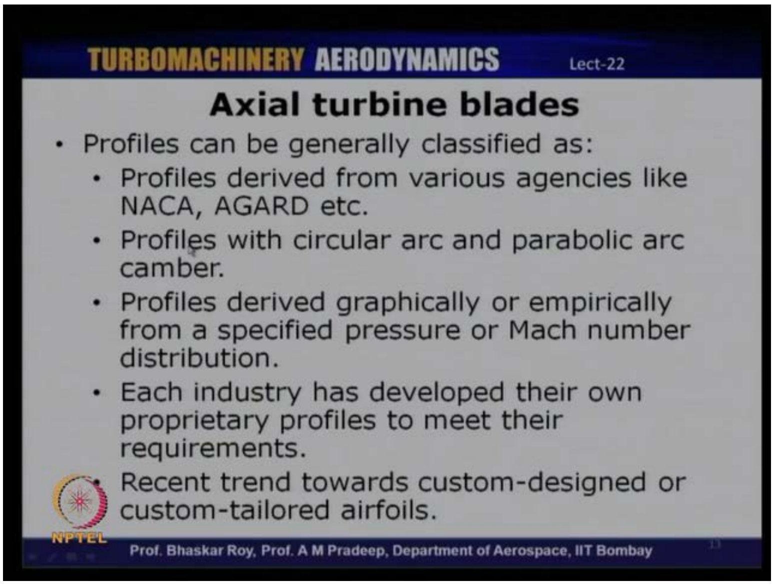

So, some of these I have listed here and the most fundamental form of these blades are derived from the NACA series, you could also have turbine blades from the AGARD series or one could use profiles with circular arc or parabolic arc camber like what is done in the case of compressors; and profiles could also been derived graphically or empirically from a specified pressure distribution or Mach number distribution; and most of the engine industries have their own specific proprietary, turbine blades shapes, which they have developed over past many years, and so they have around specifics form for a shape blade shapes the proprietary to their product, and they have develop these over the past many, many years; and there is also been in a recent trend towards developing custom designed or custom tailored airfoils and which are not really related to any this of profiles that have mentioned like NACA series or any other series, but to develop and design airfoils, which are specific to particular turbine geometry, which meets set of design parameters.

So, turbine profiles, blade profiles can be developed and designed through the variety of these methods which is also very much applicable for compressors. Compressor blades are also can be derived either from some of these conventional blades like NACA series or it could be circular arc or parabolic arc or custom built airfoils which many of these industries have developed over many years. So, let us take it look at some of these very typical blades which have been developed and used in the last 40 years or also.

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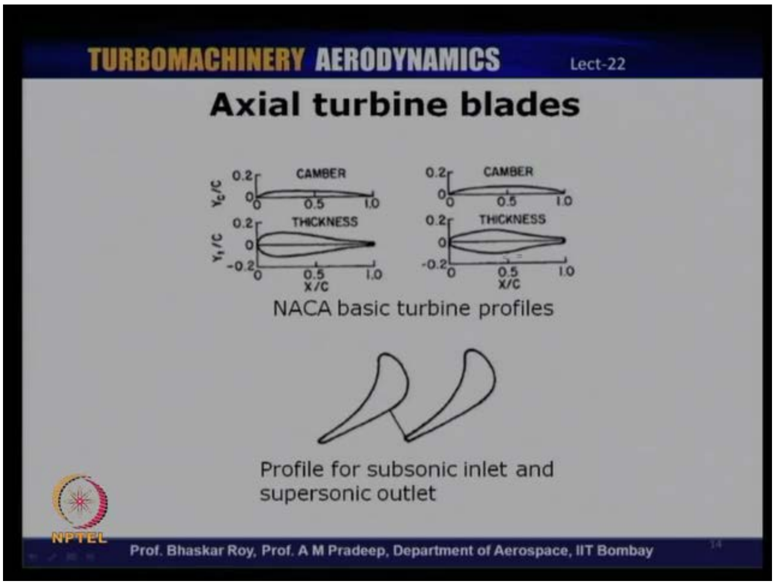

So, some of the very basic turbine profiles, which have been derived from the NACA series are shown here. These are two distinct types of turbine blades, which are derivatives of been NACA series and where they have certain thickness distribution we can see here and a certain camber distribution as well, and so, you can see here between this two profiles, the thickness distribution as well as camber distribution is quite different, and this is from this is along the chord the airfoil, and this of course, thickness distribution of airfoil. One could have profiles, which have designed for a subsonic inlet and supersonic outlet and this is as discussed in the last lecture very similar to convergent divergent which has subsonic inlet throat and then supersonic or divergence section which leads to a supersonic flow in the exit. So, one might have an inlet flow which is subsonic and that accelerates and reaches at the throat that and then again there is a divergence section which is leads to supersonic flow at the exit. One may have blades, blade shapes which are very different from what I just shown.

