Turbomachinery Aerodynamics

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Lecture No. # 27

Turbine Blade Cooling – Fundamentals of Heat Transfer, Blade Cooling Requirements

Hello and welcome to lecture number twenty-seven of this lecture series on turbo machinery aero dynamics. Last few lectures, we have been discussing extensively on turbines, and we have actually started with an introductory lecture on turbines, different types of turbines, and then, we emphasized on the axial turbines, and we had quite lot of discussion, and lot of lectures devoted exclusively to the various aspects of axial flow turbines, starting from very basic thermodynamics principles and working of axial turbines, two-dimensional flow and analysis in axial turbines, and then, the losses and their estimation, the efficiencies and then moving towards the 3 D flows and 3 D design of turbine blades and so on.

So, and also of course, we had a tutorial session on turbines. So, all these lectures I believe have been quite interesting as well as educational for you in understanding the basic working of axial turbines. What we going to do today is basically to a initiate some discussion on a very important aspect which is associated with turbine blades and that is to do with the turbine blade cooling, and I think you are very well aware that the turbine inlet temperature plays a significant role in the overall performance of the engine, and it is in this context that we talking about Turbine blade cooling and the various methods that are employed in turbine blade cooling.

Just to keep you informed turbine blade cooling continuous to be a very active area of research all over the world, where all the engine manufactures and universities where research is going on and research labs. Turbine blade cooling and associated problems which, which, of course, I am going to highlight today are bring extensively studied and modified and improve upon every year. With the sole objective that the Turbine inlet temperature can be increased to as higher level as possible without increasing the associated penalties. Some of these things of course, I will be discussing in today's class.

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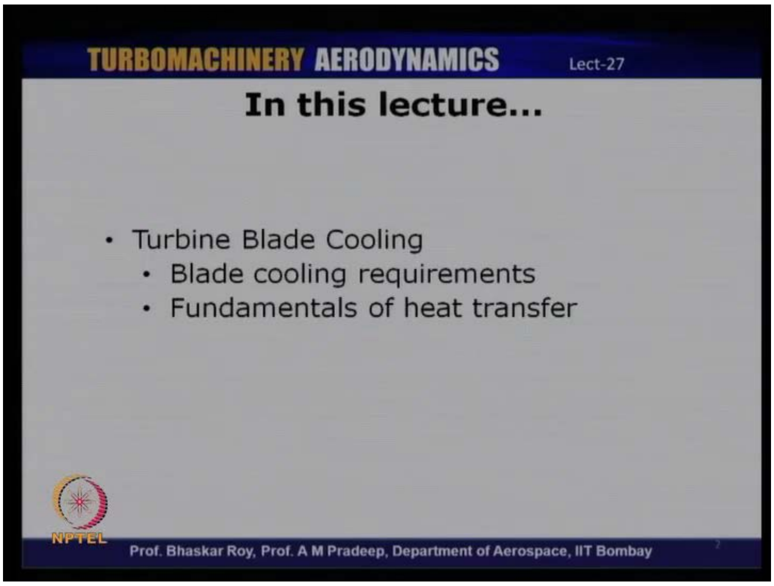

So, there are two distinct aspects that I am going to talk about in today's class. We will start with some introduction to the turbine blade and balding, blade cooling requirements where I will kind of explore the requirements of turbine blade cooling and why we need blade cooling and so on. Subsequently I will spend some time in elaborating the fundamentals of heat transfer. I guess you must have undergone a course in heat transfer, but let me, I will portably just touch up on a few topics which according to me would be very much essential for deeper and proper understanding of the Turbine blade flows.

So, we will also spend a few, some minutes on discussion on very fundamentals of heat transfer and those aspects of heat transfer which are of significance in reference to Turbine blade cooling. So, I, what I will do is I will start with a slide which I had shown in a couple of lectures earlier where we had discussed about the, the, two-dimensional blades and blade geometries and so on. So, I think I mentioned that the Turbine inlet temperature is a very significant parameter when you consider the overall engine performance. I think I had mentioned some number with reference to this, that is, if you have one percent increase in the Turbine inlet temperature, it is likely to result in two to three percent increase in the overall engine output.

So, that is the level of importance that the turbine inlet temperature has for the whole cycle, and therefore, it is necessary that we arrange or elaborate methods by which, we can increase the turbine inlet temperature, but what is the limit? Why are we not increasing the temperature to as higher level as possible? The basic reason is that the current day materials have a certain temperature up to which they can function properly; beyond that temperature, the material would fail, and therefore, and add to this the fact the Turbine blades also undergo extreme levels of stresses because of the higher rotational speeds, and so, there are centrifugal stresses, there are bending stresses because of the blade loading, and of course, because of high temperature, there are there are thermal stresses. So, and are all theses stresses the Turbines rotor also there said lot of limitations in terms of the temperature levels which, which, we can use for a typical Turbine blades given the current materials that we have.

So, with this in mind, we need to still ensure that we can or at least make an attempt to increase the Turbine inlet temperature to as high level as possible. One of the ways of doing that is to use blade cooling techniques. The other ways of course, you could give a ceramic coating to the blades, some research is also going on in this direction that you can coat the blade with ceramics. Ceramics as you know can which stands extremely high temperatures, but the main disadvantage is that ceramics are highly brittle. So, they, on they are down, they probably would it be able to which stands the stresses, and therefore, there are there are lot of research work going on, on, trying to coat a standard Turbine blade with ceramics and possibly use much higher temperatures in the Turbine.

So, but we are not going to look at ceramic coating as our discussion here. We will look at pure the method which is currently used, that is to used blade cooling method, and so, they are lot of blade cooling methods which I think we will be discussing in next class. Today’s a class is basically aimed looking at the requirement why do we need blade cooling and the thermo dynamics benefits of blade cooling and also some heat transfer related issues which are associated inherently with blade cooling techniques.

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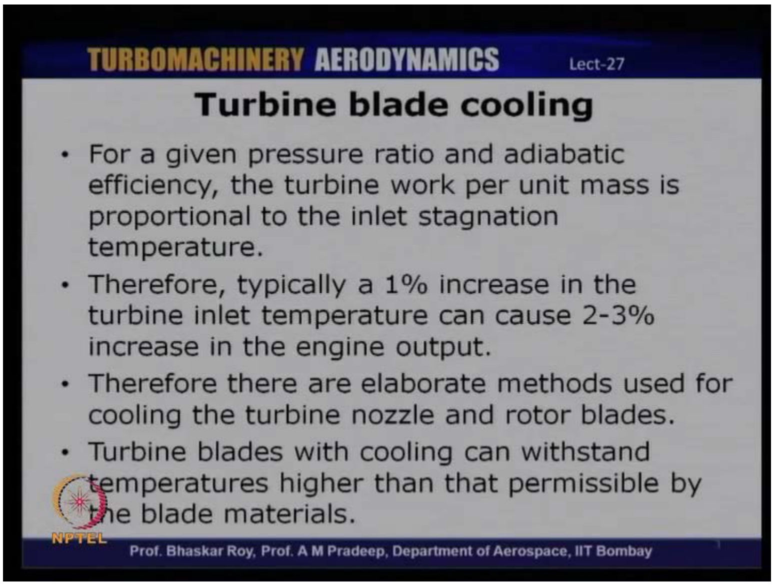

So, what I mentioned was that, for a given pressure ratio and efficiency, the turbine work per unit mass obviously is proportional to the inlet stagnation temperature, and I mentioned that typically of course, is adjusted ball for figures one percent increase in the turbine inlet temperature can cause about two to three percent increase in the engine output, and therefore, we would like to use extensive techniques or methods to increase the turbine inlet temperature, because that is the amount of significance that Turbine inlet temperature has with reference to the engine performance.

Now, if you have undergone course in basic course in thermo dynamics which I presumed you would have, then I am I am sure you would have carried out a bray ton cycle analysis. Bray ton cycle as you know is the basic Fundamental cycle of a gas Turbine engine, and in bray ton cycle, you know that there is a significant effect of the maximum cycle temperature on the work output and efficiency, and in the case of gas turbine engines, the maximum cycle temperature is the turbine inlet temperature, and therefore, that is the kind of significance that bray ton cycle has, well, bray ton cycle depends on the turbine inlet temperature.

