Jet aircraft propulsion

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Lecture No. # 21

Multi-staging: Axial turbine; Turbine Cooling Technology

We are talking about axial flow turbines; axial flow turbines that used in aircraft jet engines there also called gas turbines. In so for as they use the hot gases that come from the combustion chamber to produce work, and as we have discuss before, this work is essentially used to run the compressor of a typical aircraft engine. Now, in the last class we had quick look at what a basic axial flow turbine looks like? How does it work? And how does it work which done by axial flow turbines can be quantified in terms of work done, in terms of efficiency so on and so forth. Today, we will try to take a look at number of things; one is how such a turbines are characterized? You have done in your compressor chapter that typical compressors are also characterized, and they are also often or simply refer to as characteristic maps.

So, we will take a look at such a characteristic map today. We will also take a look at what it involves in multi staging of turbines. As we have discussed, if the aggregate amount of what that needs to be supplied to run the compressor or the fan of a turbofan or running a propeller of a turboprop requires large amount of work to be done by the turbine, quite often it may not be possible to do it in one stage of turbine. In which case multi staging often is required, and we will take a look at what this multi staging involves. And typically much of these multi staging may involved multi spooling; that means, we will have two spools or two sharps to concerting sharps as we have again discuss before, and those two spools how do they actually look like, how do they operate? And what happens to their characteristics.

So, we will take a look at some of these issues, and then afterwards we will take a look at the turbine blade cooling technology, because this is the technology that is dominated the turbine development over last 50 years. Much of the development of actual flow turbine, specially with reference to aircraft engines has been around the blade cooling, because simple thermodynamics have already told has in very clear terms that higher the entry temperature to the turbine; higher is the work extraction capability of the turbine. And also it impacts on the overall efficiency of the cycle; the jet engine cycle, and higher the temperature, higher is the efficiency of such a cycle.

This efficiency shows up in the form of fuel efficiency. So, higher turbine entry temperature or higher temperature coming from the combustion chamber thus mean; double benefit more work by the turbine and more efficiency of the working engine cycle. Now, to take full benefit of this high temperature, it is necessary to protect the turbines from completely getting burned or charged, because that can happen even as we use high temperature materials the turbine blades are quite amenable to getting completely charged; if such high temperatures persist for quite some time.

Hence, it is required to have certain cooling technologies incorporated in the turbine blades for continuous cooling of these blades. Hence, these cooling technologies are essentially the lifeline of the turbine blades without these cooling technologies incorporated in the turbine blades. These blades actually would not survive for sometimes more than a few minutes. So, we are talking about a cooling technology that is integral to the development of axial flow turbines as used in aircraft engines. So, let us take a look at some of these issues related to axial flow turbines, specifically as used in aircraft engines.

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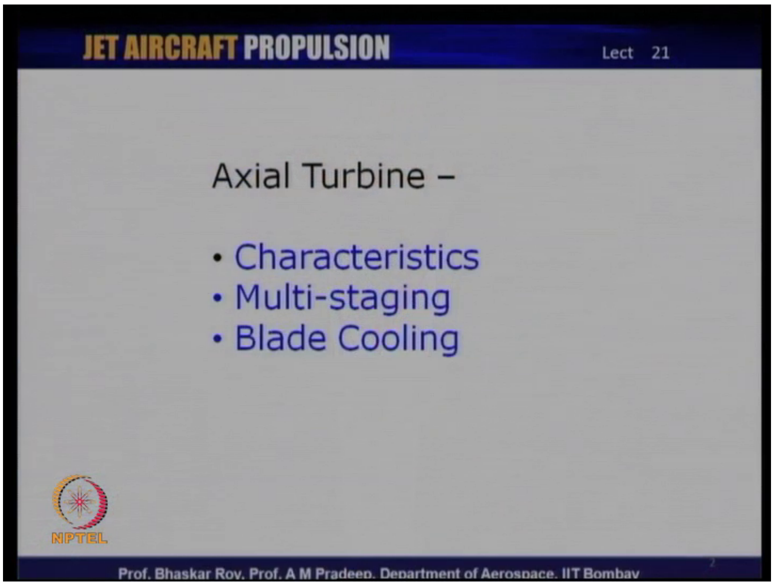

So, as I mentioned today will be taking a look at three things: the characteristic, the multi staging of the turbines, and the blade cooling technology used in the modern aircraft engines. Let us start with the characteristics of axial flow turbines, now axial flow turbines do have characteristics similar to that of compressors; axial flow compressors or centrifugal flow compressors that you have done before and they are call characteristics simply because they actually characterized a particular turbine. Every turbine every turbine as its own characteristics there is nothing like generalized characteristics of all kinds of turbines. So, every turbine needs to be characterized immediately after its creation; immediately after its design and made it needs to be characterized. The first characterization is normally done now a days in a computerize manner. However, that needs to be also validated through rig testing and once of rig testing is over.

We have a certain characteristic map that characterizes; that particular axial flow turbine, which would then be used for characterizing not only characterizing the turbine, but matching this turbine with rest of the engine that goes on the aircraft. This characteristic map would also be used for control of the turbine; the control of the engine along with the various control rules that govern the control of the engine, along with the control of the aircraft. So, these characteristics are extremely important for operation of the turbine. In so for as operation of the entire jet engine and as a result of which this characteristic map is one of the first things that you would need to have with you immediately after the turbine is created. So, let us take a look at what a typical characteristics map of axial flow turbine looks like? And what does it actually mean?

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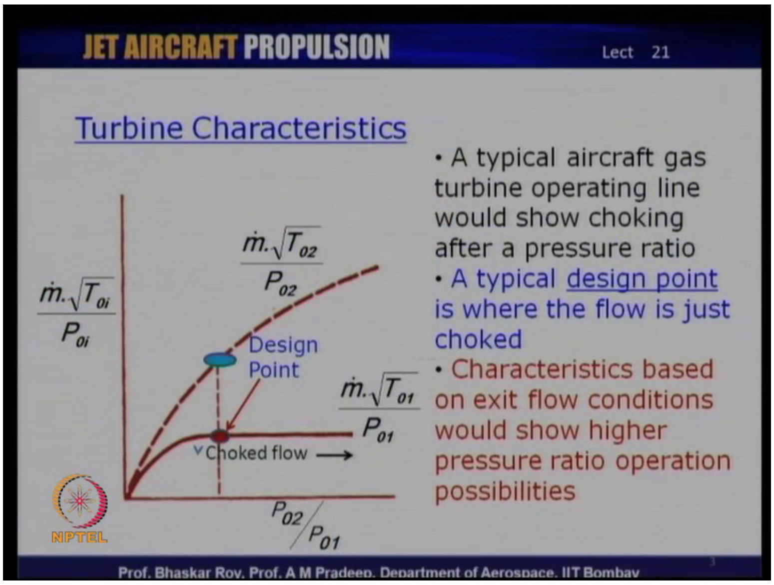

Now, the turbine characteristics as given in this map are typically drawn with a mass flow parameter on the y axis and the pressure ratio across the turbine as the x axis. Now, this is slightly different from the weight is done for example, in case of compressors as we have done before. In case of compressors typically the pressure ratio is shown on the y axis and the mass flow parameter as it is shown, here is shown in the x axis. So, in case of turbine; this is switched around the two axes are essentially switched around also notice that we are using a normalized mass flow parameter. So, we are not using the mass flow directly; we are using normalize mass flow parameter normalize by the temperature and pressure of the turbine of the operating point of the turbine or at the to the turbine.