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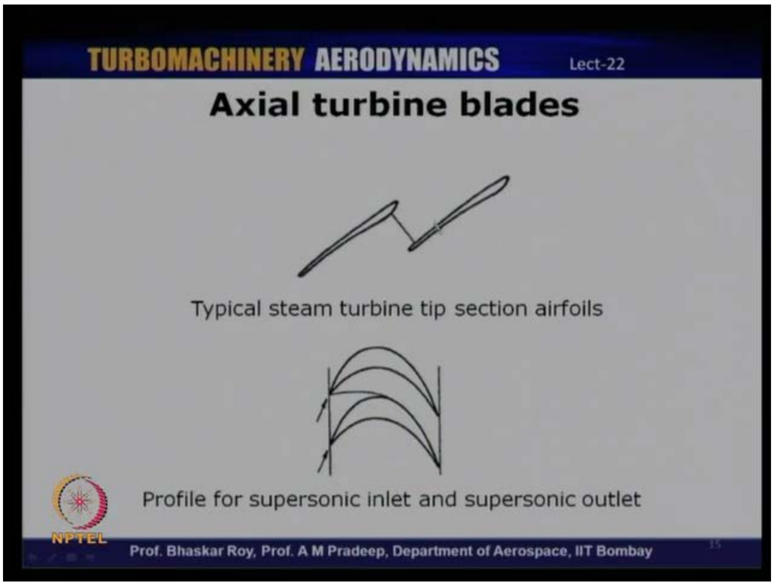

For example, typical let us say steam turbine and blade which is used and one which I just showed here for tip section of typical steam turbine blades, and you may also have blades which have supersonic inlet and supersonic outlet like what as shown here and so, as you can see between these 4 or 5 different examples that I just shown, the turbine blades can be entirely different from depending upon the kind of application for which has developed and designer for. So, turbine blade shapes can be quite extremely different, for example, if you look at the blade, which was used for subsonic inlet to supersonic outlet kind of geometry; compare that with the very traditional NACA type of airfoil which is generally tends towards the subsonic kind of application, one would see that the blade shapes can be quite different, and so how does one arrive at a this kind of blade shapes.

So, that is something that will basically depend upon the application as I mentioned and that boils down to the kind of work output that the turbine is supposed to generate, and if we look at that work output from an airfoil sense or from the airfoil point of view it basically boils down to the pressure distribution on the airfoil surface or the loading of the blade itself, and so the blade shape basically dictates the loading of the blade or the amount of pressure distribution on the section surface and the pressure surface. So, the variation of the pressure static pressure on the section and pressure surface basically gives some of the loading that the particular blade profile are the airfoils section has been derived for.

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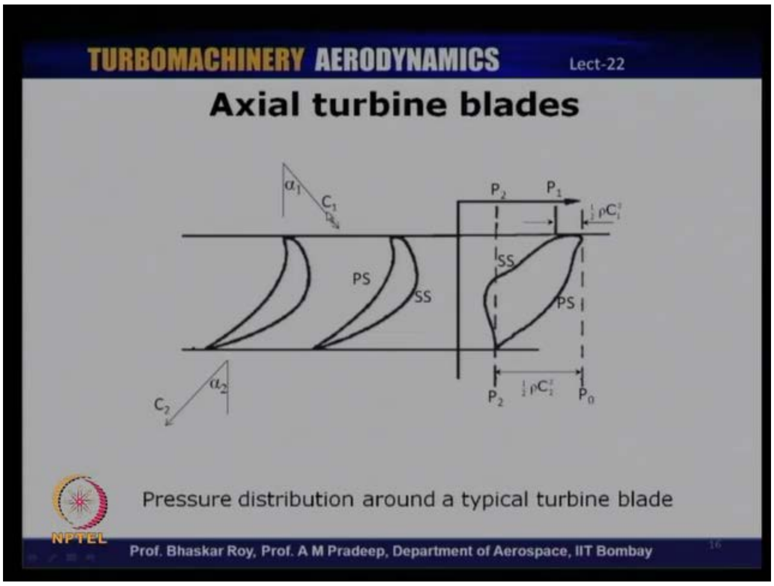

So, let us take a look at a typical turbine blade and try to look at understand the pressure distribution around such a typical turbine blade. So, here we have very standard so called standard turbine profile, and we have an inlet velocity of absolute velocity of C 1 which is entering angle of alpha 1, and it exits at a velocity of C 2 angle alpha 2. So, here as you have seen in the first lecture on the axial turbine, there is a pressure surface and there is section surface like any typical airfoil, and so if we see look at how the flow behaves as it moves on both these surfaces, the section surfaces and the pressure surfaces. So, I have plotted the pressure distribution on what is seeing here the static distribution between inlet and outlet of the turbine blade.