Current day materials cannot really which stands temperature greater than thirteen hundred Kelvin and that kind of put a limitation on the maximum efficiency that one can get, because as you know the efficiency is in some sense, a function of the ratio of the maximum temperature to the minimum temperatures. So, if a maximum temperature is fixed, minimum temperature you cannot change because that is the ambient temperature and that is fixed, and once you fixed the max temperature, then that also puts a limit on the max efficiency of the engine. You would not want to have a certain limitation; you would like to extend that limit further take the efficiency to higher levels. Now, there are obviously inherent benefits to blade cooling techniques which can permit as to use much higher turbine inlet temperatures.

At the same time, there also lot of disadvantages an associated here. Disadvantage in the sense that it, it, increase the complexity of the whole process by orders of magnitude. It leads to mechanical complexities; because you need to incorporate methods which can leads to blade cooling; you would also leads to aerodynamics complexities because you have a cooling flow which is interacting with the hot gases. So, that leads to aerodynamics issues and obviously the thermodynamics issues because of stresses and so on. So, it, it, changes the whole boil game of design an analysis of a Turbine which has these techniques being used. The turbine blade cooling obviously will increase the complexities by orders of magnitudes. So, that is one important message that you need to keep in mind that of course, you get a lot of benefit in the same time that is with a cost and that cost is the extreme complexity that is associated with the whole aspect of turbine blade cooling.

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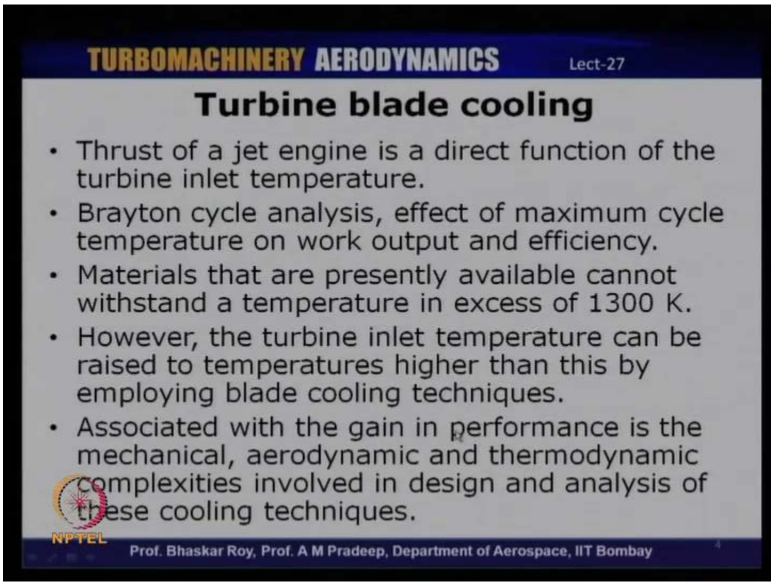

So, so with the gain in performance we have mechanical aerodynamics thermodynamic complexities which are involved in design and analysis of these cooling techniques and ah

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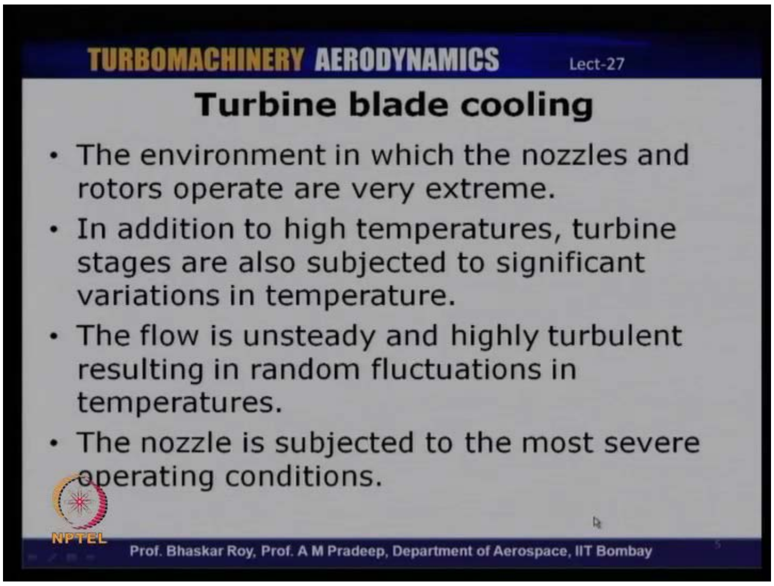

So, if you now look at a Turbine stage, you know it consists of nozzles and rotors. They operate in very extreme environment and the extreme environment is because of hot gases which are at very high temperatures. At the same, time they are also at very high velocities, because a nozzle accelerates the flow to very high speeds. Therefore, the flow is coming in the very high velocity; it also has high temperature, and possibly, the compensation of the gases itself is not just air. So, all kinds of combustion products are involved there and that makes it highly, very highly extreme operating conditions for the nozzle as well as the rotor, and therefore, it is this one of the challenges of cooling designers is to take care of these complexities in terms of high temperatures, high velocities and gas mixture. Now, the other aspect of the, well, the others higher level of the complexity is the fact that the high temperatures are really fixed.

There are significant variation or fluctuation in these temperatures because of the fact that the flows highly unsteady and highly turbulent, and therefore, random fluctuations like the way coming from the rotor interacting with the stator or the nozzle downstream. So, the flows extremely unsteady, it is highly turbulent, and therefore, the random fluctuations in temperature which you cannot really take care of while designing turbine blade of course, with the modern design tools like CFD and so on. It is possible to partially take care of this complexity, but it still is a very challenging area of designing and continuous to be very significant area of importance in terms of research.

Now, if you compare a nozzle with rotor, you may be surprised to know that a nozzle is subject to a slightly higher level of extremity in terms of temperature. The basic reason here is that because of the relative motion between the nozzle and the rotor, the rotor actually sees the stagnation temperature which is in the related frame, which is slightly lower than that the nozzle. It is probably about 200 to 300 Kelvin lower than the temperature which is the nozzle faces.

Therefore, nozzle is actually facing temperature environment which is more severe than that of an a rotor, but this is only in the in terms of temperatures being look at others complexities like stresses, the bending stress, centrifugal stress and the thermal stress, then of course the rotor obviously has much more to endeavor than nozzle, and so, it is in this context that I just mentioned that nozzle is subject to more severe operating conditions. The rotor is also subject to severe operating conditions, but if you look at simply the temperature, the nozzle actually faces slightly higher temperature.

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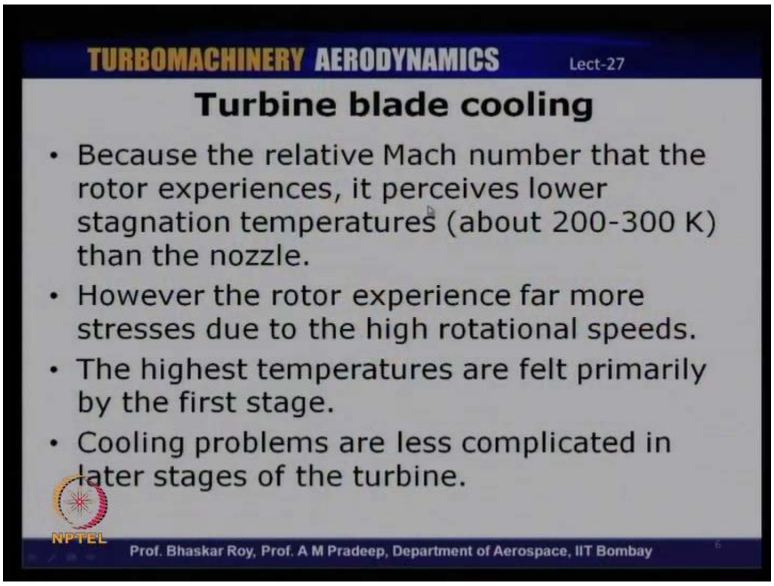

Now the main reasons why the nozzle and rotor faced different levels of complexities in terms of temperature is because of the fact that rotor experiences slightly lower stagnation temperature probably 200 to 300 Kelvin lower than the nozzle, but of course, it experiences far most stresses due to high rotational speeds, and the highest temperatures are basically felt in the first stage, and as you move towards this and later stages, the cooling problems become lesser and lesser complicated in the later stages, which is obvious because the later stages do not really have that higher temperature as the case with the initial stages of the turbine now.

What we will do is let us take a look at what are the modes of failure. Let us say you do not employ any cooling technique. Then in the first place, why should we worry about cooling at all? I think I mentioned that the material image that will fix the turbine temperature. Given a certain material, you cannot go beyond a certain temperature unless one uses artificial methods of keeping the temperature, metal temperature lower than the gas temperature itself.