The present a map actually shows m dot into route over T 0i divided by P 0i, because we have drawn the characteristics with two different sets of T 0 and P 01 is T 01, P 01 with reference to the entry of the axial flow turbine and then T 0 2, P 0 2, which is the exit of the axial flow turbine also notice that we are using the total parameters: total temperature and total pressure to signify or normalize this mass flow parameter. As you see it is done with reference to two different stations: one is the entry station of the turbine; another is the exit station of the turbine and p 0 2 by p 0 1 is the pressure ratio across the turbine. As you know, there is going to be pressure drop cross the turbine. So, essentially this is the pressure drop ratio across the turbine.

Now, what happens is if you show it with reference to let us say the entry point parameters of the turbine; the mass flow parameter the characteristic map would typically follow this red line and at a certain point of time it will simple become a flat line and that is because some are over here the flow actually goes choking. So, typical aircraft gas turbine engine operates most of the time in a choked manner. Now, this is the reason is the pressure ratio that operates across a typical turbine is often higher than the required theoretical choking pressure ratio. This is something which most of the aircraft gas turbines are deliberately design for and as a result of which most of the aircraft gas turbines specially the early gas turbines the first one or two stages of the gas turbine or in variably choked.

This means; that typical design point at which of turbine is most likely to operate is actually operating under choked condition and this that is shown here in the red block. It shows that the flow is actually choked through the turbine; that means it is reached maximum mass flow, if you continue to increase your pressure drop across the turbine further and further mass flow through this turbine is not going to increase any more. That means, that the mass flow through the entire engine as now, reached maximum it cannot go above this mass flow anymore, because some are in the engine and in this case across this particular turbine the flow as got choked.

It cannot increase mass flow anymore this is typically the condition under which a most aircraft gas turbines actually indeed operate and hence even if you increase the pressure ratio you are not going to get more mass flow; if you increase the pressure ratio as we know you can indeed get more work done, as we have done in the cycle analysis we can get more work done, but you are not going to get more mass flow through the turbines anymore. On the other hand, if the characteristics are actually drawn with reference to the exit flow conditions we see this dotted line over here it continuous to rise with the pressure rise. As a result of which the design point, which you shown here is already choked flow condition would now, actually be some are over here; where it is still arising characteristic, now this dotted line which is drawn with reference to the exit of the turbine can also be said to the entry to the next stage of turbine, if it is a multi stage turbine.

So, this corresponds to the next stage of a multi stage turbine, which we shall have a look at in a few minutes from now. So, it means that flow which is choked under the entry flow conditions may indeed look a chock; if it is plotted against exit flow condition. Now, this is what the turbine characteristics mean and we shall take a look at what it means, when you have multi stage turbines.

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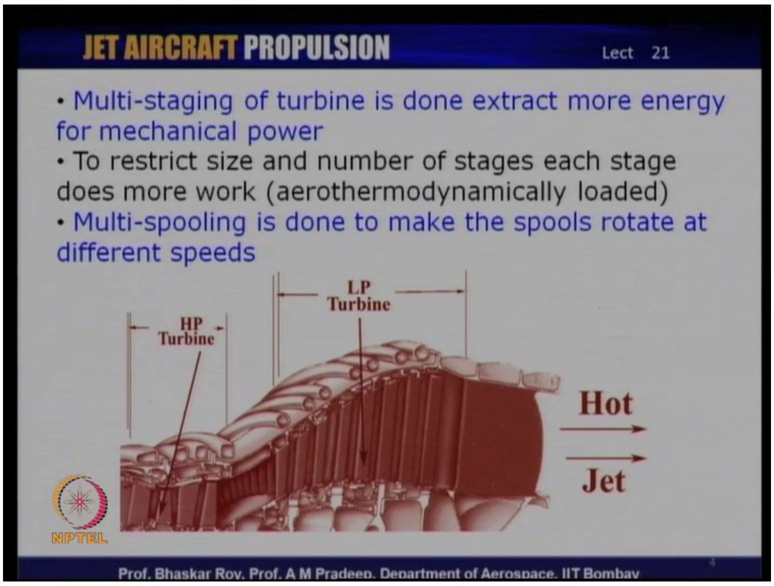

Now, multi staging of the turbine is essentially done for two or three main reasons: one of the reason is that; it is done to extract more aggregate energy or mechanical power which is needed either to run the compressor or to run fan or number of stages of fan; whatever the engine configuration is and as a result the turbines are required to produce more work to be supplied to the compressor or a fan or a combination of compressors and fans. There is another reason, why sometime multi staging is an important issue; the issue is that if each stage has to do more work and in aircraft engine. Typically, it requires that the turbine is not very large in size, if you keep on increasing the number of stages the total amount of space that needs to be allotted to the turbines would go up.

The length of the engine would go up; the weight of the engine would go up and many of these things are not really acceptable to an aircraft application or to aircraft design a really speaking and as a result of which such turbines and such engines are unlikely to be accepted for aircraft applications. In such a case, it is required that each of these stages is also highly loaded. Now, when we talk about loading; we are talking about aero thermodynamic loading, some of these loading parameters or what we have talked about before in with reference to your cycle. Analysis the loading essentially refers to the amount of work that it can do in a single stage across one row of rooter.

Let us say and that is signified by the aerothermodynamics loading, which mean the typical aircraft gas turbine is typically much more aero thermodynamically loaded compared to any other kind of turbine or gas turbine, which may be used in land based applications, where the restriction of size and weight does not quite apply so, frequently. As a result of this the aircraft gas turbines, essentially need to be highly loaded even when they are multi stage. So, multi staging may not be the only solution one has to go for aerothermodynamics loading, which has we just saw beings that the more and more stages are likely to be choked. That mean they would be loaded to the maximum with reference to the working capability.

There is a third reason why multi spooling is often resorted to in aircraft gas turbine engines quite often, multi spooling is not necessary in land base gas turbine engines land base gas turbine engines are indeed much bigger an larger than aircraft engines. They produce much more power than aircraft engines. But multi spooling is often not restored to in land base engines and one of the reasons is in aircraft operation it has to work under various operating conditions during its flight; during takeoff; during claim; during cruise all these conditions require different kind of atmospheric conditions; differing kind of working conditions in front of the turbine.

And as a result of which the turbines may be ask to or required to operate under different operating speeds or rotating speeds; that means, if you look at this multi stage turbine now, we have an HP turbine and then we have a set of LP turbines. Now, as we can see here the HP turbine as two stages: stator, a rotor and then stator, rotor as we have seen typical turbines stages made up of a stator and a rotor. So, we see here two stages of HP turbine. Then we see here something like four stages of LP turbine: stator, rotor, stator, rotor etcetera and as a result of which we have a set of LP turbines.