So, if we look at the section surface pressure distribution that is shown here. What is seen is the drastic drop; in this static pressure up to certain level and the static pressure again begins to increase. So, if we look at the flow that as it passes over the section surfaces of an of a turbine blade this basically means that flow accelerates and the acceleration is quite steep as depend by the slope of this pressure curve. So, this is steep curve here or steep drop of in the static pressure for indicates that there is rapid acceleration of flow along the section surface and that progress continues quite for certain distance along length of the blade and after certain distance the static pressure again usually begins to grow of course, this depends very much abound blade geometry. But in a typical turbine blade, one may also have recovery of static pressure after reaches in minimum, which means that could be certain gain in the static pressure towards the exit towards the trialing edge of the blade.

And this is typical pressure distribution, on the pressure surface, you see there is a mild availed, initially it kind of remains constant well the slope is much shall over compare to the section surface and would in still in stage the drop in the section well static pressure of on the pressure surface as well. If we compare the pressure static pressure as at the inlet that is what you see here by let us say denoted by P 1 and compare that average static pressure at the exit. Basically, this tell us the amount of this acceleration that has taken place in the blade passage and so the area between these two curve that is to section surface and the pressure surface gives as the loading that this particular blade has been designed for.

And what is shown here has been what is basically referring to the stagnation pressure which occurs at this stagnation point of the blade which could be point somewhere here and so, the maximum pressure that you see here in this particular blade geometry is basically this stagnation pressure which is proof for any airfoil and exit pressure that is denoted by P 2 is substantially different from what you see at the inlet and that is the difference between these two basically to given by the dynamic head across the speed particular blade. So, this is pressure distribution which is of a typical turbine blade, and if you look at the pressure distribution of all those blade geometry is had shown in the few slides the earlier. The pressure distribution can be quite different, but the general trend is quite is going to be quite similar to what you see here have just seen now, and then in generally you see that there is an acceleration of flow right from the inlet to the exit of the turbine except for the section surface; while in some cases of you might have a local flow deceleration, which in some cases might to lead to pockets of flow separation under certain of designer conditions something I had mentioned in the last class well, and unlike in the case of compressors, the flow in the case of compressors is is going to undergo steady increasing static pressure, and this basically adverse pressure gradient which quite different exactly opposite that we have seen in the case of typically axial flow turbine.

Now, this is also means that there is a significant defect of the where the blades of placed as well. So, that if you have to get decelerating flow or accelerating flow that will very much depend of on the stagor of the blades and also the number of blades. So, if you have more number of blades or if you try to put more number of blades in on the annulus, this means that are more number of blades which can take up the loads, and so the loading per blade would reduced, and therefore, the the stress associated with blade loading also comes known. At the same time, more number of blades mean means that you would need it the overall weight of the… And the blades would increase, and therefore the associated cost and complexity increases. At the same time, if you look at configuration which has lesser number of blades this means that each blade has to now take up a load which is more than what it. It was previews case, but at same time, you safe on the way of this blades and complexity and shown. So, is there any certain kind of an optimum number of blades that can be used for given configuration?

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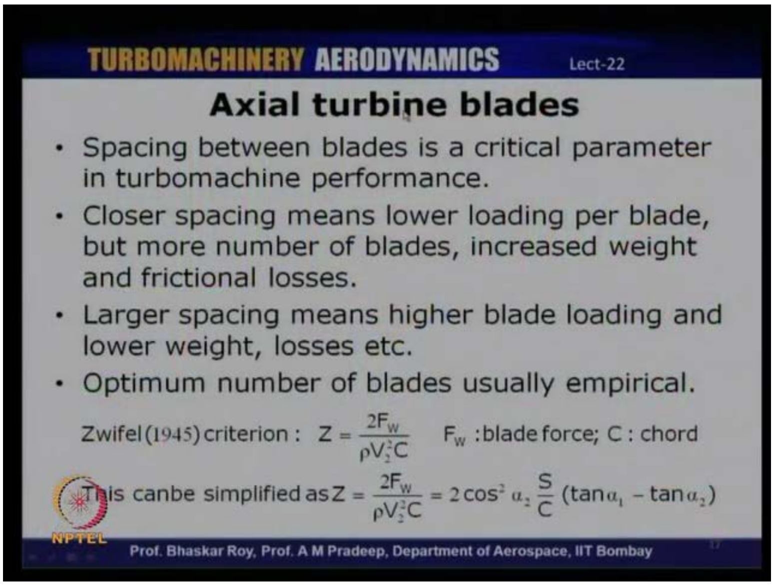

So, spacing between this blades, because is a very crucial parameter there is certain in again and empirical correlation which was develop way back in 40s and of course, this has been modified in the modern version of the criteria which is currently available used by the industry and so, how does one arrive it optimum number of blades for a given turbine configuration. So, there is a criteria, which was developed in 1945 by Zwifel which relates the blade loading or the blade force to some of the aerodynamic parameters. So, this is again empirical correlation which is also related to the blade geometric parameters. So, Zwifel criteria, originally was defined as the blade force divided by half row into V 2 square into C blade called so, this can be related to the the geometric parameters of the blade and so, Zwifel's of criteria Z is also equal to 2 into cos square alpha 2 S by C tan alpha 1 minus tan alpha 2. So, here you can see that this S by C is basically the spacing to chord ratio and generally accepted optimum Zwifel parameter this taken as around point 8. So, if you fix a Zwifel parameter as point 8 and one can actually calculate the optimum spacing ratio from assuming Zwifel criteria of around point 8 and also the blade parameters like angles alpha 1, alpha 2 and so on.