So, there are different modes by which turbine blade can failed where we can categorize them into three distinct classes - one of them is to do with the oxidation or corrosion or erosion of the blades which is because of the chemical and particulate attacks from the gases, that is, the combustion products which enter the turbine may have some amount of particular matter unburned fuel and so on, which might damage the blades because they are coming in an extremely high speeds. We may also have certain chemical reaction taking place due do oxidation on the blade surface. So, that is one of the modes of failure, that is, eventually if this is allowed to grow obviously, it will lead to failure.

The other mode is because of creep that is has Turbine blade is exposed to high temperature for prolong periods of time, then the blades will undergo what is known as creep failure, and one may also have the third mode of failure which called a thermal fatigue because of the repeated cycling. As the turbine operates through a cycle, that is, it is started and then taken to max temperature and eventually it stops and it turbine blades cool down, and then, it again, after sometimes it is started and so on. So, as the Turbine undergoes these cycles of operation, it undergoes fatigue, and therefore, it leads to high thermal stresses during these cyclic loading in terms of temperature and that also leads to failure in terms of a thermal fatigue.

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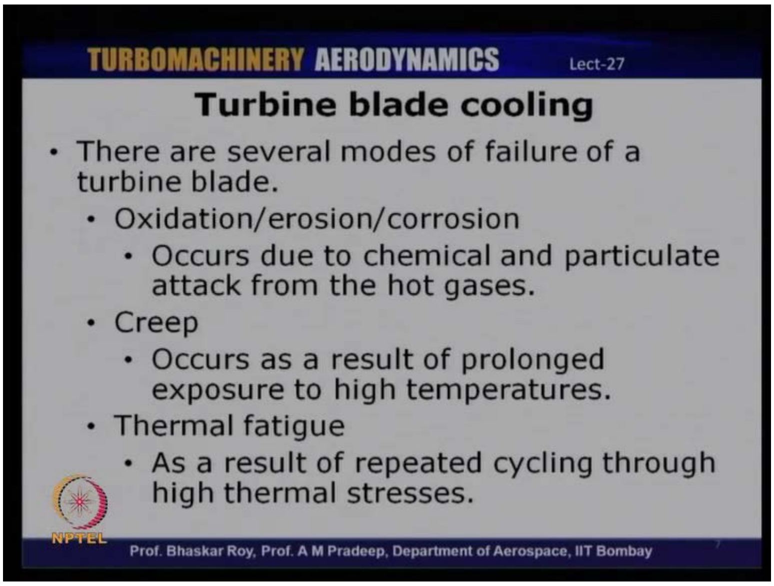

So, these are three different modes of failure which are possible in the case of a turbine, and one may have, if one does not employee any cooling techniques, one is likely to encounter either of these modes or a combination of these modes which can lead to a early failure of the turbine blades; obviously, you cannot really operate a turbine at a temperature which is higher than the material limit itself. Let us say material limit says that max temperature is 1300 Kelvin; obviously, you cannot design a blade for operating at 1400 or 1500 Kelvin. It has to be lower than thus limit. Even then the turbine blades eventually will undergo one or more of these modes of failure, and that is something that, as a designer one would like to avoid and prolong the life of a turbine blade by using some of these blade coding techniques.

So, I think I mentioned in couple of slides earlier that a turbine blade will undergo a variation in temperature, and in the sense that it if the combustion chamber is operating at a certain temperature, the combustion products eventually pass through the nozzle, and then, subsequently put the rotor, and if there are subsequent stages, obviously through those stages as well. Now, in most of the common turbines, it is seen that of course, during a simplistic a beginning level design, one would like to assume that the turbine faces a temperature distribution which is kind of uniform.

Well that is still an idealistic scenario where, you know, one may have a uniform temperature profile, but what is seen is that, most of the cases because of the unsteady transient nature of the flow, the flow is hard; the temperature distribution is hardly ever uniform.

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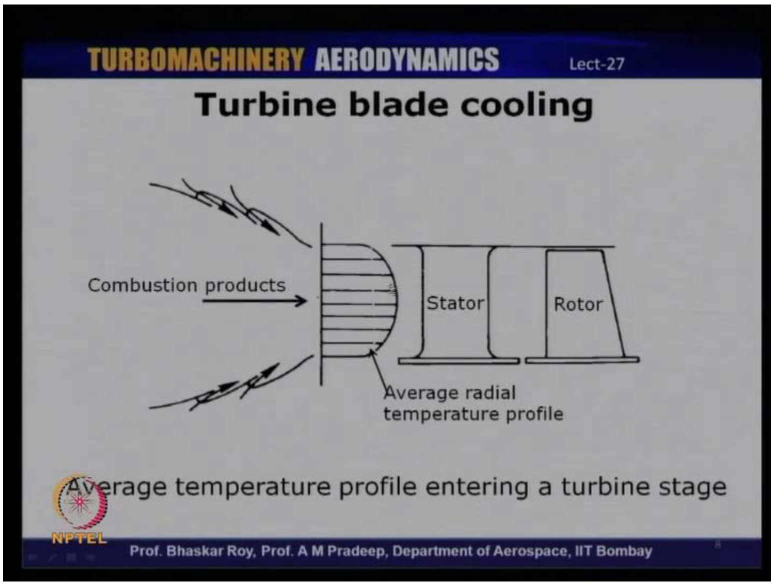

Just you give me some idea if you look at this particular schematic where we have an average temperature profile which has been plotted. This is an average radial temperature profile. So, this is a typical average temperature profile, radial temperature profile, that is, from the hub of the blades to the a shroud and combination products enter the stator typically with an a certain temperature profile.

Now, it is one can always assume that the profile has a shape like this, but of course, depending upon the operating conditions, one may or may not really have a uniform profile like what you seen here. It may have substantial variation in the temperature though the combustion designers would, combustion chamber designers would like to keep these profiles as uniform as possible, but under extreme operating conditions, one may have significant variations in the temperature profile from what we shown here.

And thus the flow passes from the inlet of the stator to the exit. It again undergoes a change in it is profile, temperature profile entering the rotor can also be quiet different, and that is one of the reasons what, why the design of a cooling system becomes even more complicated, because how do you take care of these non uniformities in the temperature profile which obviously depend upon the flow, because there is as we will see very shortly, there is a very strong coupling between the velocity field and the temperature field.

For normal low speed applications, one would kind of like to assume that the velocity field and temperature field are decoupled and thus hardly any linking between them, but in, in, a high temperature, high speed flow like that of these turbine flows. The coupling is inevitable; one cannot simply neglect the coupling between temperature and velocity.

So, design of a cooling system for a flow which is likely to be highly unsteady and turbulent is extremely complex because you cannot really predict the temperature variations, because the flow itself is unsteady, and therefore, design and that is why I am mentioned that turbine blade cooling continues to be inactive, very active research and designers all over the world are trying to and researchers are trying to develop better methods of designing cooling techniques for a turbine blade.

So, with this background, I guess now you must have understood the significance of the this particular topic of turbine blade cooling, and why I said that one needs to employee a blade cooling techniques, and now, that we have understood or had some background of the requirement of turbine blade cooling. I think it is about time that we also look at methods by which, one can estimate the cooling requirements.

I mentioned that turbine blade cooling is inherently heat transfer problem which, which, also involves certain coupling with the fluid mechanics. So, it is an aerodynamic and heat transfer problem where both of these vast areas have to come together to arrive at a certain configuration which can serve this particular purpose.

So, what we will do is to have an overview of the heat transfer, fundamentals of heat transfer and with this specific relevant to this particular topic of turbine blade cooling. So, Turbine blade cooling inherently involves a application of concepts of heat transfer. Heat transfer as you know is a very well established area like fluid mechanics or aero dynamics and substantial knowledge base is available in the form of books journals and other form of literature.

What we will do is to take a brief overview of the different concepts of heat transfer which will be required for an efficient design of a cooling system. So, let us go through some of the very fundamental aspects of heat transfer. I think you must have learn this several times in this earlier on in heat transfer courses thermodynamics and so on.

You probably aware that, I am sure you were aware that there are three modes of heat transfer – conduction, convection and radiation. So, what are these different modes of heat transfer? Conduction basically involves heat transfer between two bodies or two parts of the same body through molecular level and which are more or less stationary, that is the body stationary conduction is heat transfer between the molecules of the body or between two bodies which are actually stationary. So, conduction is something that occurs in basically because of the molecular motion; we are not talking about any mass motion of the fluid itself. It is just a result of energy interaction or energy transfer between molecules.