Now, such LP turbine in an aircraft engine would typically be design to operate at a different r p m most notably it will be operating at an rpm. Substantially, lower than that of the HP turbine; typically HP turbine would be rotating at very high rpm of the order of 10000 r p m or more where as LP turbine is most likely to operate at much lower r p m could be of the order of 7000 or 8000 r p m or even may be lower than that, because this LP turbine is most likely to be powering fans of a turbofan engine. Now, fans of a turbofan engine as you have done earlier before. Actually are expected to operate under slightly lower r p ms than the high pressure compressors the reason being the typical aircraft fans goes supersonic at certain speeds, operating speeds.

However, very high supersonic speeds, even today are not very comfortable both by the designer as well as by operational conditions. And as a result the compressor and fan designers try to avoid very high supersonic operating speeds through these compressors. Now, to restrict this speed operating fluid, mechanical or fluid dynamics speed through this a compressors. The compressor rotating speed needs to be limited to certain values. So, the turbines which drive the compressors directly through a concentric shaft also need to conform to this restriction of rotating speeds. As a result of which LP turbines would need to be rotated at a somewhat, low speed than typical HP turbines.

So, these are some of the fundamental reasons for multi staging and these reasons; allow the aircraft designer a lot of flexibility in design; lot of flexibility to the operation of the typical aircraft engine and these operational flexibilities are what needs to be design into the aircraft engine gas turbine. Now, gas turbines are designed to then have these flexibilities. They are various operational loadings under various operating conditions; they operate at various speeds under various operating conditions and also they can be made to operate under various kinds of temperatures which comes from the combustion chamber, because combustion chamber you can increase or decrease the combustion chamber delivery temperature by simply increasing or decreasing the fuel that is burnt in the combustion chamber.

So, the turbine should also be able to operate at various incoming temperature levels along with various speeds and as a result of which the turbines would be operating under various loading conditions. So, all these needs to be build into the design of the axial flow turbine and this design should then conform to the need of the entire engine, as you have done in cycle analysis and that engine would then be fit for going on an aircraft machine. Now, let us take a look at what happens if you have a multi stage turbine and then this multi stage turbine needs to again have characteristics.

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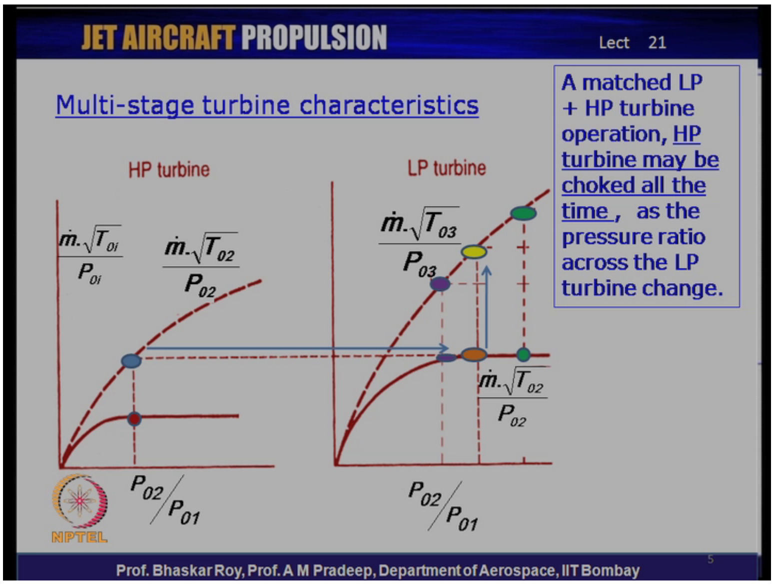

Now, let us take look at this multi stage turbine characteristic. See, now you have HP turbine and you also have LP turbine. Now, these HP turbine characteristics we had look at earlier, and as we can see here the turbine is essentially let us say choked. Now, this choking condition corresponds to an exit condition over here, which is shows a rising characteristic, and then this is a translated to the next map, which is that of the LP turbine. And this LP turbine now is operating at this condition which we can see now is also choked. So, the present design is such that the way it is operative the set of HP turbine, let us you know conform to the earlier diagram we have set of HP turbine, we have a set of LP turbines.

Now this HP turbine, let say characteristics is representing the set of HP turbines and this LP turbine characteristic let us say is representing that set of LP turbines. Now all of them together, then it show that while the HP turbines set is choked at the same time the LP turbine also looks choked, when you take the exit condition of the LP turbine and the mass flow parameter, normalize mass flow parameter is shown. It shows that it shows the raising characteristic; that means, with varying pressure ratio it can continue to show raising characteristics. Now, these characteristics are essentially then show that both the turbines are capable or working under chocked condition.

However, if let us say under some operating condition the LP turbine is now required to operate at a lower operating speed, rotating speed. In which case it could actually get unchoked. It could get slightly unchoked and then, if you translate that slightly unchoked condition to the HP turbine, we will see that HP turbine is most slightly to be still choked. So, if we translate some of the slightly unchoked operating conditions of LP turbine, back to HP turbine. We will see that they are still choked conditions through the various operating conditions of an LP turbine.

It is most slightly that the HP turbine will continuously remain choked. On the other hand, if we go to the right of the characteristic design point and look at this green point, where LP turbine is operating at a higher pressure ratio; that means, it is now made to operate at a higher rotating speed, it is fully choked now. Corresponding to that the hp turbine will continue to remain choked not only it will continue to the remain choked it will continue to remain operative under same operating condition; that means, it is choked condition will remain exactly same as it was which means that under variable operating conditions of a LP turbine, where it can go down to even unchoked or highly choked you know fully choked.

The hp turbine will continue to operate under stable single operating condition. Now, this is the important point that LP turbine may have variable operating conditions from unchoked to choked, where as hp turbine through all this will continue to remain stable under one single choking operating condition. Now, this is how normally the HP and LP turbines are designed together; they are match together and we will probably have look at some of these matching issues later on in the course of this lecture series. So, this is how multi stage turbine is often characterized.

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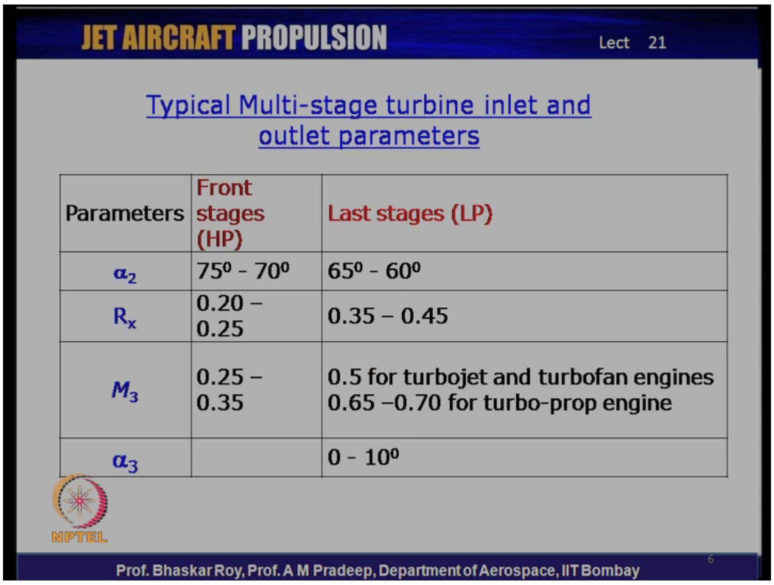

Let us a take look at: what happens? When you have multi stage turbine the inlet and outlet operating conditions can now be varied slightly. For example, we had looked at the velocity diagram. So, the vector diagrams in which alpha 2 was the exit angle from the stator nozzle on to the rotor and what we see here that in the HP turbines the front stages the alpha 2 values can be very high because that is, where we are looking at very high velocity choked fully choked flow condition. As, we have just seen and flow is gone completely sonic may be slightly supersonic. On the other hand the last stages, the flow may not be sonic may or may not be sonic and the angle is slightly on the lower side corresponding to the exit flow condition from the stator nozzle of that particular stage.

