Turbomachinery Aerodynamics

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Lecture No. # 28
Turbine Blade Cooling Technologies

You have just had a good exposure to the various fundamental heat transfer science, and an indication how that science of heat transfer is used for axial flow turbine cooling. In today's lecture, we will be looking at the technology of gas turbine cooling. Now, cooling of axial flow turbines especially in aero engines have been in above for nearly 50 years now. So, the cooling technologies, indeed 50 years, it did not start with cooling technology axial flow turbines in the early era were without cooling technology.

However, for nearly 50 years now, various kinds of cooling technology are being used and we will look at these entire generations of cooling technologies in today's lecture. In fact, all kinds of those cooling technologies are still in use today, because you need some of those cooling technologies are even today in simple gas turbine engines, whereas more modern or more ambitious, high performance gas turbine engine may require more advanced cooling system.

So, if you are creating a simple gas turbine engine, old fashioned cooling technology would still be useful, and hence, those technologies are still in use in some form or other in many gas turbine engines especially in aero engines even today. So, we will look at all those technologies that have developed over last 50 years. Now, as I mentioned the cooling technology is based primarily on the science of heat transfer.

The idea of cooling actually came from the gas turbine thermodynamic cycle analysis, which very clearly showed that, if you can increase the turbine into temperature, you would get a substantial benefit in terms of the work done by the cycle, which of course, in terms of the gas turbine engine means more work done by the turbine, more work available either for creation of thrust for aero engines or for running a propeller which creates thrust, or for land based application, it simply means that you can get more power output out of the single gas turbine engine.

So, those fundamental science of thermodynamics finally bore down on the fact that you need to have cooling, because the material science was unable to go beyond a certain level to provide material or alloys, metal alloys that could withstand temperature beyond a certain limit which is roughly of the order of 1,000 degree key. Now, beyond that, it became very apparent that, ordinary material technology is not going to really, be really greatly helpful, and in which case, additional techniques are required if you want the turbine entry temperature to go even higher.

And that is when the cooling technology came in and of course, the entire field of heat transfer had to be utilized. So, in today's class, we will look at the technology. In the last class, you had exposure to the science of heat transfer and we have done all the aerodynamic that is necessary on axial flow turbines. So, in today's class, let us take a look at various kinds of axial flow turbine cooling technologies.

Now, much of these cooling technology does in indeed involved a lot of engineering. You will see that lot of things are engineered in science of heat transfer creates the basic fundamental basis. As I mentioned, a thermodynamics showed as the way that you need to have high turbine entry temperature, which then requires cooling, which uses the science of heat transfer, and then, there is a whole lot of engineering the thermal engineering, the mechanical engineering, the manufacturing technology, all that comes into picture and we will have a look at some of these technologies in today's lecture one by one. Let us take a look at what are the fundamental issues involved and how the whole thing has developed over little more than 50 years.

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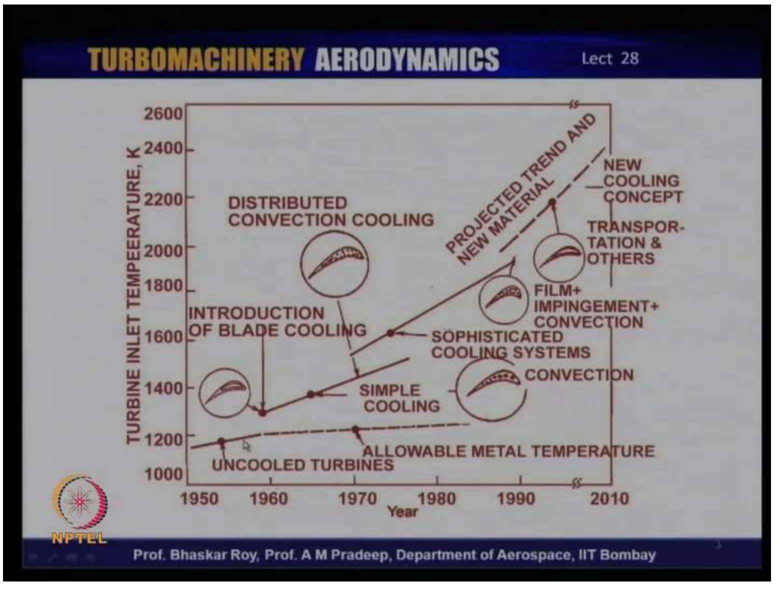

If you look at the graph which is available in any books probably, easily see that in the early era in 1950 or so, most of the blades were actually on cool blades. So, but they could take up to about 1000 degree centigrade or so, and then from there onwards if you are an aspiring toward higher turbine into temperature, you have to resort to some kind of cooling technology beyond; otherwise, the turbine in inlet temperature could not be improved upon, and irrespective of what material used; the material technology was not quite in your helping the matters.

So, are simple cooling technology was used in which certain amount of cold air was indeed passed through the blade. This provided a little bit of cooling of the order of 25-30 degrees to begin with and that was quite of insufficient to raise the temperature by 50 degrees or there about, and slowly the temperature started rising as the cooling technology improved upon their it, its, is basically in engineering method coupled with the heat transfer science of heat transfer, and as a result of which, the temperature could go up to near about 1400 degree also, and then of course, people realized that you need more complex cooling technology to go higher up, and hence, more complicated cooling technology came which we will be talking about in today's lecture, and hence, more sophisticated cooling system came in which involve film cooling and then injected impingement cooling so on and so forth, which has taken the turbine entry temperature to near about 2000 degrees.

So, very modern gas turbines do have turbine into temperature very close to1900 or 2000 K. However, the material, as I mentioned the material technology has not really helped matters a great deal over here, and the projected trend that was shown earlier and by now we should have reached values of the order of 2200 or 2300 degree k, that is indeed actually not happen, and one of the reasons is some of the cooling technologies that were projected and we will be talking about it. For example, transpiration cooling, those kind of cooling technologies have not matured. One of the reasons again is the material technology.

The new material, the porous material which was to facilitate transpiration cooling has not really happen, and as a result of which, the cooling technology did not project beyond what is shown here and this projected development not really quite matured. There is a lot of research still going on and we are not quite as yet crossing the 2200 k mark in actual commercial applications.

So, that is where we are. We are near about 2000 or so and that is good enough for us actually to use in most of the modern gas turbine engines, and we shall see that since the pressure ratio has gone up, the efficiency of the turbine has been actually upgraded hugely through up gradation of compression ratio, and this up gradation of turbine entry temperature coupled with a high compression ratio has given gas turbine engines huge efficiency boost, and in terms of fuel saving, there is a huge fuel saving in the modern engines. So, turbine entry temperature boost actually is known from fundamental thermodynamics to give better and more efficient engines and provide more power.

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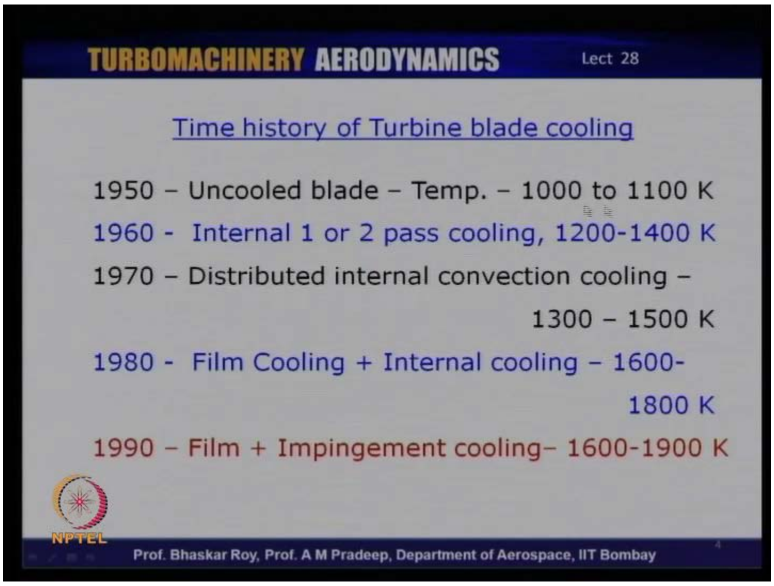

Now, if we simply summarize the whole thing, in the fifties the blades were uncooled the early era of gas turbine engines, and as a result, the temperature is were some or around 1000 till 100 K. And then of course, the cooling technology came which were internal 1 or 2 pass cooling. We will look at this one to pass cooling a very soon today, and that and the temperature could go up to about 1200 to 1400 k that is about 150 degree more where possible with cooling. Later on the cooling technology developed into internal convection cooling which allowed lot more coolant to be used and not more elaborate cooling system, and temperature could be pushed to 1300 to 1500 K, and then, came of course, the film cooling towards the end of seventies which existed along with the internal convection cooling.