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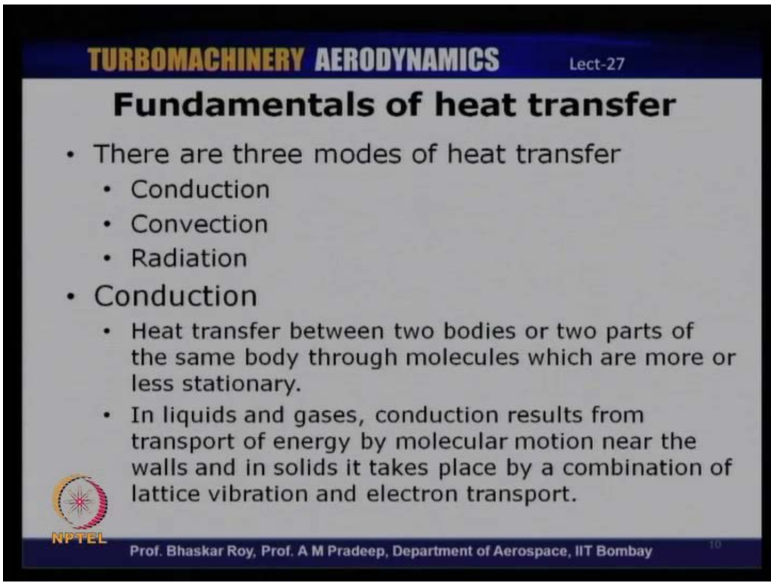

And so, and in the case of gases and liquids, conduction basically results from transport of energy by molecular motion near the walls, and in solids, it takes place by a combination of lattice vibration and electron transport.

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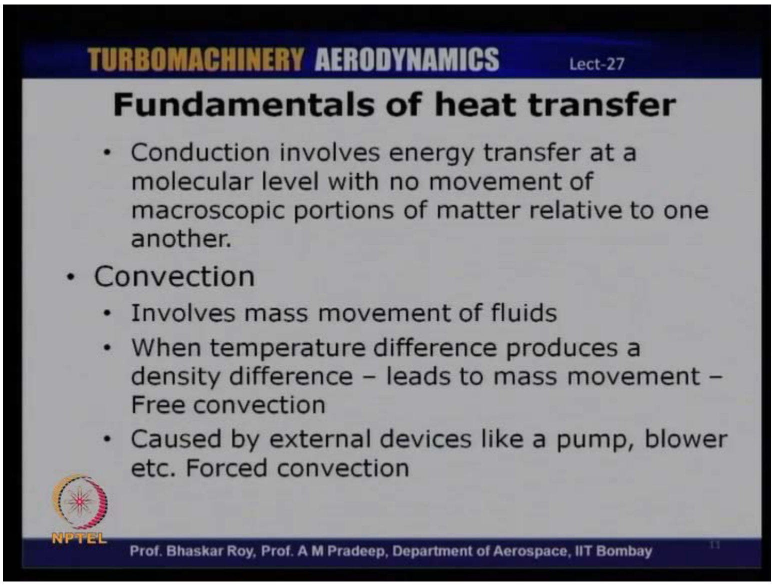

Conduction as I mentioned is energy transfer at a molecular level. There is no mass movement or macroscopic movement of matter relative to one another. Now, the other mode of heat transfer is convection, and convection is something that involves motion, mass motion of fluid and it is not something which occurs on a molecular levels. So, there is much more than just molecular motion; it involves basically mass motion of fluids either liquids or gasses.

Now, you may have conduction again taking place in different modes. You could have conduction taking place just because of change in density which is again as a result of temperature difference and that is called free convection, that is, when heat transfer takes place as a result of temperature difference, and therefore, density difference and a result of that, it is to what is known as free convection.

Now, if you use an artificial mode of a inducing convection, that is known as forced convection. Let us say use of pump or a blow or compressor, then that mode of heat transfer is known as forced convection. And heat transfer in turbine blade which involves blade cooling techniques is essentially a forced convection problem because we are actually introducing external air, which is basically air taken from the later stages of a compressor which is used for cooling a turbine blade.

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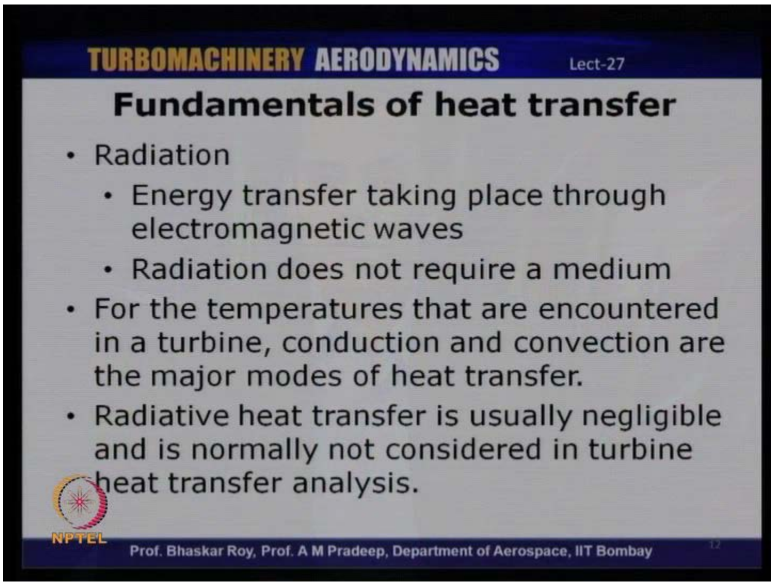

Now, the third mode of heat transfer is radiation and radiation is basically energy transfer taking place through electromagnetic waves, and obviously, it does not need any medium. For example, sun radiates heat to the earth and there is no medium between the sun and the earth and does not require a medium, but for the temperatures that we are looking at in a turbine, it, the major modes of heat transfer are through conduction and convection and radiation is of course present. We cannot say it is 0, but compare to the heat transfer taking place to conduction and convection, radiative wave transfer is usually negligible and it, it, is not usually considered that significant in the case of turbine blade cooling in heat transfer in a turbine blade.

So, we will be restricting our discussion on heat transfer in turbine blades to conduction and convection. Now, let us take a, first look at the conduction little more detail, and subsequently, will locate convection and both of these of course, in the context of heat transfer in a turbine blade.

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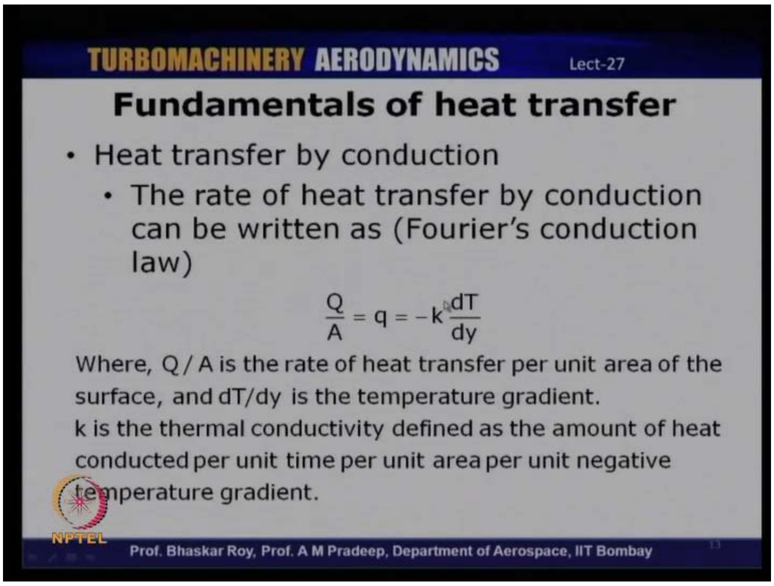

Now, one of the Fundamental loss of conduction is the Fourier conduction law as I am sure you must have leaned, which basically relates the rate of heat transfer to the temperature gradient and that is through the thermal conductivity. So, rate of heat transfer per unit area q by a or it is denoted by q is proportional to the temperature gradient, and temperature gradient obviously in the y direction normal to the surface and that is the function proportionality constant is the thermal conductivity which is basically the defined as a amount of heat conductor per unit time, per unit area per unit negative temperature gradient. So, thermal conductivity obviously is a property of the surface itself of these solids and it basically is a constant which relates the rate of heat transfer to the temperature gradient.