The degree of reaction R x in turbines as we know typically they are on the lower side compare what you may have seen in the compressors that you give reaction in turbine system substantially lower, which means; that more of static changes are occurring in the stator and less of them in the rotor. This is by design the static change that occurs in the rotor actually corresponds to the reaction turbine. In an impulse turbine the reaction that we are showing here degree of reaction would indeed be 0. So, an impulse turbine as a 0 degree of reaction, where as reaction turbine typically as used in aircraft gas turbines would have positive values, but these values are nowhere near as high as you have seen in case of axial flow compressors.

There also is a slide variation in the front stages in the HP stages the values are of the order of 0.2 to 0.25 whereas, in the later stages the values are slightly on the higher side; that means, more reaction is obtained from the LP stages. Whereas in the HP stages, the reaction force that is obtained through the reaction mechanism in the rotor is somewhat on the lower side and one of the reason is the HP stages the flow is already of very high energy. As a result the work being preformed through the impulse force is already of a very high order whereas, in the later stages the potential energy available in the LP turbines is somewhat of a lower order and hence an effort is made to obtain more from the reaction force, because less is available from the impulse force for running of the turbine.

The exit Mach number as we can see here, from the front stages is not very high because it is coming with a low mach number from the combustion chamber. So, in the front stages the exit Mach number is of the order of 0.25 or 0.35. I mind you this is Mach number are dependent on the local temperature. So, one as to factor in the local temperature to actually find out or figure out what the actual velocity would be in case of turbojet and turbofan engines the LP stage of the last stage exit condition would probably show a Mach number of the order of 0.5. This flow is indeed going into a nozzle, where it will get subsequently even more accelerated through the nozzle to create the jet thrust. On the other hand, if it is a turboprop engine you normally in the ever to create more work out of the turbines, to run the propeller.

Hence you do not like to have exit flow containing a lot of energy anymore and hence you extract maximum amount of work from the turbine and then let it go with slightly actually higher Mach number, because you are not trying to get a lot of nozzle thrust anymore; you simple want the flow to go out with may be or very small amount of thrust creation. So, more of the work is being done through the propeller whereas, in turbojet and turbofan the typical full jet engines. You still have a nozzle as another component of the engine and that nozzle is going to create higher acceleration and a high velocity jet for thrust creation. The exit angle from the turbines, typically in the front stages there is indeed no prescription of what the angle could be; it could be a little on the higher side, because it is going into the later stages.

It depends on the designer to create what angle he chooses to be the best possible angle. However, in the last stages one would like to see it going out with very low angle. The reason is you do not want lot of wild component or tangential component of the jet that is going out from the turbine, because that component is not usefully for thrust creation. Now, this is something known very well special for aircraft gas turbine engines. for aircraft jet engines and hence you let the flow go out of the turbine with minimum possible angle or wild angle. So, that it does not have wastage of energy in the wild component of the outgoing flow.

Now, this is the situation that is normally kind of prescribe for typical aircraft gas turbines, especially when you have multi staging of gas turbines meant for aircraft usage. These are prescriptions not very binding actual design values would vary from one kind of turbine to another. Now, let us take a look at various kinds of cooling mechanism that is normally used in various kinds of aircraft cooling, gas turbine cooling. Now, you see the gas turbines in aircraft typically or subject to very high temperature. In fact, as we have noted before in thermodynamics it clearly states that if you have higher and higher entry temperature to turbine you get more and more work extraction possibility; you also of course get a higher cycle efficiency or engine efficiency reflected in the fuel efficiency.

A high turbine temperature is something, which every turbine designer for aircraft usage as been working on for over last 50 years. That entry temperature is going up all the time over the last 50 years. So, fifty years back the LP temperature to turbine was of the order of 1000 degree; 1000 degree centigrade or even lower about 85 degree centigrade about 1000 degree Kelvin. Today, that temperature is of the order of 18 to 119 degree Kelvin and it is even now going up depending on the cooling technology that is available at hand. So, let us take a look at this history of cooling that is being going on for a period of almost little more than actually 50 years.

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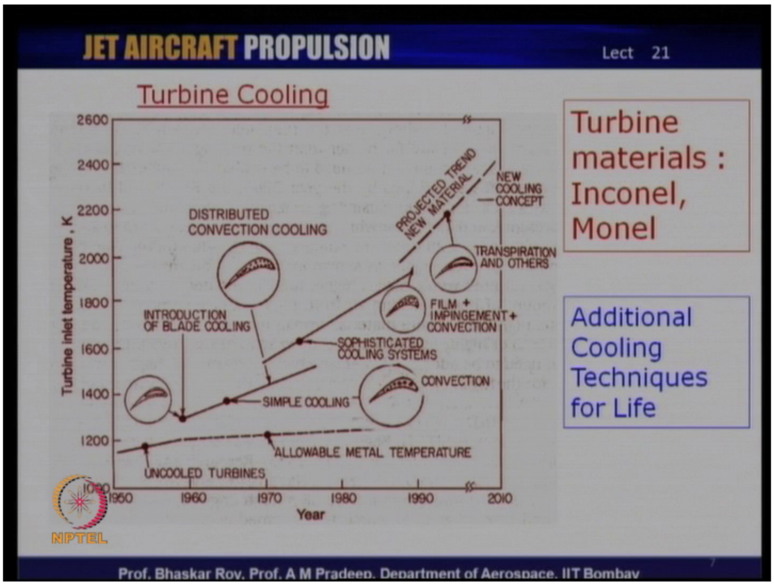

Now, if you look at this diagram here, it shows the temperature which the turbines are being subjected to on the y axis and the chronological development over the year from 1950 when the jet engine started flying. Till today, now what it shows is that in the early years the turbine blades, where indeed on cooled there where made of so called high temperature materials, which are typically inconel and Monel. These are nickel based alloys, which have been used for gas turbines for over last 50 years. Now, these where use without any cooling technology in the early years and that allowed one to go may be up to something like 1100 degree Kelvin, but after that these blades would not survive. In fact, indeed if you increase the temperature from 1200 to 1300 the same blade would probably get charged in matter of few minutes. You cannot possible have turbines operating at that kind of temperature anymore.