So, film in cooling plus internal convection cooling pushed the turbine inlet temperature to higher than 1600 k, and then of course, the impingement cooling matured. The idea which has been around for a long time and has pushed that temperature is now too close to 2000 K. There about are the whole thing is kind of a stagnated a little because the transpiration cooling has not quite matured. It has been as an idea, it has been around for nearly 50 years it involved micro channel cooling methodology. The science of features a well known, but the technology is not quite available as of today, and the porous material that can withstand the stresses in a turbine blade has also not quite matured as of today to the best of our knowledge. So, the turbine technology has matured hugely over a period of 50 years and as resulted in engines that are more powerful and of course, which are indeed smaller in size.

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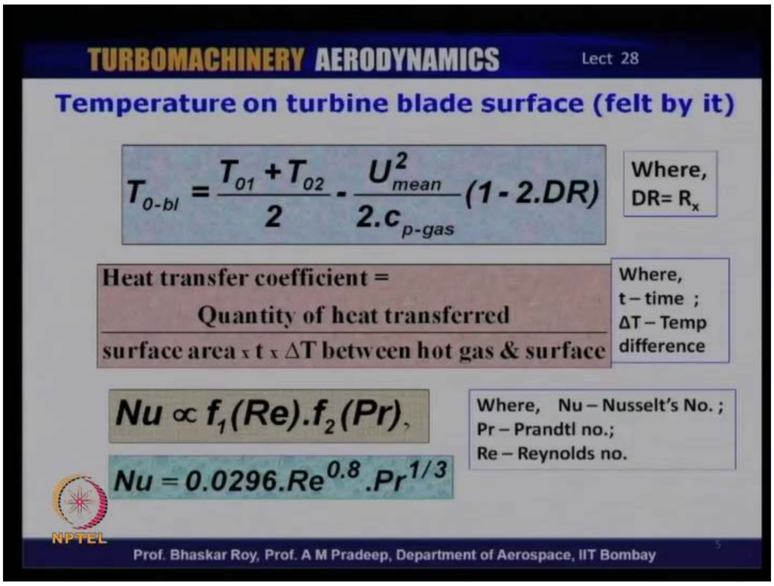

Now, will be talk about turbine cooling. The first thing that comes to mind is the water you cooling. You see that turbine is, is, processing gas which is hot and of course, high pressure, but the blade feels at temperature, the feeling of the blade here is the important issue. The blade feels a temperature which is not same as the turbine entry temperature. Say the turbine entry temperature T 0 1 and the blade exit temperature is T 0 2. What the blade would feel is an average of the 2 minus the rotating kinetic head which is shown as u mean square by twice c p of the gas which is passing through plus the degree of reaction factored in here. Now, this gives rise to the situation that other Blade temperature has felt on the blade surface. Average blade temperature is something quite different from the gas temperature.

So, gas temperature is not what the blade feels. The blade feels a different temperature arguably and as is quite obviously it will feel at temperature lower than a gas temperature. So, the requirement for cooling is not with respect to the gas temperature; it is more with respect to what the blade actually feels. So, that is a temperature that has to be cooled through cooling technology. The science of the transfer that have done in the last class; we can simply bring in here.

The fact that the heat transfer coefficient is equal to the quantity of heat to be transferred at any local point on the blade, on the blade surface in at the location of the blade which is normally given core wise in terms of often x y c on the core, and in the local surface area over there, the temperature differential between the hot gas and the surface as we have just seen. The blade surface temperature is indeed less than hot gas at temperature and it will vary from the local point to point on the blade surface, and then of course, the time that is required to affect the heat transfer.

Quite often the heat transfer is expressed as we have done in the last class in some detail, in terms of Nusselts number and they are known to be proportional to Reynolds number Pand prandtl number. This is also an semi empirical relationship which has been developed essentially for simple systems like flat plate, and Nusselts number is a directly relatable to Reynolds number and Prandtl number. For simple systems through some constant terms which are used to create this semi empirical relationship. Now, this is the kind of science or technology that one would need to bring forth in the turbine cooling business.

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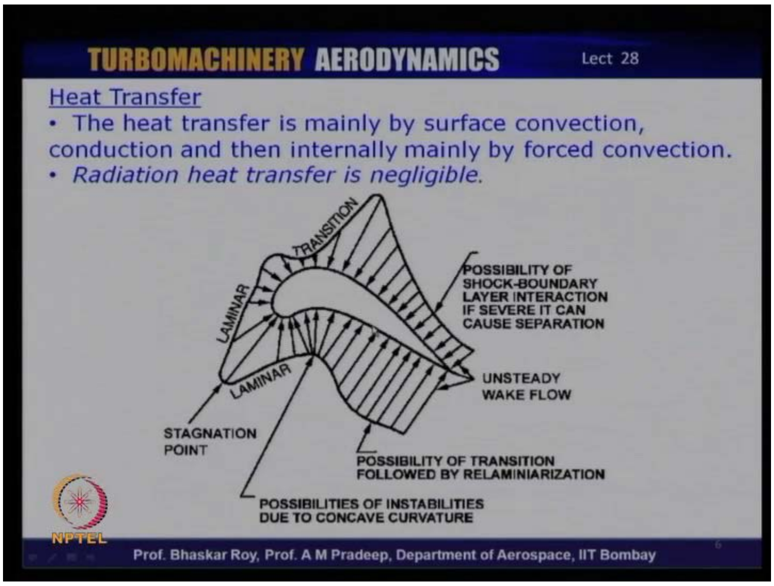

Now, let us look at the technology. What happens is, when you have ah blade, this is a typical turbine blade and you are looking at a diagram which probably you had at look at in the last lecture also, but let us discuss this again. The flow comes in here, and at this point, you have the leading end which is the stagnation point.

Now, what happens at stagnation point? The flow comes to a halt. When the flow comes to a halt, thermally that place the total temperature is equal to the static temperature, which means this point of the blade. The blade feels the entire total temperature of the gas flow; that means a static temperature plus the kinetic head that the gas is carrying. The entire thing is felt over here at the stagnation point.

So, the stagnation point is indeed the Hot Spot, the hottest spot on the blade surface. As the blade picks up speed, it actually drops of the temperature, and then, through the transition from laminar to a turbulent flow as the, it flows over the gas blade surface, the gas actually accelerates. As it accelerates, the local temperature, the static temperature.

Remember is the static temperature that blade would be indeed stealing. So, the local static temperature starts falling off. So, as you have expansion or acceleration over the blade surface, the static temperature indeed falls of; however, as you are a where aerodynamically towards a trailing edge, there is an another possible stagnation point depending on the flow situation, and summer on that stagnation point he would again feel Hot Spot.

So, the flow again would feel the full temperature field over, there that is, static plus kinetic at that point same thing happens over the pressure surface. So, the temperature there is a continuous variation of temperature. So, just like pressure, you can see that as the pressure varies over the blade surfaces; the temperature also would vary over the blade surfaces and inner turbine. This variation is a huge unlike in a compressor where the pressure varies hugely, but that temperature does not probably vary so much in turbine of the temperature would vary hugely.

Now, as you have done in the last class as the flow transits from laminar to turbulent flow through the transition. The head transfer from the hot gas to the body of the blade is facilitated, which means more transfer across the body of the blade as a result, the blade would actually be getting more heated towards the rear part of the blade where the static temperature may be falling off. Here, the blade is probably somewhat shielded by the laminar layers, and as a result of which, the blade feels lower temperature even though the temperature outside is actually much hotter.

So, near the leading edge, temperature outside is much hotter but the blade feels less, but later on, even if the temperature is falling off, the blade actually is made to feel much higher temperature on the blade surface because the boundary layer outside is turbulent boundary layer. So, with this knowledge, if, we can move towards the technology.