So, this kind of gives some empirical some idea about how much the blades spacing should be given this parameters like the blade angles alpha 1 alpha 2 and so on. This was of course, developed about 60 years ago even more than that have been several modifications to this there are modified version of this Zwifel criteria which are available and used by industry for developing are arriving certain amount of optimum spacing to coordinate ratio and so, what is also noticeable here is the fact that though this parameters was of course, developed with back in the 40s only certain defined version these are available and even though it was developed a way back in the 40s, it is still being consider as lot of empirical thumb rule parameter which can be used at the design point at as starting point of a turbine designer level.

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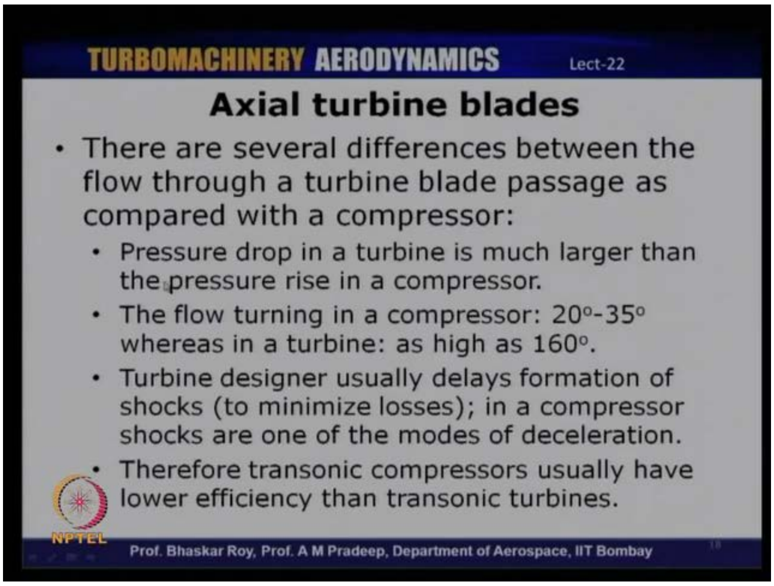

Now what are we will do now is to summarize difference between turbine blades and compressors blades, and of course, subsequently discuss about turbine and exit nozzle matching. So, before we are move on to matching between turbine exit and nozzle let me just quickly summarize some difference is between turbine blade passages as compared with a compressor.

One of the obvious difference is the is the fact that the pressure drop in a turbine is much larger than the pressure rise in a single stage of compressor. The flow turning in a compressor is usually restricted to 20 to 35 degrees, whereas in a turbine can as high as 160 degrees, as you already seen the flow turning is substantially different from that of compressor. In a turbine designer tends to sort of delay, the formation of shocks. So, that the losses across shocks of the minimize, where is in typical transonic compressor shocks lot of form one of the modes of declaration and themselves. So, then no way designer can actually delay the occurrence of the shock, because of that is one of modes the declaration in a transonic compressor and that is one of the reasons why transonic compressors generally have much flow efficiency is then corresponding turbines, because of that fact that in turbine, it is still possible for the designer to delay that occurrence of shock till the later part of the blades and towards trailing edge and so, the losses shocks actually occurred in the lower Mach number regional number also the losses associated with the flow across the shock in lower than that in the case of typical kinds on of compressors where in deceleration itself in carried out through the current of shocks.

So, these are some fundamental differences between turbine blade and a compressor blade, and I think that something that we need to understand very carefully, which is of course, from the fundamentally aerodyne aero thermodynamics on the flow through it compressor and turbine that dictates these fundamentally differences in the blade shapes that tells. So, let us now take up slides different has aspects of the turbine flow and now try to understand the effect of the turbine exit flow on some of the downstream components, see the nozzle; how is the exit flow of turbine matched with that of the exit component like on nozzle. So, the operation of a turbine as you already understood that turbine is link to variety of other components, like the combustion chamber or the compressor, and it is actually mechanically directly couple to the compressor. It is also connected to the some of the thermodynamic or aerodynamically connected to some downstream components like the nozzle. So, all the upstream and down steam components have a significant effect on the turbine performance