So, once the temperature crosses the 1000 centigrade mark cooling became an absolute necessarily for all kinds of aircraft engines. Now, what happens is you can see here in the early years there was some simple cooling mechanism, which is used in passing some cooling air through the blades and this introduction to blade cooling provided some relief and certain amount of increase in temperature could be easily achieved. Once that possibility was exhausted more and more and in those days it was simple called convection cooling, because the air was passes through the blade and so called cold air passing through the blade took away. Some of the heat and the amount of cooling that could be achieved was order of 50 to 100 degrees only and that was sufficient to give the blades a reasonable life of the order of few 1000 working hours.

As, I mentioned without that cooling the blades would have got charged in a matter of one or two minutes so form one or two minutes the blades could be render a life of the order of few 1000 working hours through this simple convection cooling only. However, as the designers want to go for a higher and higher temperature, more and more sophisticated cooling techniques where required and some of these cooling techniques than came into the picture these are; we will have a look at some of these in a few minutes from now, but these are called film cooling and impingement cooling and these where added to the convection cooling. So, convection cooling as a fundamental cooling technology remains, but additional cooling technology is where added inside the blades. So, the inside with the blade become more and more complex and we will have look at them in a few minutes now.

And as a result of which the cooling technique now available in actually involve. At least three kinds of cooling the film cooling the impingement cooling and the convection cooling the combination of these is what is normally used in many of the modern gas turbine engines. One of the futuristic thing that people have been talking about for almost thirty forty years now is a transpirations cooling, but it is not really been you know incorporated in the blades as yet, because it requires a new material technology development which is not happen. So, this has been extended and we have reach temperatures of the order of 2000 Kelvin which is of the order of 1700 degree centigrade as of today in turbine operation anything more than that indeed requires a jump in the cooling technology.

A new kind of cooling technology, which peoples are still researching for the material technology also, is being researched for; so, combination of new material technology and new cooling technology would hopefully take us to higher temperatures in the years to come. That the additional cooling technology is that: I was talking about that is the additional film and impingement cooling, essentially renders more life to the turbine blades, the life we are now talking about is in terms of according to present regulations of turbine usage. It as to be of the order of something like 10000 working hours or running hours, now to render that kind of life with higher operating condition requires that you have very extensive cooling technology build into the typical turbine blades. This is what this combination cooling the film and impingement cooling is essentially, trying to achieve that at such high temperature the turbine blade without the cooling would have got charged in a matter of seconds. So, from getting charged in a matter of seconds to rendering a life of order of something like 10000 working hours is what this cooling technology have indeed achieved now this is what we are going to talk about in this lecture today.

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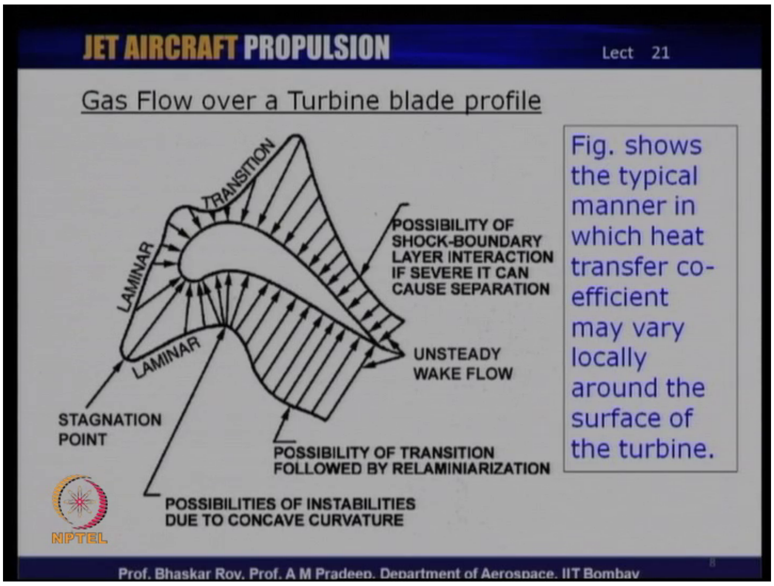

Now, let us take a look at what this cooling technology fundamentally involves? When the gas flows over a turbine blade it creates a certain flow field around it and this fluid flow field around actually involve a laminar flow around it and then there is a transition from laminar and then the flow indeed becomes turbulent. So, most of the surface of a turbine blade, actually experience turbulent flow over it only the leading age part of it experiences laminar flow around the leading edge area and then after that the flow transits to turbulent flow. Now, when the flow transients form laminar to turbulent flow is heat transfer characteristic also changes.

In a laminar flow, as the definition of laminar flow is known to you there is no mass or heat flux across the laminous of the flow, which mean the laminous segregate each other. Hence those laminous do not allow any high temperature to flow in from the hot gas into the blade;

however, at the stagnation point here when the flow indeed comes almost to stagnation or theoretically to stagnation the entire hot gas kinetic energy is now available in terms of potential energy. So, the total temperature at this point is equal to the static temperature and that is exactly what is indeed felt at the stagnation point.

So, this stagnation point is indeed the hot spot of a typical gas turbine blade. Now ,this hot spot is what everybody is most worried about and we shall see very soon how this hot spot is expected to be cooled or in belt to be cooled through impingement cooling from inside. So, this stagnation point is one of the problems of heat transfer cooling of typical gas turbine blades, after that the flow is laminar ands as we can see the flow naturally does not provide a lot of weight transfer and then immediately after work at the flow accelerate over this surface very fast. In this acceleration actually converts from the flow from laminar flow to turbulent flow through this transition. Once the transition occurs and the flow has become turbulent, the heat transfers across the laminous actually now start taking place.

So, the hot gas now can easily pass on its heat to the turbine blades. And the turbine blades could indeed get badly heated up and that can happen from both the surfaces from the upper surface as well as from the lower surface. Now, what we shall see now is that this heat transfer actually continuously changes over the blade surface. We depending on the blade curvature of each of the surfaces the C p or coefficient of pressure over the blade surface is continuously changing. So, the velocity field over the surface is continuously changing and the local temperature is continuously changing; that means, the heat transfer coefficient is continuously changing. Now, this continuous change of local heat transfer coefficient means that you need to indeed provide differential cooling at different point of the turbine.

We have just seen that the stagnation point is a hot spot; we also know that someone near the twilling hedge there could be another local stagnation point which would indeed become another hot spot, because the local temperature there would be equivalent to the stagnation temperature. There are many such areas over the gas turbine, where the blade is extremely sensitive. The suction surface of the blade which actually participates more in the working of the gas turbine needs to be protected and as a result of this you need to provide differential cooling over this gas turbine surfaces.