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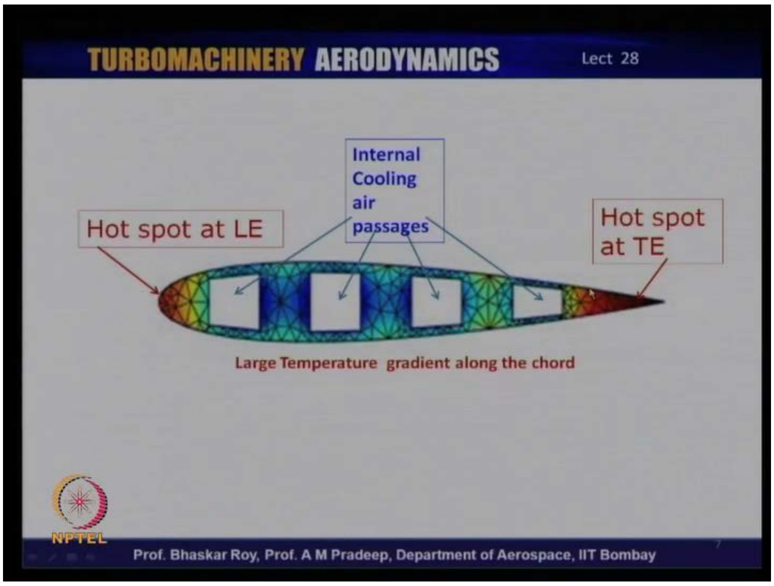

Now, what happens is as we were discussing, we have a Hot Spot on the leading edge. You have a Hot Spot at the trailing edge; a simple aerofoil is being shown here and you have a huge temperature gradient on the chord wise direction on the blade surface, on both the surfaces. In a rear turbine, two surfaces and unequal what is simply done as you create blade passages, internal passages through which cold air is passed.

Let us say from one end of the blade to another which is from hub to tip. Now, the first row of Blades is of course, the stator which is fixed at both ends. So, you can indeed pass air from hub to tip or a tip to hub cold air, and then, that cold air would convict away, carry away heat. That heat has to first conduct itself through the blade solid body from the surface into this cold air and then the cold air would carry away the heat on a continuous basis. So, there is a continuous conduction across the solid body of the blade surface, and then, continuous convection by the cooling air which is passing through the passages on a continuous basis. So, there is a continuous requirement of cooling air when the gas turbine is operational. So, this is a simple method by which the cooling technology was inducted into the gas turbine cooling.

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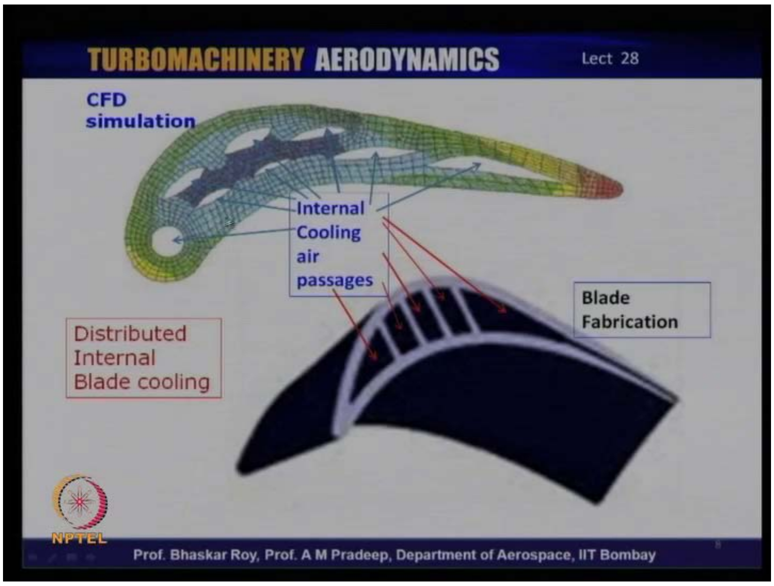

If we look at a little more elaborate system this is the CFD plus and this simulation and it gives an idea about the kind of temperature profile you have in a typical gas turbine Blade, and what you do required to do cooling? You have a Hot Spot here; you have Hot Spot around here. The trailing edges very thin and is very difficult to provide cooling over there air in terms of internal passages.

So, these are the internal passages as you can see here, the shapes have evolved to not only allow more passages in a distributed manner. So, you have more distributed passages, also you have more control over the amount of cool and passing through these passages. So, you have more control over what is happening. So, this is one passage which is let us say cooling mode near the leading edge area, which as be discussed is area and then they are distributed coolant passages so that the cooling is distributed over the Blade surfaces from both the surfaces.

So, this is a rear Blade that has been fabricated, and one can see that these are the various kind of passages that have been created by through modern fabrication technology in high temperature material. Remember, turbine uses high temperature material. So, making such passages is requires very modern manufacturing technology. The upper plate that you see actually is a forged Blade were these passages were created and the Blade was made by forging and the passages which were before forging looks something like this, and once the Blade is forged into the shade, the passages take shapes. However, this Blade is fabricated; that means these passages and machine in high temperature material which requires very high modern fabrication technology.

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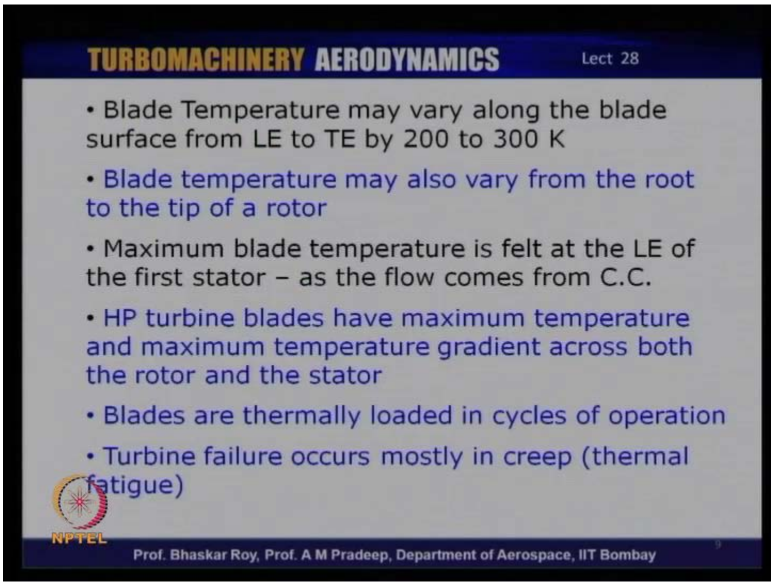

Now, what we see is that the blade temperature may vary along the blade surface from leading edge to trailing edge by almost 200 to 300 k and that is a very large variation to carted to, which means that temperature over here or over here may be 200 to 300 more than the temperature over here and the temperature is very all along the Blade surface.

Now, this requires a cooling technology which would create to the amount of cooling required here, the amount of cooling required here, here and here. So, that is what we discussing that the amount of coolant to be used here, over here. over here, and then, the other trailing edge over here would indeed vary substantially depending on the Blade shape, depending on the temperature at which is an operating, and of course, depending on the cooling air that is made available.

Now, all this needs to be calculated very accurately. This accurate calculation is where engineering and heat transfer science comes in very strongly. You need to calculated very accurately what is the amount of air going to each of those channels, and as you can see the shape of the channels, size of the channel varies depending on where the channel is located on the Blade.

Now, this requires that you have a very accurate method of calculating how much cooling air is required where. Now as we can see here the temperature and the heat requirement cooling requirement varies substantially. So, this needs to be very accurately calculated. So, and then of course, as you can see, you have to technology in which these shapes are created. So, now, the shapes carry a certain amount of cooling air, and as you can see here, this has been created. Finally, it will exit through the trailing edge. As I was mentioning trailing edge cooling is a possible problem, where as the trailing edge in know is a Hot Spot.

So, the modern as has created facilitated a process by which the cooling air finally may exit through the trailing edge, cooling the trailing edge itself. So, those are the various technologies that have to be brought into in the turbine cooling business. So, as we are way of saying that the Blade temperature also may vary from root to the tip of a rotor. Stator by design as we have seen may be kept and twisted, but the rotor may have a little bit of twist and that will give rise to temperature gradient from root to tip.