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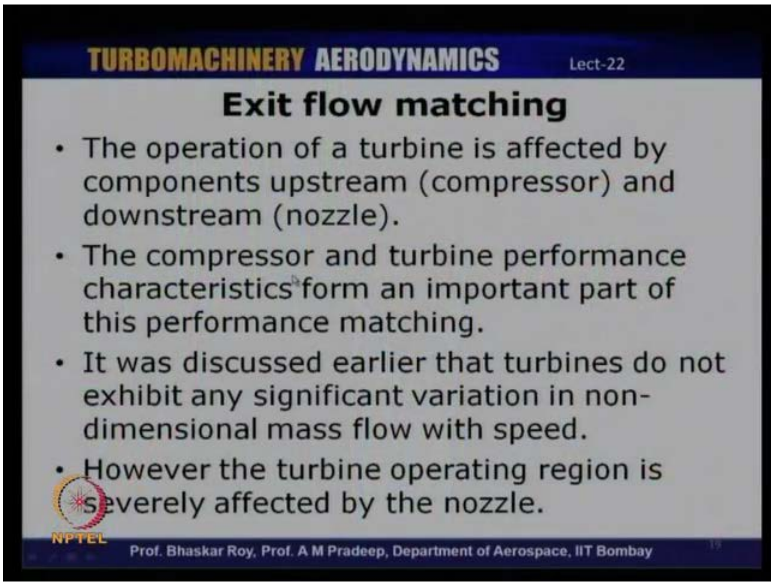

And so, in a typical design exercise, the compressor and turbine performance characteristics would form a very important aspect of engine integration and matching of the performance of the whole engines as well. So, we have seen that in the case of turbine performance very much unlike that of compressors. Turbines do not really exhibit very significant variation in non-dimensional mass flow with speed, which is quite unlike the case of compressors, which exhibit drastic change in the performance characteristics with speed, and so the turbine operation… So, if we look at the turbine performance characteristics one might wonder that turbine, because the performance does not really change much with that speed, it would be rather easy to control the performance of the turbine and match with compressors.

But what is significant here is the fact the turbine performance is actually limited by the nozzle, which is downstream of the turbine, because there is certain amount of mass flow, which is the down nozzle can handle and even if the turbine is able to operate at different amount mass flow rate, the nozzle downstream would solve lot of dictated the amount of maximum mass flow that the turbine can actually handle. What we will very soon see is that most to the modern engines for a majority of the operation would be operating with the both the turbine as well as the nozzle under choked conditions.

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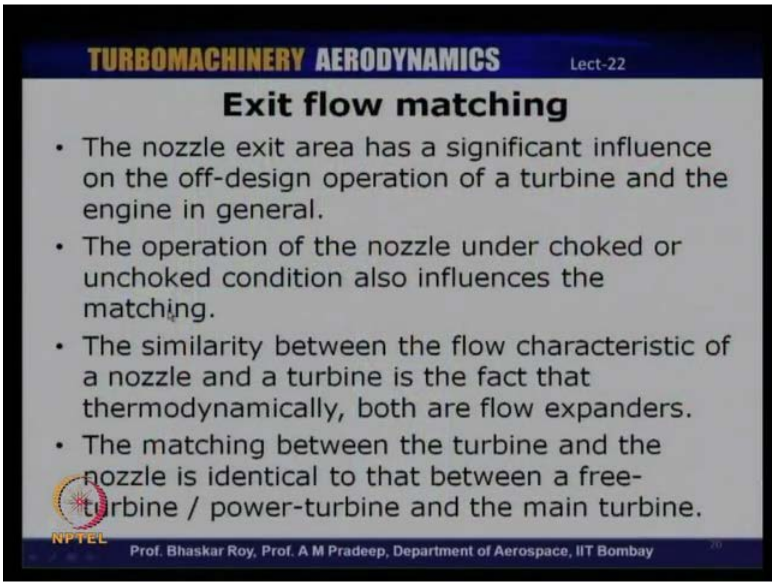

So, the nozzle exit area has a very significant effect on the turbine performance and the its operation, and so whether the nozzle is operating under choked or un-choked condition would have a significant influence on this matching exercise; and so, though if you look at turbine and nozzle from a fundamentally thermodynamics point of view and not, without actually worrying about what constitutes these components, both these components are thermodynamically identical; in the sense that both of these components are expanders; that is flow expands through a turbine, the flow expands through a nozzle as well of course, there as functions entirely different, but if you plot a turbine process and nozzle process on a temperature versus entropy diagram, both these are identical, they are both expanding process, flow expands through turbines and also expands through nozzle.

And so, the matching of turbine with that of nozzle is very much identical do that of matching between in a gas generator turbine with that of power turbine. If we recall, in the some of the forms of engines like turbo prop engine, separate turbine is used for driving let say the propeller, and there is a turbine which actually derives, the separate turbines which is drive compressors. So, there is also matching exercise between this kind of turbine with the power turbine and the matching between or the matching process between a turbine, which is connected to the compressor with that of power turbine or nozzle that quite identical, because thermodynamically, all these components are very much the same.