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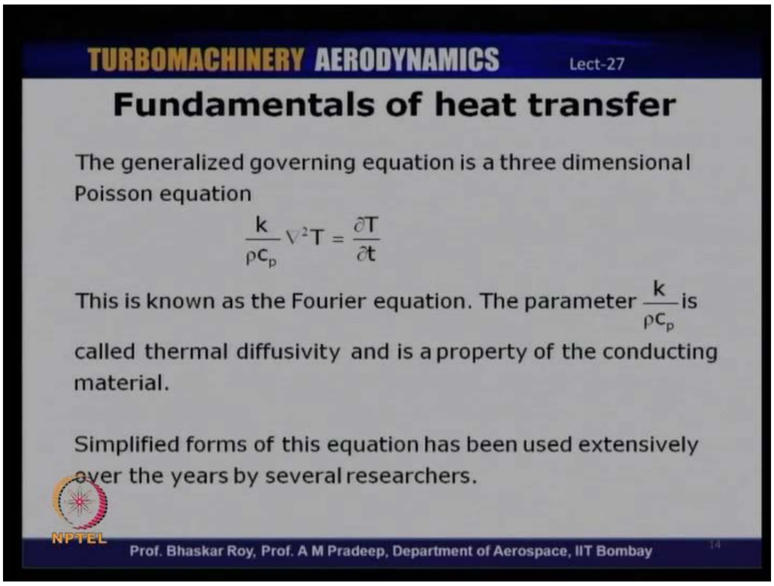

Now, this equation we can generalize and we can write a generalize governing equation in a three-dimensional Poisson equation form and which is basically stated as by rho cp del square t is equal to del t by the rate of change of temperature are with time. So, there is transient temperature term here. The temperature denser here and the parameter that you see here, that is, k by rho cp is known as thermal diffusivity which is again a property of the conductivity material.

So, this is basically known as the Fourier equation of course, the generalized version of the Fourier equation. It is used in simplified versions with lot of assumptions in normal design level calculations where one would like to carry out design of let us say cooling system in a simplified fashion to begin with and therefore, simplified versions of these equations away extensively used by researches working in the area of heat transfer of turbine blade cooling methods.

Now, so, the first form of heat transfer that we have just discussed is conduction and described very well by the Fourier's equation, which relates the heat transfer to the temperature gradient. Now, the other mode of heat transfer which is the, which is basically to do with interaction between the fluid and the solid itself, and as a result of mass motion of the fluid, that is known as the convective heat transfer.

So, in convective mode of heat transfer, we have seen that in, in, solids for example, the mode of heat transfer in just a solid is purely by conduction, that is, there is no mass motion of fluid if you look at just a solid as a hole and heat transfer takes place just because of transfer of energy from one molecule to another. So, conduction is the only mode of heat transfer that is possible in a solid in and of course, you may have radiation depending upon the temperature.

But if you look at a fluid, the liquid or gases, both these modes, that is, conduction as well as convection heat transfer are possible. Conduction is possible because molecules can interact with each other and transfer energy from one to another and convection is possible because liquids and gases can, would involve mass motion of molecules and that leads to convective heat transfer as well.

Now, the other important aspect of convective heat transfer is the fact that there is a very strong coupling between temperature and the velocity fields, which is especially true for high velocity, high temperature like in case of turbines that way currently talking about. In low speed in compressible flow, normally it is a practice to decouple temperature and velocity field and just calculate the velocity field, because we are primarily interested in the velocity field. In this case of turbines, that is not possible, that we, it is not correct to decouple temperature and velocity fields, but because they are strongly coupled as we going to see very soon in, in, the side of equation which will reveal the fact that this fields are very much strongly coupled and it is not possible to decouple them.

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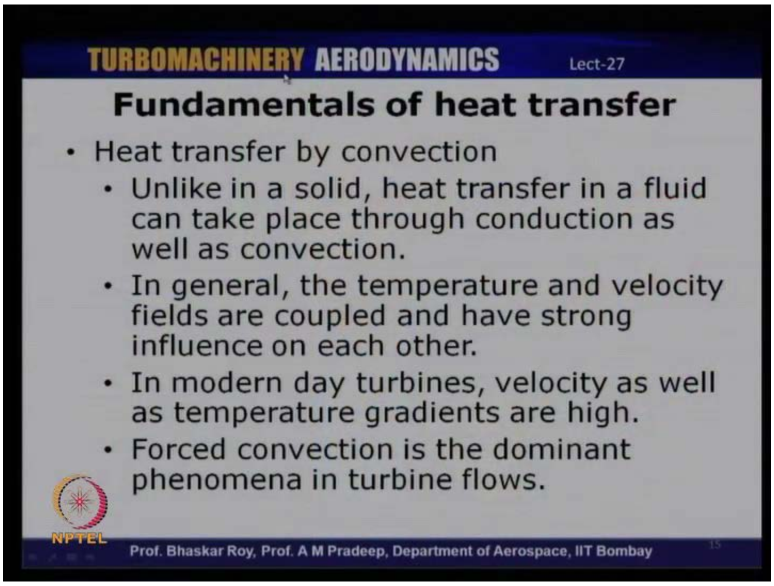

Now, in ah modern day turbine scenario, we, the coupling is even more significant because of the fact that velocity as well as temperature gradients are very high, and in that scenario, the coupling between the temperature and velocity fields will have a very strong influence on each other, and turbine blade which is and do which is being design, which has been design for cooling methods will involved forced convection and that is the dominant phenomenon of a heat transfer in turbine flows.

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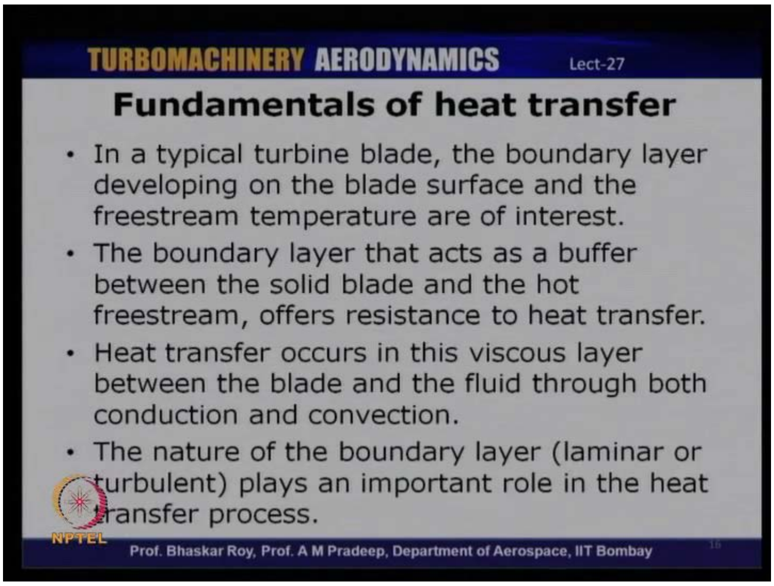

Now, in a typical turbine blade, the boundary layer developing on the blade surface is also of significant interest, because boundary layer sort of acts as a buffer between the solid blade and the hot free stream and it offers resistance to heat transfer between the blade and the free stream. Now, the heat transfer that is taking place in this boundary layer, the thin discuss layer is both by conduction as well as convection. Conduction it basically transfers heat from the fluid which is at much higher temperature to be solid that is the blade, and at the same time, it also transfer heat to the solid through convection.

So, there is heat transfer mechanism involving both conduction as well as convection between the free stream which is at a much higher temperature as well as the solid, which is the turbine blade and this heat transfer is a largely dependent on the nature of the boundary layer, that is, the boundary layer laminar or turbulent, the nature of the heat transfer is quite different depending upon the type of boundary layer that one is encounter.

So, on a typical turbine blade which will see very soon, there is change in the nature of boundary layer from the leading edge that, say the stagnation point all the way up to the trailing edge. Boundary layer changes from initially its stagnation point. There is growth of boundary layer it is initially laminar, then it transaction and become trouble.

So, as the flow becomes are as the flow becomes laminar and transaction, and then, the finally, become turbulent. The nature of the heat transfer through each of these layers is quite different and there are separate method of calculating heat transfer through each of these distinct element of the boundary layer. Whether it is laminar or transactional or turbulent, the heat transfer or calculation of heat transfer is quite different and that is handle separately by separate tools or methods, and what we will say in next slide is typical distribution of the heat transfer rates in a typical turbine blade.