So, that again needs to be factored into this very accurate cooling technology that we need to incorporate in modern the actual flow turbines. Now, maximum temperature is felt at the leading edge of the first stator as the flow just comes from the combustion chamber. So, the first rotor in his first stator is what requires the best of the cooling technology if you increase the turbine entry temperature.

Now, we will talk about more modern cooling technology as we go along today. The HP turbine Blades both the stator and the rotor face maximum temperature across the rotor and the stator. So, almost all modern aero engine HP turbine Blade stator and rotor are cooled. In the earlier nineties only the hp stator was cooled, but later on both rotor and stator are cool, and in today's modern aero engine, HP turbine first stage as well as second stage are most likely to be both rotor and stator are likely to be cooled. Now, there is on other issue here - the Blades are thermally loaded in cycles of operation.

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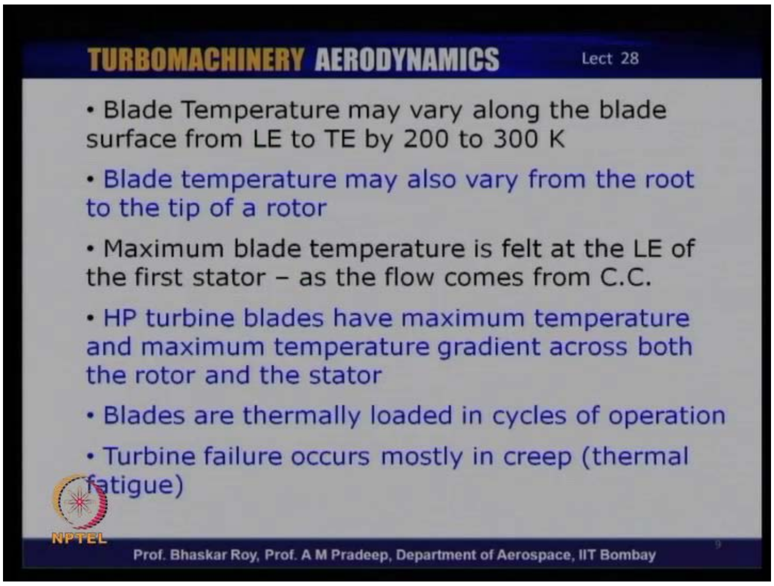

Now, this essentially means that you have a situation when that gas turbine starts operating. That are while gets heated up, it goes to full temperature, and then, it operates at full temperature during let us say when the aircraft is flying from takeoff to climb and then it goes to cruise. Now, when it goes to cruise, as you know that are while is actually brought down to lower temperature level, lower speed level lower are rpm rotating, and hence, its operating at a lower temperature.

Then after some time, the turbine engine is brought down to a lower in operating speed, slowly the aircraft comes down, it touches down and it comes to halt; the engine is close down. So, the turbine is heated up; then it is cool down, operates in slightly less heat condition through the cruise and then is shut up.

So, the turbine is continuously going through this cycle of temperature. For long period of time, when the engine is not operational, it is a cold turbine; it is just static. When the engine is operational, it goes through heat cycles of the very height cycles. If its military engine, it is going through very short transients. Very high temperature sometimes not so high temperature some other times. So, it is going through cycles of temperatures, and then, again when the engine is grounded, the aircraft is grounded, it is cold.

So, the material of the turbine is continuously being treated to high temperature, and then, for long period of time to cold state of static in operation. So, this gives rise to the fact that the turbine is treated to a cycles of temperature. So, many of the turbine failures occurred in this fatigue failure which is due to this cyclic loading of the Blades. Now, remember, turbine is also a rotor is especially getting highly loaded due to the aerodynamic loading; the aerodynamic load is huge when the gas is flowing pass the turbine Blades.

So, this aerodynamic load is now compounded with the thermal loading which as we are just seeing changes from leading edge to trailing edge, from root to tip. There is a continuous variation of temperature on the Blade surface over the entire Blade of the turbine. Now, this guide gives rise to temperature gradient and loading pattern changes, and when coupled with aerodynamic loading, it gives rise to a very complicated loading pattern and very complicated stress pattern, which as we see now actually goes through cycles of operation depending on whether the turbine is operating or it is grounded and static. The result is that turbine failure of often occurs in creep mainly due to the, this thermal cycles.

So, creep is the fatigue failure due to cyclic operation of the gas turbine engines. So, the failure of the gas turbine often occurs in creep which is the thermal fatigue kind of compounded stress at occurs mainly due to the thermal fatigue. The compressor Blades for example, do not fail in creep, they fail only in a marlin loads during operation, those Blades of course a much thinner. The turbine Blades are much thicker as we have seen, but the thermal load indeed creates a lot of problem.

So, even though turbine blades are thicker, they are made of high temperature material even than the life of a turbine Blade is indeed often much less than that of a typical compressor Blade. So, this is a huge problem in terms of life of turbine blades, and of course, the cooling technology helps a matter. There are many blades where if you do not apply cooling, actually the blade would get chart in a matter of few minutes, whereas if you apply cooling, the blade would last for 1000s of hours of operation.

So, the difference between cooling and not cooling a modern gas turbine makes a difference in life of turbine blade by 1000 of hours. If a gas turbine into temperature is of the order of 1600 or 1700 degree k, and if that Blade is not cold, rest assured that blade will get chart in a matter of few seconds. So, that is the different between on cool blade and a cool Blade in modern gas turbine applications. So, that is rather cooling comes in.

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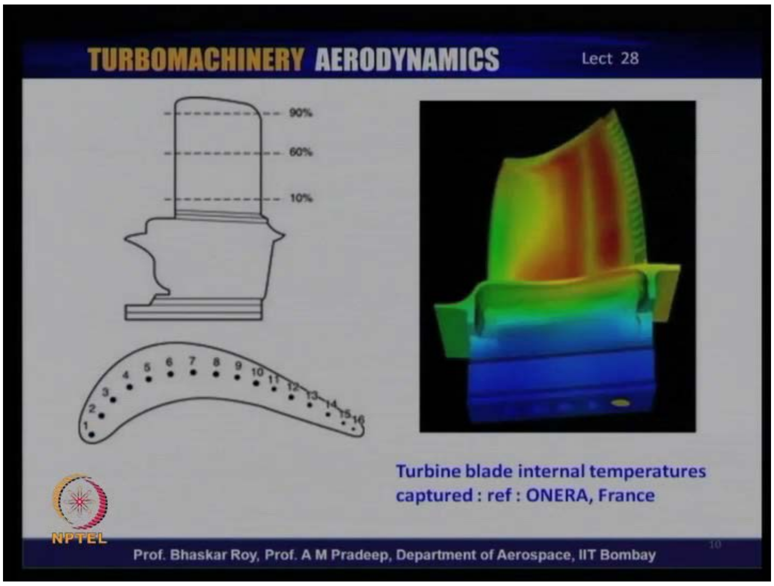

Let us take a look at the situation. If you have a typical turbine Blade and if you would have this kind of let say very a simple cooling passages so many of them, you know, 1 to 16 of them, they have to run through the entire length of the blade, of a turbine Blade from root to the tip. So, typically the air would be brought in from compressor. Compressed air to be brought in through the root system. You have the effort root fixing system here, it comes in here, and then, it gets into these passages.

You can have so many passages or you can 4 to 5 passages as we have seen in the earlier slides, and they all then go through this entire length cooling the Blade at different places in a differential manner. On the right inside, you just see research output of a internal temperatures as captured in a French laboratory, and you can see the kind of temperature profile that you get some of the internal temperatures are very high. Here, the internal temperature is somewhat less, because as we have seen the flow around here is laminar in nature, and as a result, the Blades do not feel so much. Some are over here the Blades become the outer surface, the flow becomes turbulent.

Once it becomes turbulent, the gas, hot gas temperature flows inside very quickly and then the Blades start getting hugely heated up. So, the cooling requirement indeed here is more even though the temperature near the leading edges actually more. So, this aerodynamics actually facilitates the heating of the Blades around this area, and this is where you indeed require more cooling, and that is why most of the cooling technology in the early era in 60's and 70's and indeed in 80's the cooling was mostly being done in this area, but of course, we know and we will see today that more and more modern cooling is available near the leading edge as well as near the trailing edge. As the temperature has gone up, you need to indeed cool the entire Blade.