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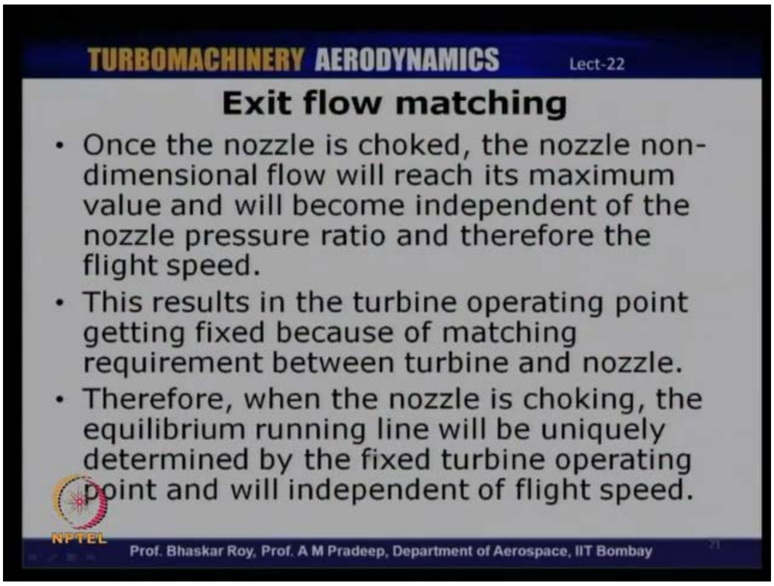

So, if we look at the the nozzle; once the nozzle is choked that means, the nozzle non-dimensional flow has reached its maximum, then it is basically independent of the nozzle pressure ratio, and therefore in some sense the flight speed, because the nozzle pressure ratio is the function of the pressure build up, which has taken place across the variety of components like the intake, the compressor, the loss of pressure, the combustion chamber and pressure drop in the turbine. So, all these, if you multiply all these pressure ratios that basically dictates the nozzle pressure ratio, which means that the once the nozzle is choked basically becomes independent of this pressure ratio and therefore, the flight speed as well. This means that once the nozzle is choked, it sort of fixes the turbine operating point, because a chock nozzle would mean that the nozzle is operating under a condition where the it has reached its maximum mass flow rate and it is no… It is not possible to enhance the mass flow rate further. The nozzle cannot handle any higher mass flow rate, and therefore the turbine also has to operate under a condition, which matches with this nozzle the chock nozzle operating condition.

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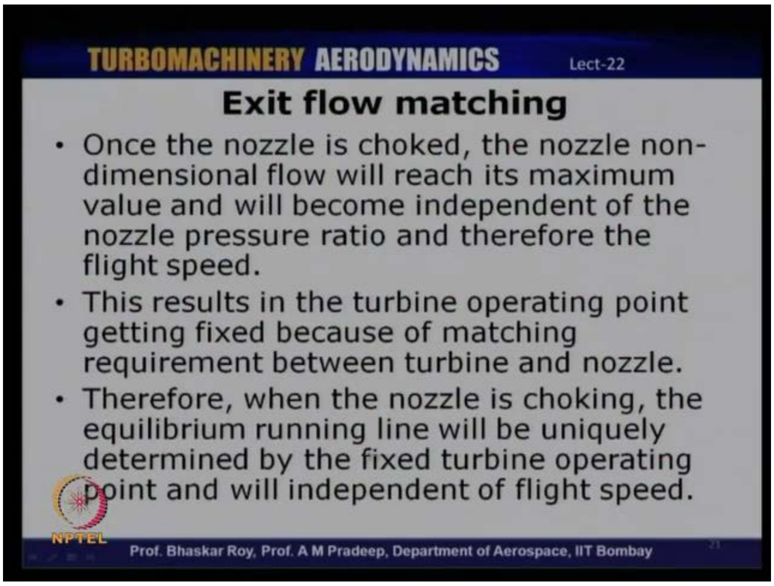

So, chock nozzle would fix the operating point of a turbine, and therefore, when the nozzle is choked or operating under a choked condition with maximum mass flow rate, the equilibrium running line or the operating line would basically be determined or fixed by the turbine operating point, and it kind of becomes independent of the flight speed itself. So, I will try to demonstrate this aspect through the performance characteristics of a turbine as well as that of a nozzle.

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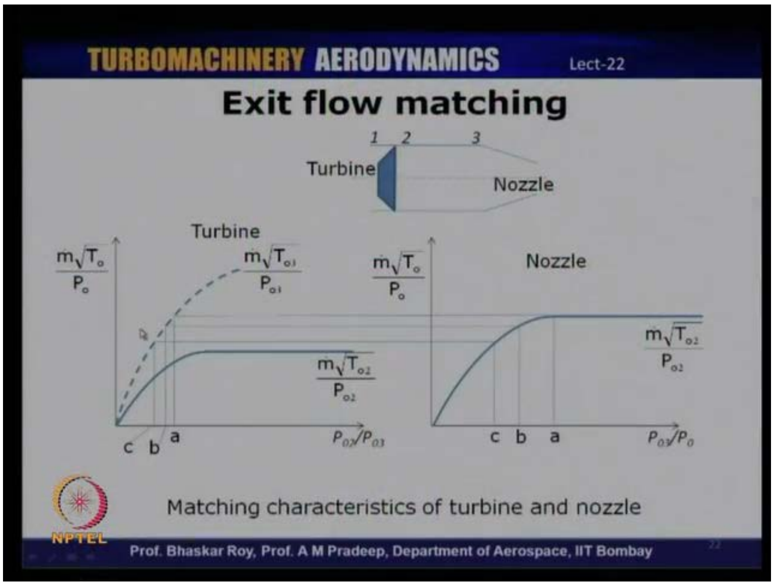