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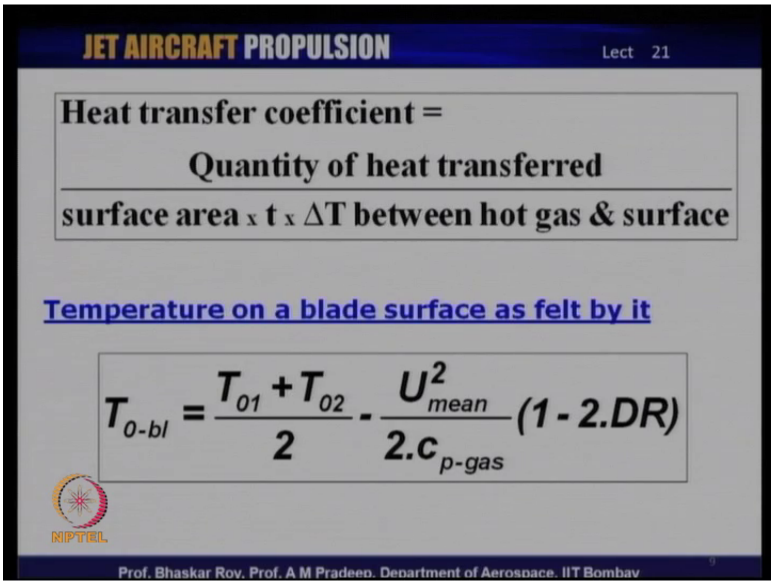

Let us see how this differential cooling can be provided, but before that we will have definition of the heat transfer coefficient. Typical definition of the heat transfer coefficient is that the quantitative of heat transferred across from the gas to the blade. Let us say is a divided by the surface area the time that is available small t and the temperature differential between the hot gas and the surface. Now, if you have cooled blade the blade is continuously being cooled and as a result of which there is continues temperature differential between the hot gas and blade surface.

And as a result of which there is continuous hit flux across from the hot gas or to the blade surface and this heat flux need to be continuously taken away by the cooling method that is defoiled inside the gas turbine. Now, this is the heat transfer coefficient one needs together too: let us also take quick look at what the temperature on a blade surface as felt by it could possibly be the typical temperature felt by the blade is to begin with mean of T 0 1 plus T 0 2 that is the temperatures across the blade row on the mean over that minus the kinetic head, which is you means square of the particular blade divided by twice of C p of the gas into 1 minus 2 into degree of reaction.

Now, this provides that the kinetic head of the flow actually as a small negative effect on the temperature felt by the blade surface. So, it means that higher the temperature incoming into the turbine, higher would be the temperature of the l by the glass now this is something which is what we are trying to gather to the turbine needs to work under high temperature conditions to extort more work. On the other hand more the increase in entry temperature more is the temperature felt by the blade and hence you need to provide more and more cooling. Now, this is something which we would need to bother about on the other hand if the work extraction capability of the turbines is enhanced T 0 2 at the end of that wind would be actually lower.

In which case the mean of this would be lower and hence one can say that towards the twilling hedge of the blade you would need probably less of cooling. So, these are the some of the issues that typical turbine blade cooling designer would have to deal with in designing the cooling technology.

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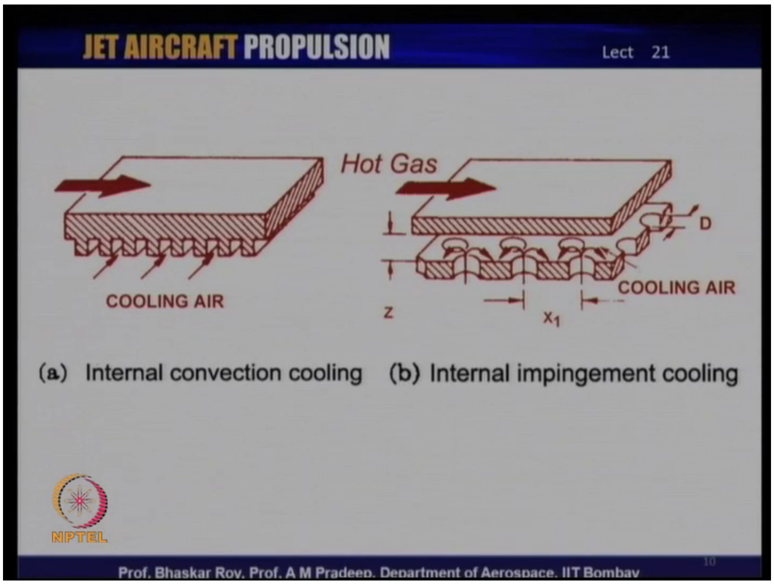

Typical turbine cooling technology; as we have been talking about started with what is known as internal convection cooling now let us take a look at how it actually works. You have a ribs like this inside the blade of a turbine cooling we are showing here, let us say flat plate and inside the flat plate on the other side. You have these ribs through the ribs if you if you pass cooling air, what the cooling air does are when you have a hot gas passing over this plate this plate is continuously getting heated up and the cooling air passing through this ribs, what we call internal convection cooling is continuously cooling the inner surface of this plate.

So, the outer surface is getting heated up by the hot gas, and then there is a heat flux across the thickness of this plate. And then the inner surface of the plate is continuously getting cooled by this cold air. As a result of which the heat does not accumulate any where it does not create hot spot there is a continuous heat flux across the plate taken away by the cooled air. As a result of which there is hot plate it said to be continuously cooled by this internal cooling air convection. So, the convection of cold air inside of the hot plate provides a continues cooling mechanism to this plate which is getting heated by the hot gas.

The next method, which came into being and which is used to typically in front of the in the front side of the blade that is the internal side of the leading edge of a blade is the impingement cooling. Now, let us see how it actual works see you see you have the hot plate over here, which is heated by the hot gas and then this hot gas is subjected to impingement from cold air from inside through this holes. This whole impinge on the inside of the hot air hot gas hot plate and then this hot plate is cold cooled from inside through the impingement of cooling air coming through this holes. So, this is called impingement cooling and this is what is defoiled in many of the modern gas turbines specially the aircraft gas turbines especially near the leading edges.

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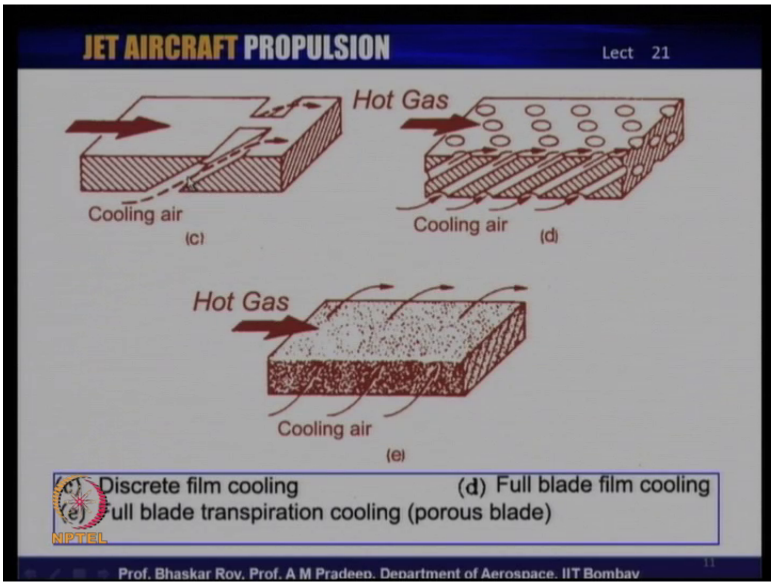

Let us take a look at some of the other cooling methods the film cooling; which I talked about what it does is if the cooling air is passing through the whole made actually in the plate in the blades actually. It passes through these holes and then gentile creates a film over this plate now this film air then is a protective layer. This protective layer than indeed actually physical protects the blade form hot gas; that means, a layer of cold air is created over the surface of the blade. This cold film creates a protective layer from the hot gas. This can be done by number of method, when you have full blade cooling you have number of designer holes that are created these are very accurately design and fabricated very sophisticated manufacturing methods are required to actually create this holes in a turbine blade, which as you known are made of high temperature materials.