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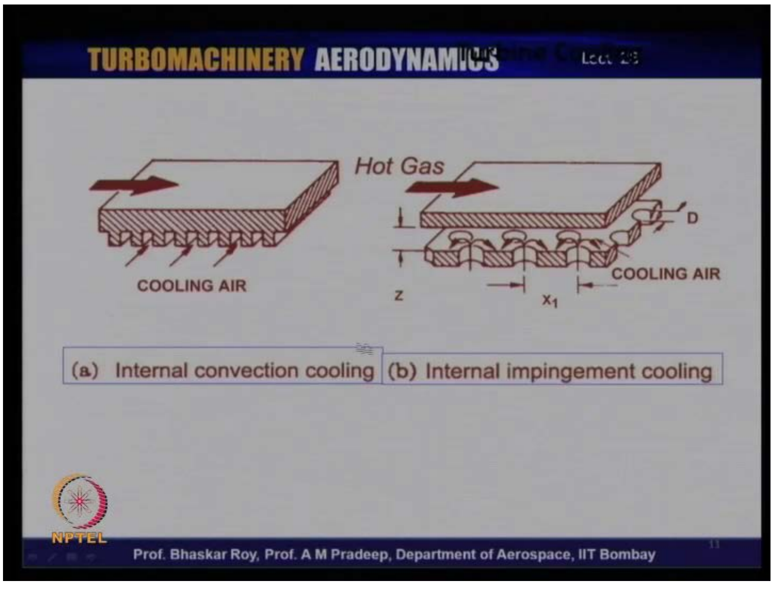

Let us take a look at the cooling technologies. The fundamentals of the cooling technologies that we are talking about. We mentioned that the cooling is done by internal convection cooling which essentially means that you have so many passages, and through them, the cooling air is passed. This is let us say the blade surface or the solid body of the blade. Inside of the solid bodies, you have are so many cooling passages through which cooling air as we passed on a continuous basis and outside you have the hot gas.

A variant of this is that the cooling air is blown into the inside surface of the outer shell of the blade. So, the Blade is made of a shell which is a solid body of course. Inside, you have another shell; inside of which you have the cooling passage may be a common cooling passage which has holds. Now, these holes allow this cooling air to come out an impinge on the entire inner surface of the outer shell, and this is called internal impingement cooling, and if you do that, the internal entire internal surface of the outer shell is cooled on a continuous basis through internal cooling system. So, this is simply called internal impingement cooling, and we shall see this is how the leading edges of most of the modern turbine Blades are actually cooled.

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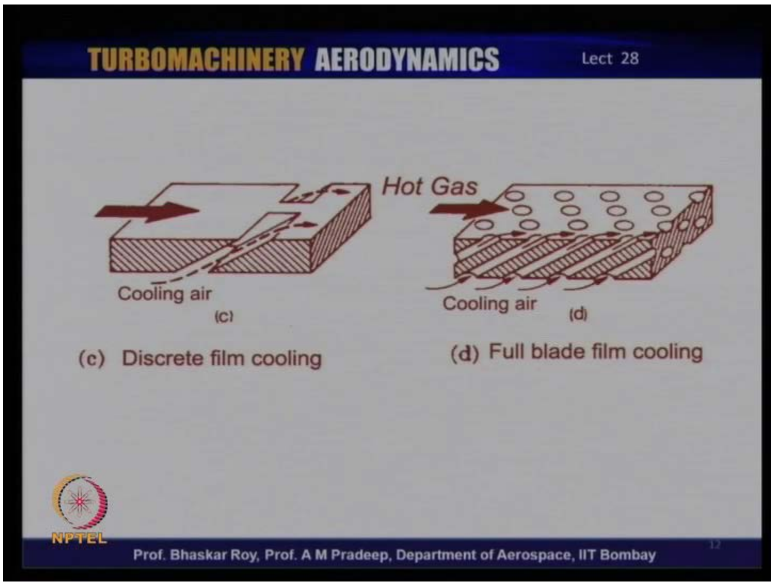

The other method is simply called film cooling. Now, the kind of matter that the sorts of the internal cooling has their limits. Once those limits are reached, you need more explicit and more active cooling system. So, the cooling air itself is now brought out; its not inside any more. You need to bring it out, and then, this cooling air is brought out through a holes and these holes (( )) out the air and then create a film on the blade surface.

So, on the blade surface, you create a film of cold air, and then, this cold air provides cold film, which means it submerges inside the boundary layer on the outside of the blade surface. So, you have a cold boundary layer on the blade surface. If you provide a distributed holes on the, inside the blade so that through various holes the inside internal cold air is brought out and is injected out onto the surface to create films of cold air on a continuous basis over the entire surface of the blade.

Now, if you do that, you have a continuous cold air. Now, what happens is, if you are for example, brought out cold air over here in the first cold, by the time it reaches some distance, that cold air would get mixed with the hot air would become hot. So, you need to bring out cold air again, which would again then become hot after as little distance.

So, you need to bring out cold air every short distance over the blade surface to keep the continuously flowing cold boundary layer on the blade surface.

Now, remember, we want a cold boundary layer. We do not want this cold air to eject out like a jet into the hot gas. That would interfere with the turbine operation and would adversely affect the turbine working. So, the work done from the turbine would go down very sharply, because the basic aerodynamics that we have discussed in detail would then be badly affected by this cold air.

We do not want that. We do not want the cold air to eject out of the those cooling holes in a stream of jets and get into the hot air and interfere with the hot air operation which is a different operation. The hot air is flowing over the turbine; it is giving up energy to the rotating turbine blades is doing work; transferring work onto the blades. The blades are rotating and creating mechanical energy. All that would be adversely affected if you allow this cold air to eject out like a jet.

We do not want jets; we do not want cool jets, we want cold air to just come out very gently through the holes and create a film on the blade surface. Then we have a film cooling. So, the boundary layer which we saw was becoming turbulent boundary layer subsumed inside the boundary layer would be this cold air, and this cold air would create some kind of a insulation between the hot gas and the body of the solid body of the blade. So, this is how the film cooling technology actually works. If you can do that correctly, you have a very good cooling system. If you cannot do it correctly, you are going to be affected by a turbine work.

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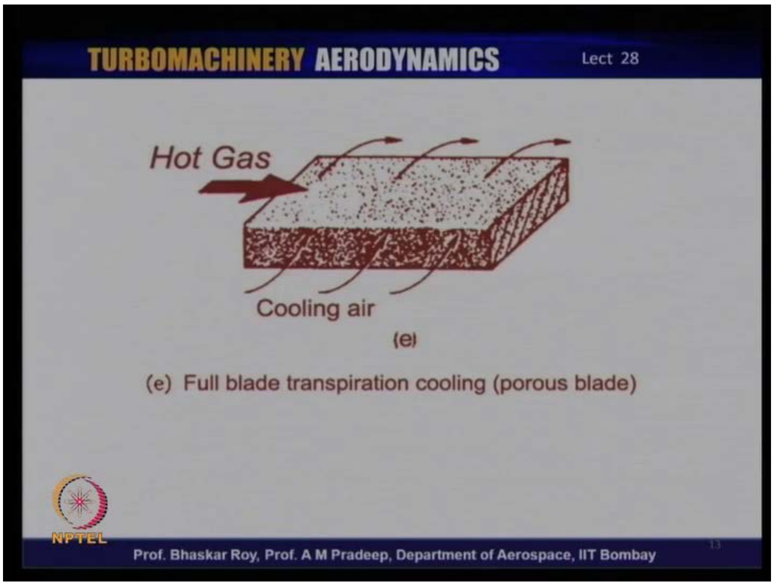

Now, the transpiration cooling which people have been talking about for 50 years now actually involves that, you have a porous solid body or outer shell of the turbine Blade. So, you have cold air oozing out like perspiration through the solid body of the blades to create continuous film cooling.