So, here we have the matching characteristics of a turbine as well as that of a nozzle. So, I have denoted station 1 for the turbine inlet, station 2 for turbine exit and station 3 for the nozzle entry. So, we have mass flow versus pressure ratio for the turbine, and on the right hand side here we have the mass flow versus the pressure ratio for the nozzle. Let us take up the nozzle first, because this is of course something you you would have learnt in your gas dynamic courses as well as the nozzle performance, as you change the pressure ratio, the mass flow rate increases, and then it reaches a peak, which is the choking mass flow after which the mass flow remains the same irrespective of the pressure ratio.

So, once the nozzle is choked, the mass flow it becomes independent of the pressure ratio and does not change in spite of changing pressure ratio to any value. So, here if we have a nozzle which is operating under a choked condition and if you look at the corresponding turbine characteristics; so, here we have the turbine characteristics, here the mass flow versus the pressure ratio. So, this you see here is the mass flow rate of the turbine as a function of its pressure ratio; so, if the nozzle is operating under choked condition, which is denoted by a let say, this letter a, that fixes the mass flow rate of the nozzle and since that fixes the mass flow rate of the nozzle that would also fix the amount of mass flow rate that the turbine can handle, but you can see here that the mass flow. This mass flow rate is higher than the choking mass flow of the turbine; choking mass flow of the turbine as denoted here as m square root of T not by P not is lower than the choking mass flow of the nozzle.

So, the turbine cannot really operate under this condition without operating at a lower pressure ratio, which means that the turbine is now operating or it is force to operate at the condition which have a pressure ratio lower than the choking pressure ratio for which the turbine can is capable of operating. Similarly, if you look at other conditions here, in which, under which the nozzle is actually un-choked. So, here the turbine is actually able to operated much higher mass flow rate as well. So, this sort of demonstrate the the fact that nozzle chocking condition would force the turbine to operate under condition which matches with that of nozzle itself; so even though the turbine in this example is actually capable of operating at higher mass flow rate. It is force to operate at lower pressure ratio, because of the fact that the down steam component is choked under that operating condition; and most of the modern date is as I mentioned would be operated under a chocked condition for majority of its operation when its operating under high thrust condition that is high mass flow condition like during takeoff or cruise except under very low thrust operating conditions like during landing or taxing, when the engine is not operating under its full mass flow condition, these components like the nozzle or the turbine tends to remain un-choked under these conditions, but other unless it is operating under these conditions most of the time engines would be operating under choked condition.

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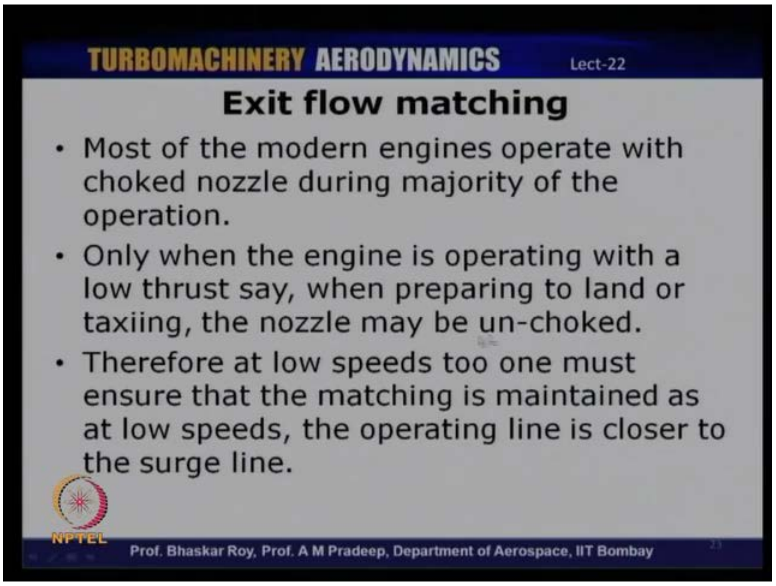

So, only when the aircraft is let say preparing to land or it is taxing, the nozzle may be un-choked; and it is also necessarily that one would have to ensure the matching even at low speeds, and it is under these operating conditions that when you try to match an un-choked nozzle with that of a turbine; and eventually with that of a compressor that there could be problems with reference to a compressor operation because under these conditions the operating line might move very close to the surge line, which is something that compressor operation the designer of the engine integrating team would have take care, because if the the operation is close to that of surge there is a risk that the compressor might enter in to surge, and of obviously, that could affect the entire engine operation itself. So, at at a very low speeds, when the operating line tends to become very close to surge, and that is where the nozzle and therefore, the turbine tends to remain un-choked that is lots of care need to be put in between matching of not just the turbine and the nozzle, but also with components of upstream like that of the compressor.