This is very sophisticated technology, now this requires this cold whole to be made very, very accurately such that the flow of cold air just comes out and creates a film. It does not loss out like jet into the actual hot gas of the turbine. So, that is what is required, the final method is the transpiration cooling which is futuristic one not yet indeed deployed in any turbines. The entire blade would be made of poorest material; that means, instead of having discreet holes like this the entire blade would be poor as and cooling air would come out of it and create gentile film all over it by providing cooling layer to the blade surface.

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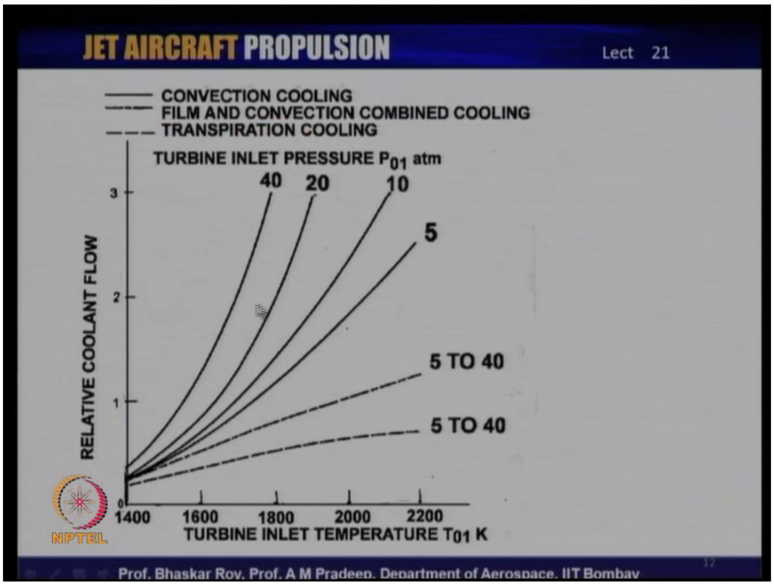

This is what the turbine blade cooling does as and when you increase the turbine blade operating a temperature. You would also need to operate at a higher and higher pressure and as a result of which the relative coolant of the flow actually goes up. So, you need to provide more and more cooling flow, if you are operating at a higher and higher temperature; if you are operating at higher and higher pressure as it is in normal many of the modern gas turbine engines you are coolant flow requirement goes down. So, you are coolant flow requirement is decided by the turbine inlet temperature at, which you are operating and to some extent it is also decided by the cooling technology, whether it is convection cooling or a combination of film convection cooling.

The futuristic transpiration cooling in which you can see here the coolant flow requirement would actually would much lower. All the way from 5 to 40 operating pressure, but such coolant technology is not yet available as of today. Research is going on hopefully to be made available to be made available future.

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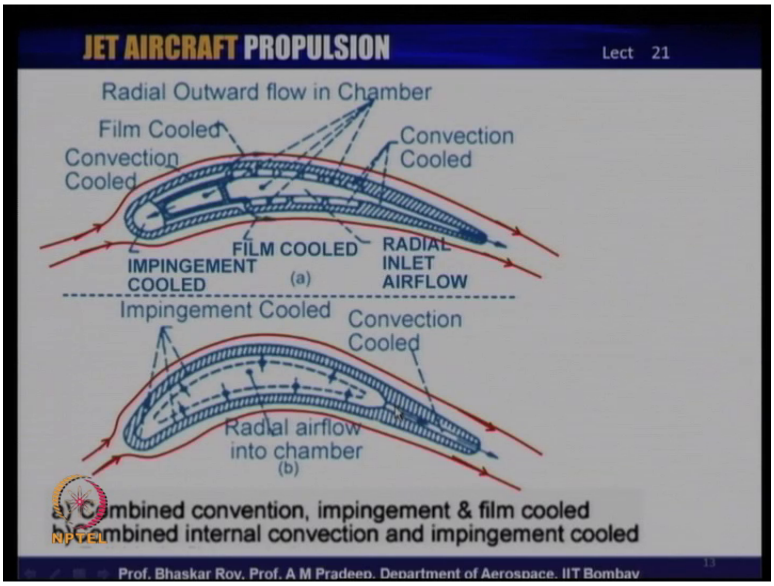

This is a kind of typical turbine blade cooling that is used. This is typical turbine blade in the front here you can see the impingement cooling technology, which is used to cool the inside of the leading hedge, which as i mentioned is a hot spot .then you have the film cooling which uses film on the blade surface to create a protective layer over the blade surfaces. That is done on both the blade surfaces the upper surface is suction surface and the pressure surface and around this blade. You have the hot gas flowing which is continuously heating up the blade.

This is often done by flow is radially inside the blade. You can have very simple cooling, which is convection cooling and then you can some kind of impingement cooling in the inside also this is a combination of convection and impingement the earlier; one was combination of convection impingement and film cooling.

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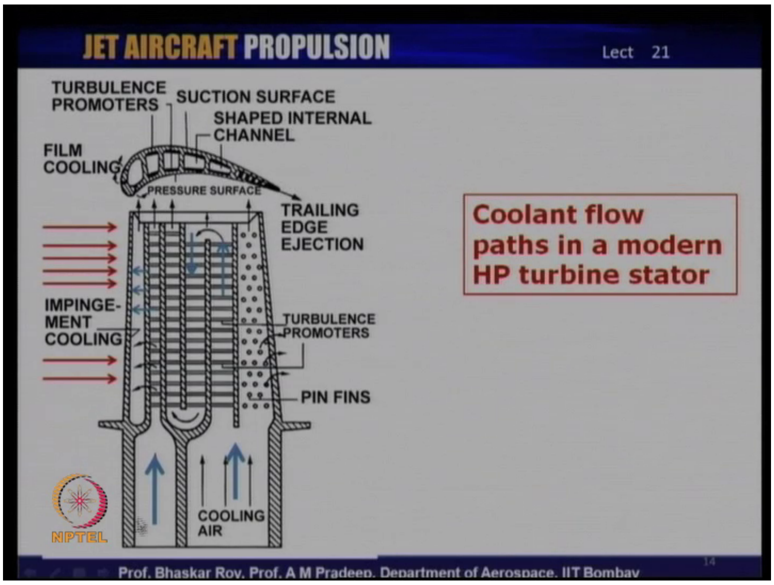

This is a typical turbine blade as i mentioned the flow goes radially it comes in typically through the root section of a stator. A stator as you know is a first row blade that faces the hot temperature and that is a one that requires indeed to be cooled first and then of course, the cooled air goes through the blades radially passes through the blades like this. Then a passage is created through, which the cooled air passes and then finally, goes out through where somewhere near the tip one of the rows of blades over here as holes through which the cooled air is impinge on the inside of the leading hedge all the way from root to the tip of the blade.