Now, this is of course, the ultimate ideal of film cooling. You just allow the in air to go inside the turbine blades, inside the blade passage internal passage of the blades with some pressure and that pressure will drive the flow out through this force. So, it is a porous body, and through which, it will create just is goes out, again there is no jet to be brought out. It will just goes out and create a film on the surface to create a cold film on a continuous basis over the entire surface. This is much the same way we actually perspire and chord body sort of gets cold when the perspiration actually evaporates from our skin.

So, it is same concept; however, what is happened is, over the years, this porous technology, porous medium that is required to make the turbine blades has not quite mature to date. It cannot take the strength. As we have just discussed, turbine blades need to be very strong withstand dynamic loads, to withstand the thermal loads; otherwise, the life of the turbine as we have seen can be up in, in, few seconds.

So, the porous material the we need to be strong enough to withstand all those cycles of temperatures and gas loading and work for 1000s of hours preferably ten 10 15 20 1000 hours. That has not happened, that material has not come through, and as a result, the transpiration cooling has not quite mature to date.

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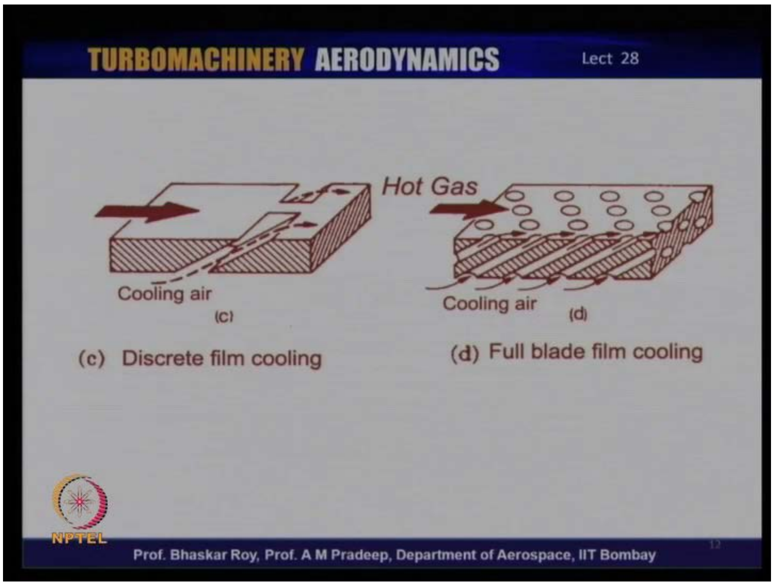

So, we have the film cooling in which, you need to very accurately calculate through each hole what should be the amount of a coming out through this hole. What should be the dimension of each of these holes depending on where the hole is on the blade, and then of course, the pressure ratio across this particular hole, because the pressure ratio will drive the flow from inside to outside and it should be just sufficient for the air to come out and create a film.

If the pressure ratio is too high, that means, if the internal pressure by some chance is much higher than the outside pressure, pressure, just over here, the air will inject out like a jet, and as we just discussed, that is most unwanted. So, we need to create a pressure ratio at each of these holes exactly as much as required for the air to come out at this particular location and just create a film. As I mentioned, this requires very accurate calculation and very accurate estimation of what is happening gas dynamically and thermally over the turbine blades .

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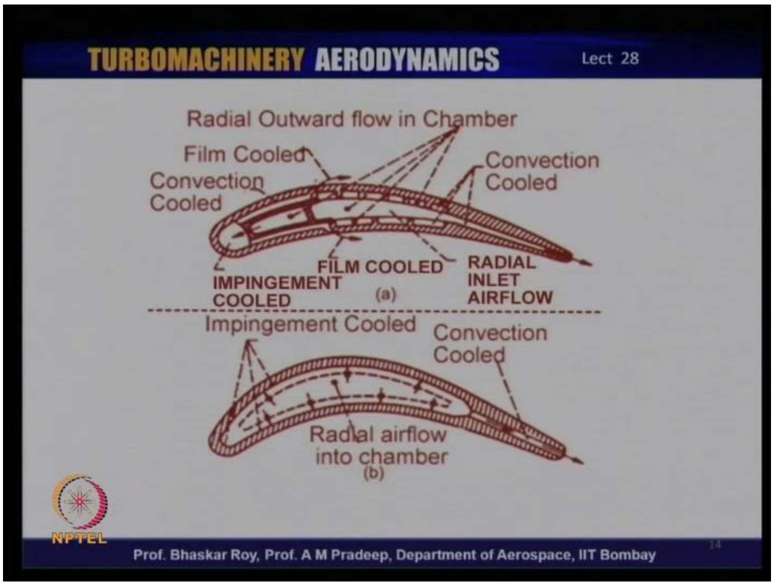

Now, let us look at some of the details of the technology. As we can see here, we have a ah system. Let us look at the bottom you have one single channel through which, the air is a ah internal cold air is being brought in mainly from the compressors, compressed air, and then, this common air flow channel is indeed making air coming out through various holes in; it cools inside surface; it cools entire surface, and finally, it comes out from the trailing edge, cooling the trailing edge as well. So, it cools the insight surface by impingement, internal impingement cooling.

So, the entire inside surface is been cooled by internal impingement cooling, whereas, here we have a holes. So, impingement cooling is used at the leading edge to cool the leading edge, which has been mentioned, it can be a Hot Spot, and then, of course, it cools the other surfaces through internal cooling system, and then again here, we allow the air to come out through that trailing edge.

In the process, cooling the trailing edge also you remember. After it cools internal surfaces, the, the cooling itself gets a little hot; however, as we have just seen the trailing edge is very hot, and compared to that, this internal air is still cold. So, all you require is air that is colder, substantially colder than the outer hot gas and it still can do a little bit of cooling. You do not need very cold air here; you need air that is a little colder than what is outside.

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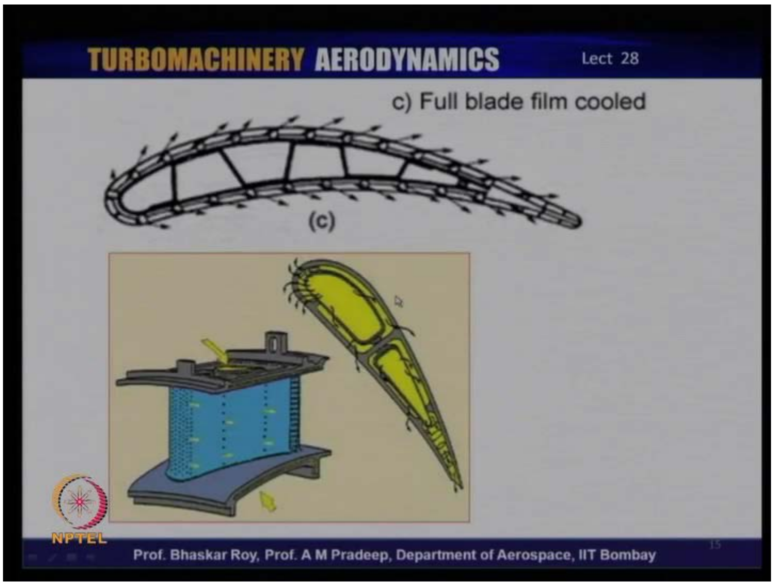

Now, this is a picture of a full bleed film cooling. We have so many passages, separate passages through which air is a brought in. Here, in this picture, you have two large passages. In the picture over here, you have number of passages. Each of which caters to one hole or two holes, and through which, air is brought out, and each of these holes, then create a little better of film over here; it is a continuous process. As we just saw, the early air gets heated up surface bring in more air is on a continuous basis cold air is brought out to create film on the blades have faced on both the surfaces really and finally, of course, certain amount of air may be brought out near the trailing edge to cool the trailing edge area.

So, you may bring out the trailing edge air through the trailing edge or through some holes near the trailing edge which creates film over the trailing edge to cool the trailing edge area here. On the surface, on the blade over here, which of course shows a three-dimensional picture, you have two large internal passages - one passage over here, another passage over here, which of course, exits a flow through the trailing edge. Many of the modern turbine trailing edges are indeed not rounded, but truncated like this or sometimes straight away blunt to allow this cold air to come out.