So, this is just quick overview of the matching operation, there is also an extensive matching that is done between the compressor and the turbine, and that is incomplete without taking this nozzle into an account, because even though a compressor and a turbine might well be matching in their operating range; it is the nozzle which would sort of dictate the or fix the turbine operating point, and then the whole matching exercise between and turbine might require another round of iteration to ensure that all these three components operate under a matched condition even at low speeds where the nozzle might be un-choked

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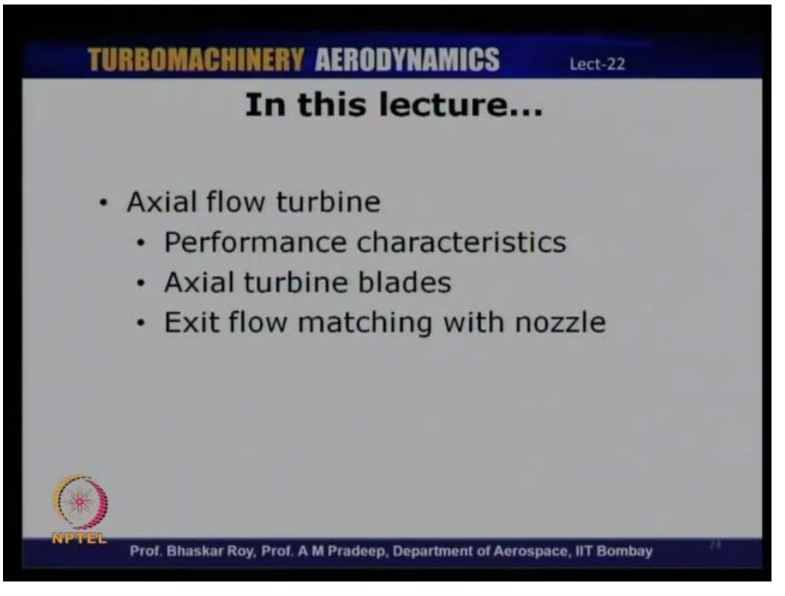

So, let me now very quickly this today's lecture, we had discussion on three distinct aspects of turbine operation, one was to do with the performance characteristic we discussed about the different performance characteristics in terms of mass flow and pressure ratio efficiency and pressure ratio; and we have seen that the turbine operate performance characteristics is quite different from that of compressor and the turbine performance and the turbine performance is usually insensitive rather relatively insensitive to varying speeds as compared to that of compressors which can be quite sensitive to operatic speeds. We also discussed about the different blade shapes which are used in turbines and the the nature of flow as it passes through some of these different blade shapes.

And lastly, we discussed about matching between the turbine and one of the downstream components like the nozzle, you might have additional downstream components like a power turbine or after (( )), we have discussed about the nozzle, because that is the sort of limiting the performance of the turbine itself. So, these were some of the topics that we had discussed in today's lecture, and so it is about time that we have session on solving some numerical problems from axial flow turbine.

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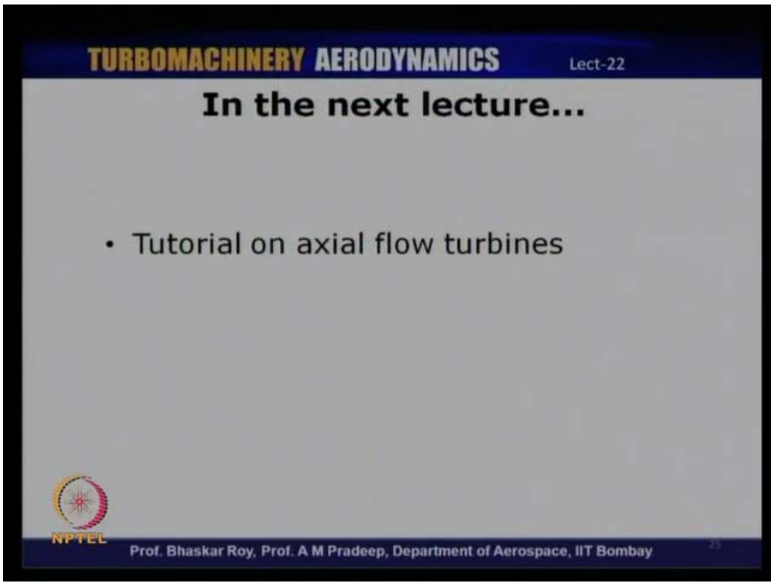

So, we will devote our next lecture towards a tutorial on axial flow turbines, where we will flow, we will be solving some problems from axial flow turbines, and I will also have some exercise problem for you, which you can solve based on our discussion in the last few lectures as well as the tutorial session itself. So, we will have a tutorial during the next lecture.