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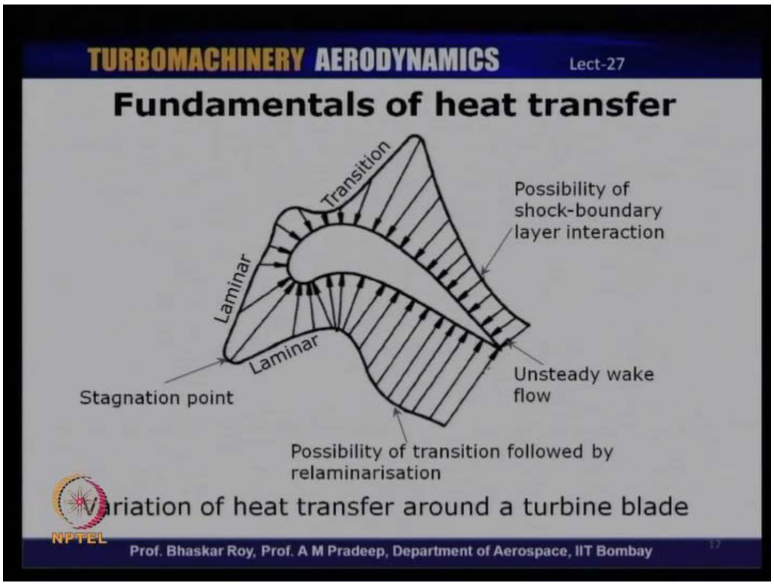

So, let us take a look at a typical turbine blade and how heat transfer way can vary around the turbine blade. So, what is indicated by these arrows are the rates of heat transfer and why it is high will be clear in a fluid slides from now. So, if you look at a stagnation point, this is the stagnation point of the blade. The boundary layer begins development from the stagnation point. It is initially laminar and then it becomes transitional and eventually it becomes turbulent and this is on the section surface. On the pressure surface, of course depending upon the nature of the blades, some of the modern blades may also have substantially high levels of acceleration leading to re laminaraisation of the flow, that is, the turbine, the flow is initially laminar. Then it transition and possibly become turbulent and then eventually it might become than laminar again.

So, what is, what are indicated by this distinct point? One is of course, the stagnation point have will highlight the significant of stagnation point little later, because that is where the maximum heat transfer is going to take gradient. I will explain that little later. Now, on the section surface, one might have presence of shocks defending upon the Mach number at which the blades are operating. I mentioned it one of my earlier lectures that it turbines designs of usually would want to delay the occurring of shocks towards the latter half of the blade, and so, you may have shocks in the, towards trailing edge of the blade especially on the section surface and. So, there is a possibility of a shock boundary layer interaction here which can of course in complicate the heat transfer substantially.

And one may have an unsteady weight flow at the trailing edge there. That again is a very challenging area of estimating heat transfer in an unsteady flow, because that also affects the temperature distribution substantially. So, these are the different distinct regions of a typical turbine blade, and where in the method of estimating heat transfer rates in all these distinct areas whether it is laminar or transition turbulent or it has become laminar again through lamenarisation or stagnation point of the turbulent way. The heat transfer rates are quite different in all these distinct areas. So, there is a separate method of calculating heat transfer through that is possible through each of these different layers are region of the boundary layer.

Now, I mentioned that there is a very close coupling between the fluid mechanics and heat transfer especially in the context of the turbine blades and Turbine with cooling with essentially.

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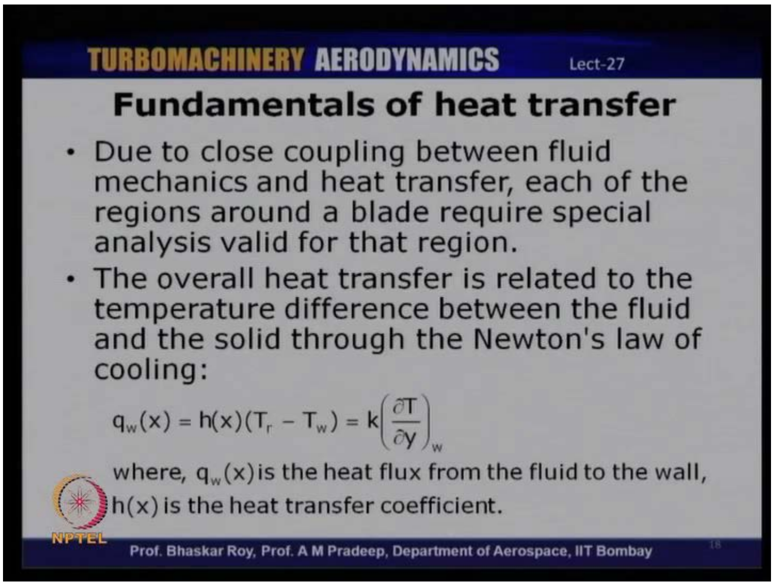

So, analysis of the flow around a blade requires special analysis which is valid for that particular region. For example, if you are looking at laminar flow that is leading edge of turbine blade, then one can analysis the heat transfer through a laminar boundary layer and has been transition and go to the later part of the turbine blade. The boundary layer is Turbulent and heat transfer through that boundary layer is quite different.

Now, in general, one can write the overall heat transfer which is related to the temperature difference between the fluid and the solid through the Newton's law of cooling which relates the heat flux, which is mention here as a q subscripts w, that is, heat transfer from the wall is proportional or is equal to heat transfer co efficient h multiplied by the temperature difference and this is again related to k times del t by del y which is the temperature gradient.

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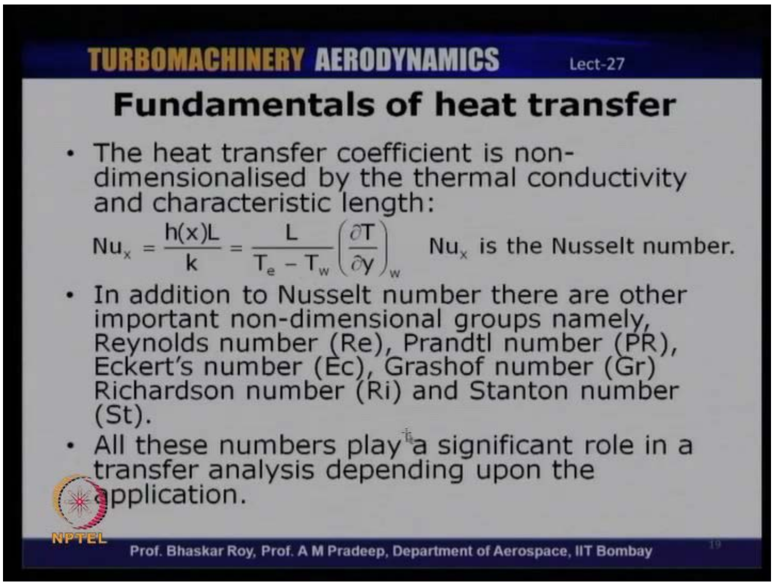

Now, this heat transfer coefficient that we have seen can be non-dimensionalized by the thermal conductivity. So, and that is through what is known as the Nusselt number. So, Nusselt number is the heat transfer coefficient multiplied by a characteristics line usually the god of the blade in these case divided by the thermal conductivity of the blade. This is also equal to l by the temperature difference t minus T w multiplied by del t by del y at the wall.

So, Nusselt number is one of the non-dimensional parameters which is the extensible used in heat transfer. There are numerous other non-dimensional groups like Reynolds number obviously, you were aware of is the Prandtl number which will seen very shortly. There is a Eckerts number, Grashof number, these two in and one may have Richardson number and Stanton number. So, these are some of these non dimensional number of groups which play very significant role in heat transfer analysis in a turbine blades, and depending upon the nature of heat transfer, one are more of these non dimensional groups well play significant role in the heat transfer characteristics.

So, what we will do next is to take two examples - one is to do with laminar flow; other is to do Turbulent flow. Both force convection because Turbine blade with cooling is a post convection problem. So, we will look at a laminar boundary layer and subsequently turbulent boundary layer, both undergoing post convection, and then, look at how we can analyze heat transfer in both these different boundary layer scenarios.