So, this is something which requires very high manufacturing technology typical for gas turbine a manufacturing, and this you shown over here. You can see the discrete holes that are made over here. On the blades surface, which allows this internal air to come out from inside onto the blades are faced and create the films on both the surfaces. Thereby, cooling this area which we are mention many times that, it is area that gets terribly heated up.

So, you are very elaborate cooling system including film cooling that comes out over here and creates film cold film over the surface. Then you have another row of blades holes coming out through the blades, which create on other row of another round of film cooling. Then, you have another again row of holes in the through which, cold air comes out and a final row of a holes near the trailing edge. So, they have calculated very accurately how many rows of blades are required and where on the blades are faced in the chord base position to create appropriate film cooling on this particular blade. So, this is how you create the cold film over the entire blade surface in a very accurate manner to affect effective cooling over the entire blade.

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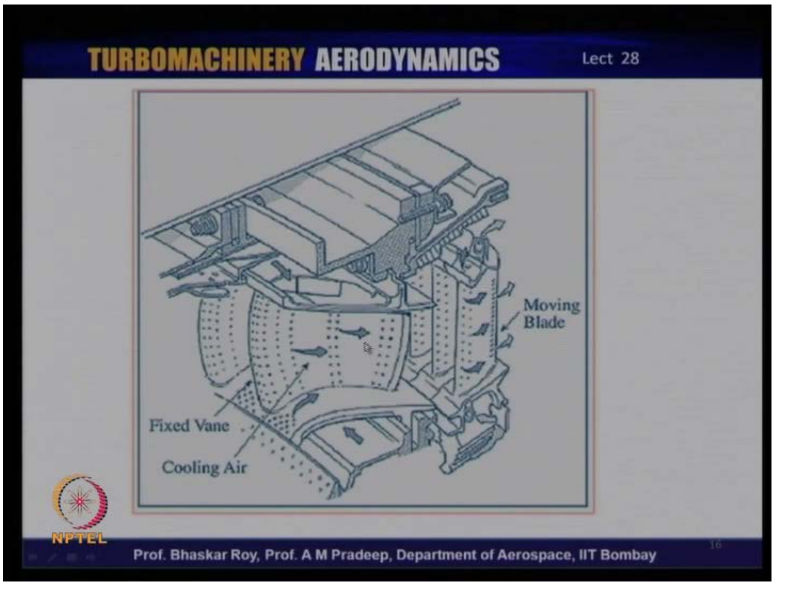

This is a picture of a, typical picture of a turbine blade of modern turbine blade. This is the stator; this is the rotor, and as you can see, both the stator and the rotor have elaborate holes over the surfaces which loose out the internal cold air on the surface and create the cold film on the necessary on the surface to affect the cooling. As you can see, the stator has much more elaborate cooling technology. The modern Blades also have, the rotors also have an elaborate cooling technology on the rotor blades, rotating blades.

So, this is the elaborate cooling technology that you need to do. Manufacturing these Blades is extremely costly affair and each single turbine Blade is an hugely costly affair. It is entirely possible that one turbine blades, one single turbine blade here could be costlier than making a whole set of compressor blades so that that is how costly the turbine blades are because they have embedded cooling technology inside those blades.

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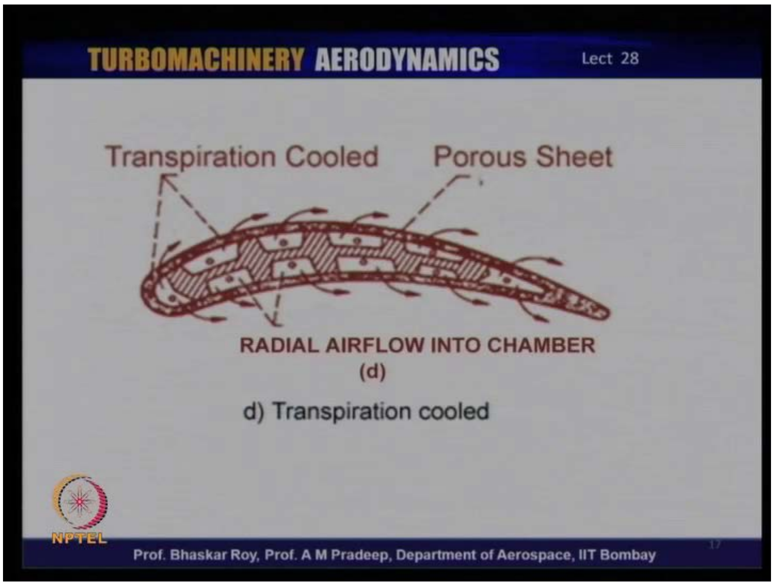

Transpiration cooling as we have seen requires. This is an attempt at a transpiration cooling as we discussed. You have the porous outer shell; you require that porous outer shell, and then, you have an elaborate internal cooling passage which has a cold and compressed air and those would be hoozing out through the pores to create film cooling.

So, you need a porous outer shell or a sheet to affect transpiration cooling, and this air of course, radially flows from hub to tip or trip to hub across the entire length of the blade to affect cooling over the entire length of the blade. Now, this is what I mention that, to the best of our knowledge, such porous technology, material technology has not yet matured, and to the best of our knowledge, that has not yet been applied commercially even though lots of research is still going on in this area.

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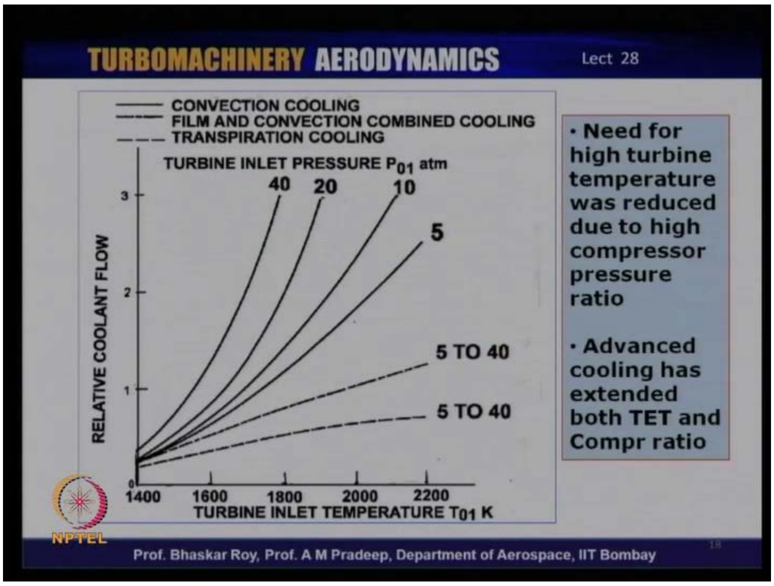

A summary of the kind of technology that has been used over the years as you can see here. In the early era, when it was only convection cooling, the advancement of compression ratio are actually a required that you can do with less cooling. So, as the compression ratio went up to forty first 20 and then 40, you can see that you can do with less of temperature, because the relative cooling flow available from high pressure compressor allows you to put in more air flow, and as you can put in more air flow at high pressure, you know you, you, can effectively do a lot of cooling; however, as the advance cooling has been extended with film cooling, film and convection combine cooling, you can cool any blade from a pressure ratio of 5 to 40.

40 is going, you know, high value of compression ratio. So, up to a pressure ratio of 40, you can keep on using the combined cooling system, and it can take you to temperature up to 20 200 transpiration cooling can give you even higher temperatures at a lower coolant film flow.

So, the more and more advance cooling technology, you can deploy, you can use less and less coolant flow because higher and higher compression ratio is now available, and then, at each of those cooling passages, you can pump in air at a higher pressure, and one you you have that availability of high pressure air, you can afford to do with less and less mass of air cold air to affect effective cooling.

So, over the years as the pressure ratio has gone up, the cooling has indeed been facilitated by high compression ratio, and this is one of the advantages of the fact that compression ratios gone up; the turbine technology has also effectively used higher turbine entry temperature. So, this is what has happened over the years the two of them have gone up together.