So, entire leading edge inside is cooled by impingement cooling from inside by radial cooled air flow impingement from inside. So, we have combination of impingement flow; the convection flow and then of course, this wholes which come out creating the film cooling.

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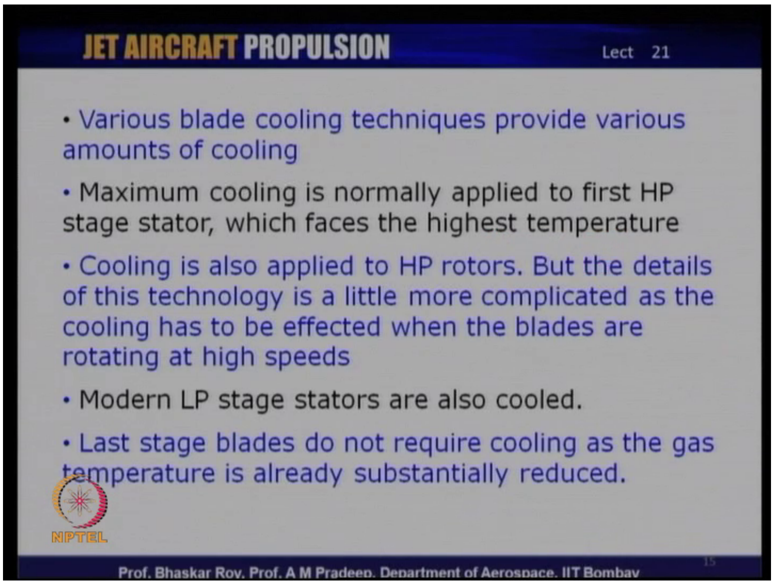

So, this is typically turbine blade cooling technology that is used in modern HP turbine stator similar, but little more complicated technology would typically we used. I modern rotors cooling is indeed normally provided first to the stator, and then you may need to provide to the rotor also special in the modern aircraft engines. That technology a little more complex, because you have rotating blades there and you have to be careful in providing your cooling technology. It should be operational during the operation of the rotor the modern LP stage stator are also often cooled. This cooling is necessary, because the temperature the front of the turbine as gone up. So, much that the LP stages also need some of the LP stages earlier, LP stages also need some amount of cooling quite often the last of the LP stage does not require any cooling. It is normally uncooled blade.

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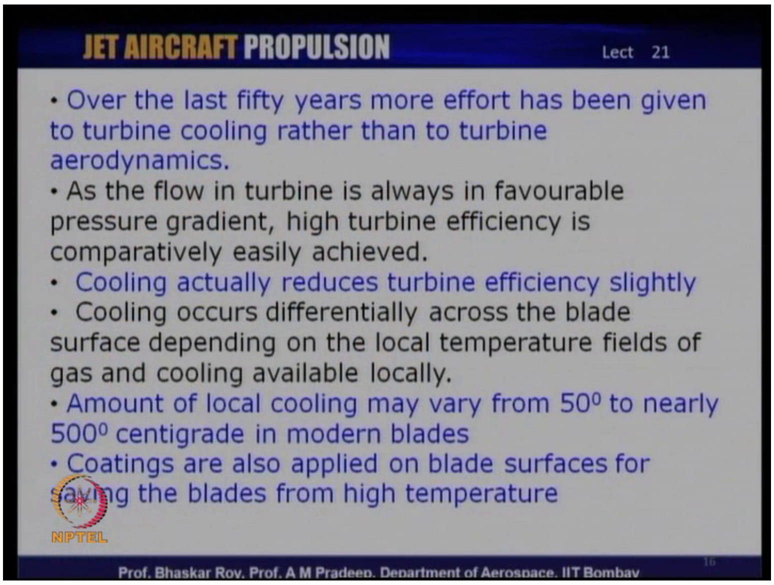

Over the last 50 years, if you see more and more effort has been given to turbine cooling rather than two turbine aerodynamic designs. As the flow in turbine is always in favorable pressure gradient, high turbine efficiency is comparatively easily achieved; however, more work done requires more temperature. That is why more effort has been given to rising the temperature. The cooling actually reduces the turbine efficiency slightly, but that is the penalty that you pay for getting more and more out of the turbine. The cooling occur differential across the blade surface depending on the local temperature field, this is what we discussed earlier and the cooling technology has to be uniquely design for each and every turbine blade.

The amount of cooling may vary from 50 degree, as it was in the earlier to nearly 500 degrees centigrade as in the modern blades. Most of the modern blades also deployed are applied a little bit of coating, which is also a blade surface coating to save the blade from high temperature. Coating is applied in addition to the cooling technology.

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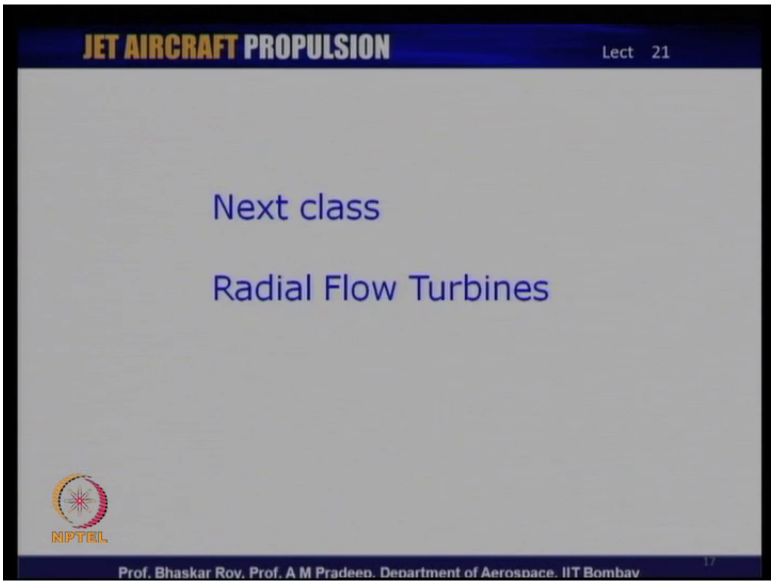

So, over the lecture today we had looked at various kinds of cooling technology that is deployed in actual flow turbine. These cooling technologies are extremely complex technologies, and have been developed over a period of last 50 years. And as I mentioned manufacturing turbine blades with this film technologies is very costly of really, each and every blade is hugely costly affair. And as a result the turbine axial flow turbine as used in aircraft engine is indeed a very costly product.

One of the reasons is employment or deployment of these cooling technologies, we had a look at the axial flow turbine over the last two lectures. In the next lecture, we will take a look at radial flow turbines, and how the radial flow turbines work. We shall see the radial flow turbines are not cooled, they operate in uncooled manner, and will have look at how the radial flow turbine works? What is the performance parameter? And how do they function? And what kind of usage they are normally deployed in aircraft engines? This is what will do in the next class.