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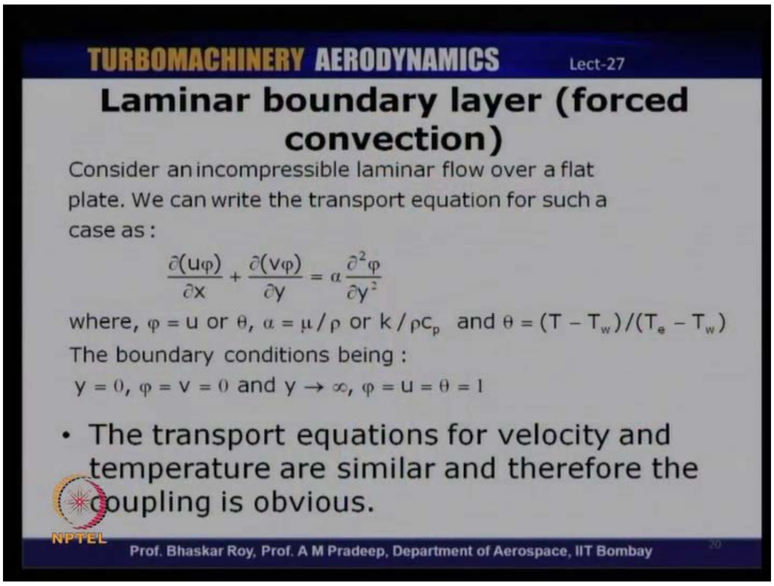

So, let us consider a very simple case of an incompressible Laminar flow over a flat plate. So, for this kind of an application, we can write the transport equation as del u phi by del x plus del V phi by del y is equal to alpha del square phi by del y square. So, here, phi could be either u or theta; alpha could be either mu by rho or k by rho C p and theta is the temperature differential t minus T w by T u minus T w.

So, for this case, the boundary condition could be at y is equal to 0 phi by could be V phi and v is equal to 0, that is at the wall, the velocity y direction is 0, and at has y tends to infinity, phi is equal to u is equal to theta is 1. So, what you can see here is that in this kind of a transport equations that you see the both the velocity and temperature equation are quite similar, and which means that the coupling between the temperature and velocity fields becomes very obvious that the complete between velocity and temperature field simply cannot be ignore especially for high temperature and high velocity flows.

And so, in a laminar flow, people have come up with empirical correlation of course, depending upon the application. Right now we are simply talking about flat plate which means there is no pressure gradient, and for a very simple application like this one can relate some of the non dimensional numbers that I mention that Nusselt number to Reynolds number and Prandtl number through some empirical co relations.

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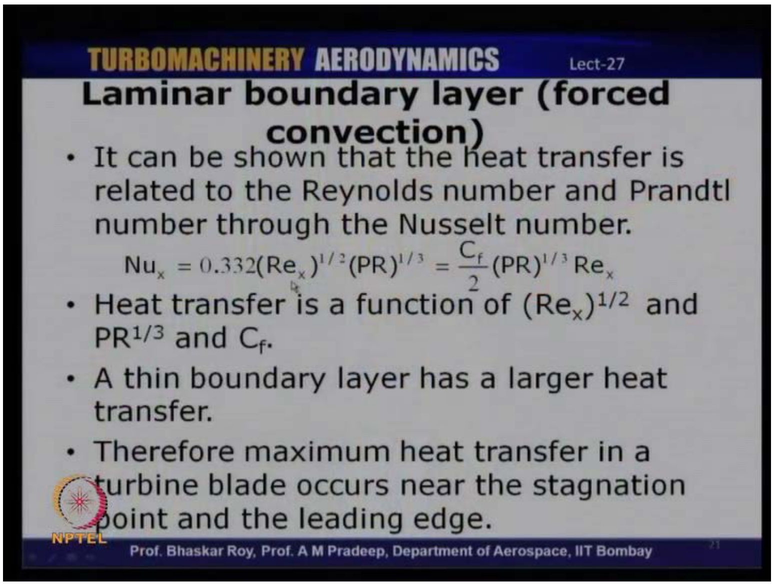

So, what is been demonstrated what has been root is that the Nusselt number can be related to Reynolds number and Prandtl number for a typical 0 pressure gradient flat plates application. Nusselt number is 0.332 times Reynolds number raise to 1 by 2 into Prandtl number raise to 1 by 3 this is all so related to the skin friction coefficient C f by 2; Prandtl number raise to one by three into Reynolds number. So, what you can see is that heat transfer is indeed a function of this square root of Reynolds number and Prandtl number is to 1 by 3 as well as this skin friction coefficient.

What is all so interesting is that a thin boundary layer has a larger heat transfer. Therefore, the thinner the boundary layer heat transfer obviously is larger, because you do not have a buffer which well separate the surface from the free stream, and therefore, the maximum heat transfer would take place at this stagnation point where the boundary layer thickness is close to 0.

So, that is where the boundary layer begins development, and since there is no buffer between the boundary layer, that buffer between the free stream which is the high temperature and this surface which is at lower temperature heat transfer rate is the maximum. Which is why if you recall the heat transfer distribution, I was showing around blade surface the maximum was at this stagnation point that is because, that is, at that point, that we have the boundary layer thickness which is at it is minimum. Thinner the boundary layer more is the heat transfer. Let us now move on to turbulent boundary layer for a very similar application that is calculate, and if you look at turbulent boundary layer, how do you calculate the heat transfer?

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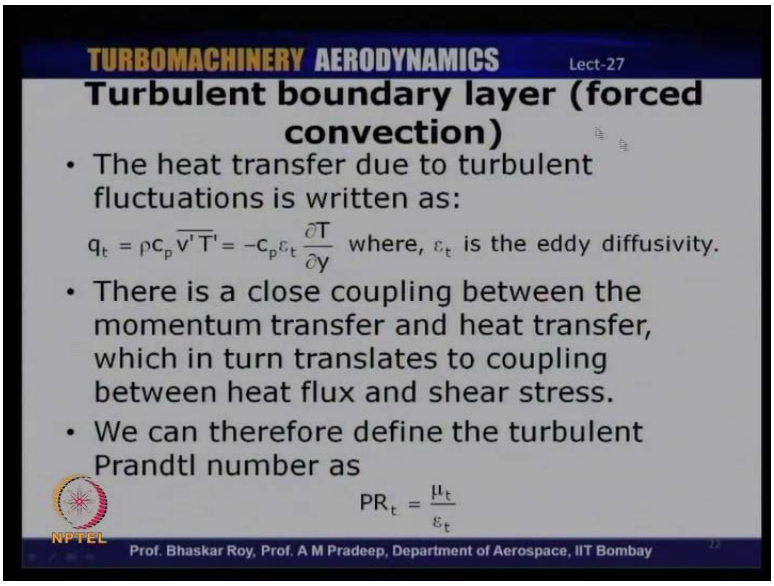

So, heat transfer to which is owing to turbulent fluctuation is can be written in the form of this equation, that is, q subscript t is equal to row C p into v prime t prime, and average of that the end symbol average of that this is minus C p into epsilon subscript t del t by del y which is at temperature gradient. Here, epsilon subscript t is the eddy diffusivity which is basically owing to the turbulent fluctuation which of present in a turbulent boundary layer.

In a turbulent flow, there is all very close coupling between the momentum transfer and heat transfer which in turn translates to the coupling between the heat flux and shear stress, because in an turbulent boundary layer, we know that there is momentum exchange between the different layers of the flow which is absent in the case of the laminar boundary layer, and therefore, there is a close coupling between the momentum transfer and heat transfer.

So, as we will see very shortly in the turbulent boundary layer, one would have much higher levels of heat transfer. That is because there is momentum exchange between the different layer of the boundary layer, which is unlike in the laminar flow where the different layer do not really mix and interact, and so, the momentum transfer between the layers in laminar flows is much less than that in a Turbulent flow. So, in turbulent boundary layer, we would define what is known as a turbulent Prandlt number and Turbulent Prandlt number is basically defined as the ratio of mu subscript t over the eddy diffusivity. So, ratio of the viscosity to the eddy diffusivity.

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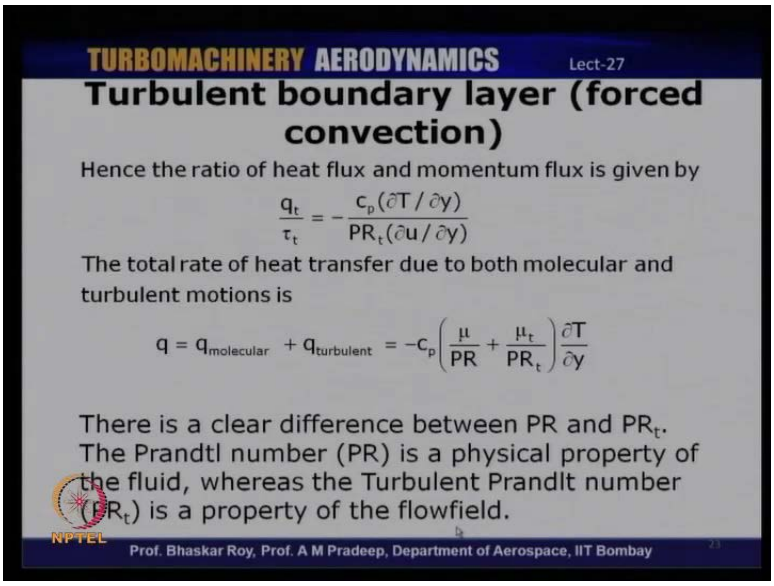

So, what is the significance of the Turbulent Prandlt number? We can express the ratio of heat flux and momentum flux as what is given here, that is, the heat transfer q t to the momentum flux is equal to the mines C p into temperature gradient and the turbulent Prandlt number multiply by the velocity gradient.