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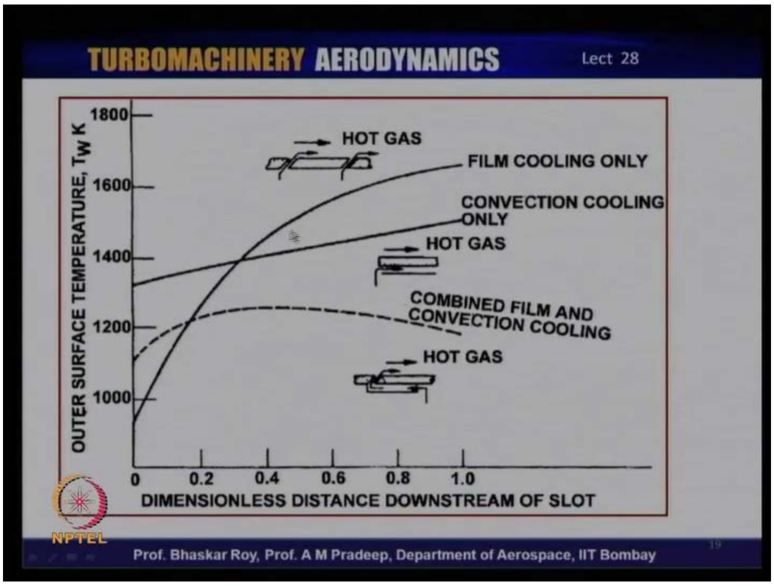

Let us look at what is happening when the surface temperature as felt the film cooling only gives so much of relief. When you have convection cooling only, it gives so much relief, but once you have a combine film and convection cooling, the surface temperature comes down substantially and this is on the blade surface. So, it, it, tells us that, on the blades surface, the temperature on the blade surface can be substantially lower if you have combined cooling system.

So, only film cooling or only convection cooling actually does not give so much relief by themselves, but when you have combined cooling system gives much more relief, and as we have seen in the earlier the slide, you can actually do that even actually with less amount of air because high pressure air is now available in modern aero engines.

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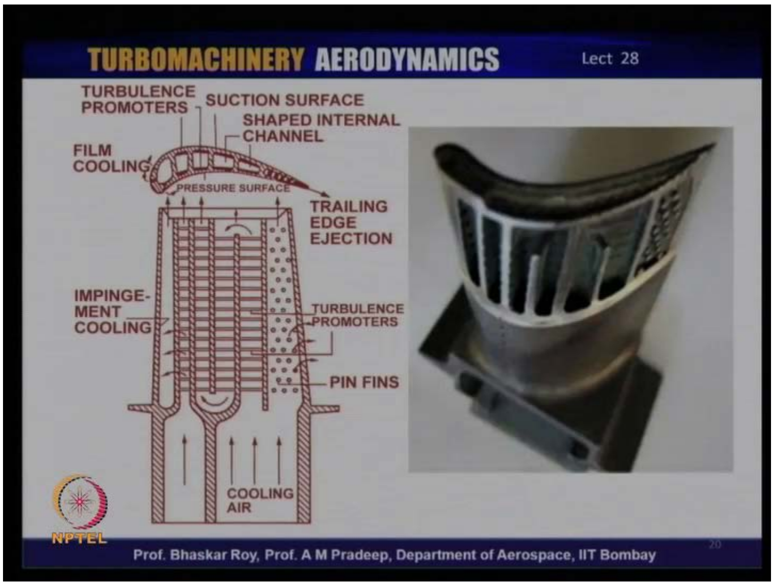

This is a picture again of a typical stator or nozzle cooling system. As you can see here, cooling air is brought in from here; it goes through these channels; it takes a turn over here, and then, it takes another turn over here and then it goes out through the tips. The other cooling air which is brought in near the leading edge goes straight out, because that is where cooling effectiveness is more and then certain amount of air is impinge cooling on the leading edge surface itself.

As we have discussed this impingement cooling is going on that air is finally also let out to the tip, and then, certain amount of air is let out through a holes near the trailing edge to affect, trailing edge cooling which again could be a Hot Spot. The inside surfaces of these cooling passages actually have turbulent promoters. The surfaces could be actually, you know, having small ribs or small bumps as you have like speed breakers on a road, those are you can probably see them here a little those ribs on the surface, that is, to promote turbulent so that the flow through these actually are actually promoted, and as a result of which, the flow is facilitated; otherwise, the flow may get impeded and may hot and may not be able to take this as quick as a root to go through the entire blade passage.

So, that needs to be facilitated through these ribs which are on the inside surface. You can probably see them a little bit over here so that, that is the kind of you know passage that typically turbine blades have, and then, they finally come out through the tips over here which also does a little bit of tip cooling. The tips need to be cooled also along with the cross flow over the tip. So, it is a elaborate cooling technology that is often used in modern hot gas blades. You, this was the stator Blade.

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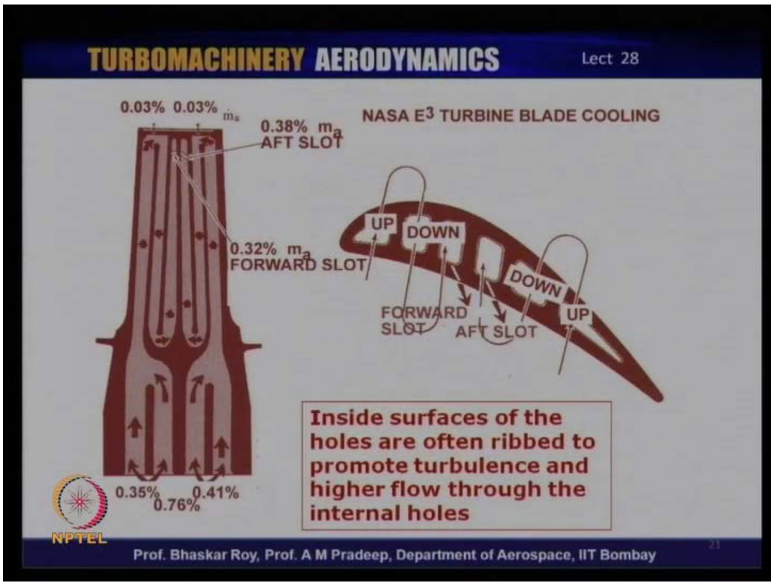

We can have a look at a rotor blade in which, the cooling technology is even more elaborate because you need to have the blades are rotating. Remember, the flow inside will be feeling the centrifugal action. So, by centrifugal action, the flow will get thrown out outwards from here. As it comes in from here, and then, that would facilitate the, that will give enough impetus to the flow to go through this channel, and then finally, come out through the tip. Same over here, it comes in over here, gets thrown out by centrifugal action. It will be promoted through ribs inside, and then through the passage, it comes out, and finally, goes out.

So, this is the up and down flow. It goes up here; it goes down there, and then, he goes up here and goes down there, and then, finally, comes out through these slots to on the tips too. So, the amount of air for example, which is going in here is .35 percent the amount that is coming out could be as low as 0.03 percent. So, the total amount of air going is 0.76 percent of the main flow that is flowing over the gas; over the whole turbine, the entire gas flow.

So, less than 1 percent of the main gas flow in terms of air mass is required for this elaborate cooling system, and if you have less than 1 percent in the early year of cooling, the amount of air required used to be of the order of 3 to 4 percent. But now, you can do with less than 1 percent. So, that much has been the advancement of cooling technology, and as a result of which, because high pressure available because of this entire manufacturing technology, the entire engineering that has gone into the turbine cooling technology has facilitated this; entirely fascinating field of turbine cooling. It is a field by itself. People, some people spend their whole life on turbine cooling technology.

It is a fascinating field, there is no question about it and it involves heat transfer science or heat transfer. It involves aerodynamics, lots of fluid mechanics, extremely high technology in manufacturing and fabrication, and then, all of it put together, best of all of them put together gives you a cool turbine blade and that is what you require to do a modern axial flow gas turbine blades. With this, we come to the end of our blade cooling technology discussion. You now know that lot of technology is required to create a modern gas turbine blade.

We will try to keep this in mind. When we go into the next class in which, we will be discussing overall actual turbine blade design. We will bring in the blade design methodology into the next class in which, we will keep in mind that certain cooling technologies are available today, and with this, we will see what kind of blades are being created for the modern gas turbines. They could be a subsonic; they could be transonic or we will see that we could even have supersonic blades for modern gas turbines. So, in the next class, we will be looking at the design methodology of modern axial flow turbines.