So, we can relate the heat transfer and or heat flux and momentum flux through the temperature gradient velocity gradient, and therefore, the total rate of heat transfer due to both molecular and turbulent motions, that is because of conduction as well as the convection involved is the some of the molecular heat transfer and the turbulent heat transfer and that is expressed as minus C p into mu by plus mu t by Turbulent Prandtl number multiply by del t by del y, and there is indeed a very clear difference between Prandtl number and the Turbulent Prandtl number. Prandtl number is a physical property of the fluid, whereas the Turbulent Prandtl number is a physical property of the flow field and not just the fluids.

So, depending upon nature of the flow whether it is Turbulent, Prandtl number is indeed a function of the flow field. Turbulent Prandtl number is the function of the flow field as against Prandtl number which is just a function of the, or it is just the property of the flow itself. Now, same as we have defined for a laminar boundary layer, we can now relate the Nusselt number to the Reynolds number and Prandtl number to again an empirical correlation which is of course, here for a flat plate.

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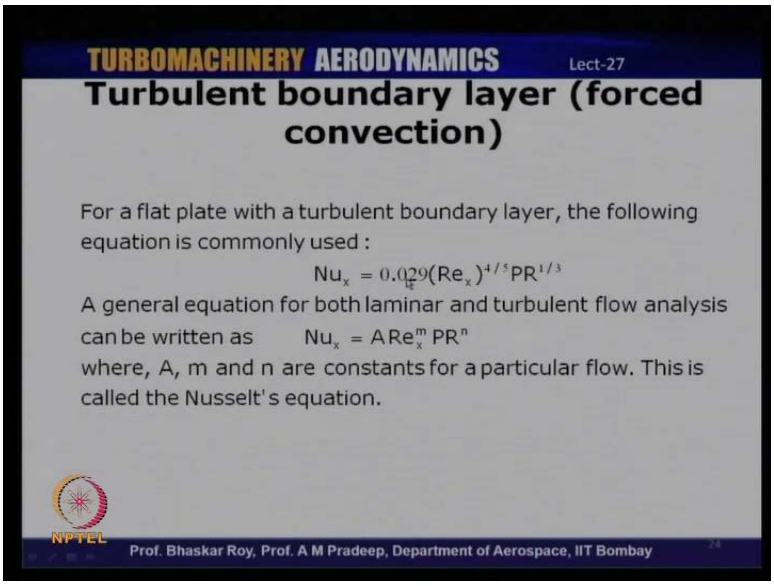

Nusselt number is related to the Reynolds and Prandtl number through this equation that is 0.029 Reynolds number is to four by five Prandtl number raise to 1 by 3. So, we can see the quite similar they both equation are very similar, the, that we have written for the laminar flow and that for a turbulent flow. In general, we can write Nusselt number is related to Reynolds number and Prandtl number through three constants and this of course, would depend upon the nature of the flow itself.

So, this is basically know as Nusselt equation, and here, this constant is indeed depend upon the particular flow and nature of the flow and the whether it is flat plate or if it is a flow with ah pressure gradient which is adverse or favorable pressure gradient, one could actually come up with empirical correlation for the Nusselt number or the Nusselt equation and relate that to the Reynolds number at the Prandtl number.

So, we have very quickly had an overview of transfer, fundamental heat transfer, of course, heat transfer itself a very vast subject; obviously, not possible to cover all the aspect of heat transfer in a few slides that I have done. This was just to give you an overview of the heat transfer. The Fundamental concept of heat transfer which are used in analysis of Turbine blade cooling.

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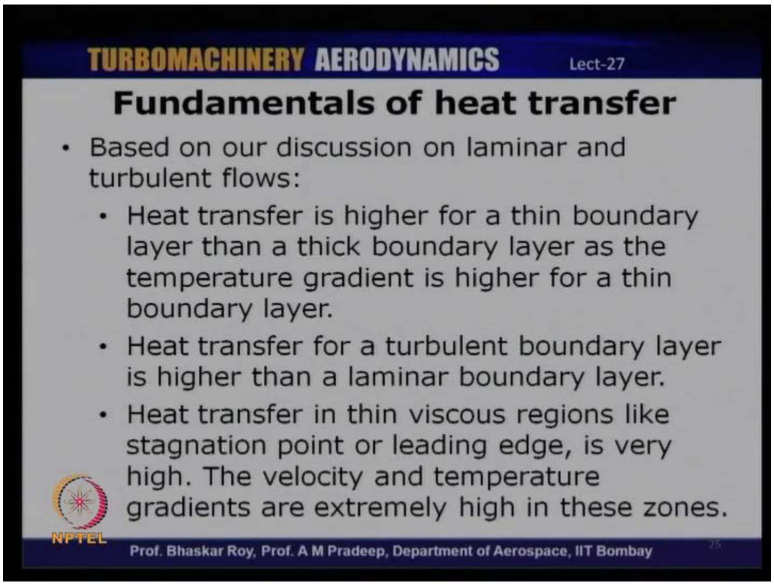

So, let me just quickly recap the different points I have mentioned on discussion on laminar and Turbulent flows. We have seen that heat transfers is higher for a thin boundary layer than a thick boundary layer as the temperature gradient of this leaves higher for a thin boundary layer, and the buffer between the solid surface and the free stream is lower in a thinner boundary layer, and heat transfers in a turbulent bound layer is higher than that of a laminar boundary layer, and this is also coming from the fact that we can see that it, then we actually defined what is known as a turbulent Prandtl number for Turbulent flows which is quite difference from the conventional Prandtl number.

And heat transfer in thin viscous region near the stagnation point of leading edge is very high, and in this region's, the velocity and temperature gradients are extremely high and that result in extremely high levels of heat transfer especially in the regions close to the stagnation point, and that explains why we have seen the high level of heat transfer taking close to the stagnation point. In fact, the maximum heat transfer actually takes place near the stagnation point, and as the flow progresses from the stagnation point to the training edge, the level of heat transfer also changes depending upon the nature of the flow itself, and that of course possesses a lot of challenge for the, the, blade cooling designers would like to place cooling holes at different location on the blade surface. So, how does one decide these cooling whole locations.

One is of course, if you look at a very steady state flow, it probably is easier to estimate the cooling whole distribution for such a flow, but as we have seen, turbine blade flows are extremely unsteady with lot of turbulent fluctuations, and because of the coupling between the velocity field and temperature field, there is a substantial variation in the temperature flow, in temperature field around a turbine blade and that is essentially not steady and one cannot really take up a steady state analysis of a turbine blade to determine the cooling blade hole distributions.

And that is where the challenge lies designing an optimum cooling blade distribution for two reason, because one requires an substantially high amount of cooling mass flow that is required in cooling a turbine blade. Modern turbine one might has use as highest twenty percent of the compressor mass flow for cooling Turbine blades, and this mass flow; obviously, does not result in much thrust because it is not really contributing to the overall pressure rise of the engine, and, and, therefore, that is a certain amount of mass flow which is not really contributing to work output. The second reason is that this cooling mass flow also interferes with aero dynamics of a turbulent flow and that can lead to substantial losses.

So, on one hand, we would like to employee cooling methods to enable us to use higher turbine inlet temperature. On the other hand, the cooling methods also lead to loss in performance of the turbine in terms of increase in losses. As a result of a cooler mass flow interacting with the hot combustion flow which is there in the turbine, and so, it can lead to problem in terms of the aero dynamics of the turbine itself, and that is where I emphasize the fact that blade cooling continuous to be a very active vary of research because one would there is still enough scope for improving the cooling methodologies which are used. To ensure than, one can minimize the amount of compressor mass flow that is used for cooling and also ensure for cooling that monitor of compressor mass flow, that is used for cooling and else ensure that cooling mass flow does not adversely affect of the aero dynamics of the turbine blades and does not really affect the turbine blade efficiency.

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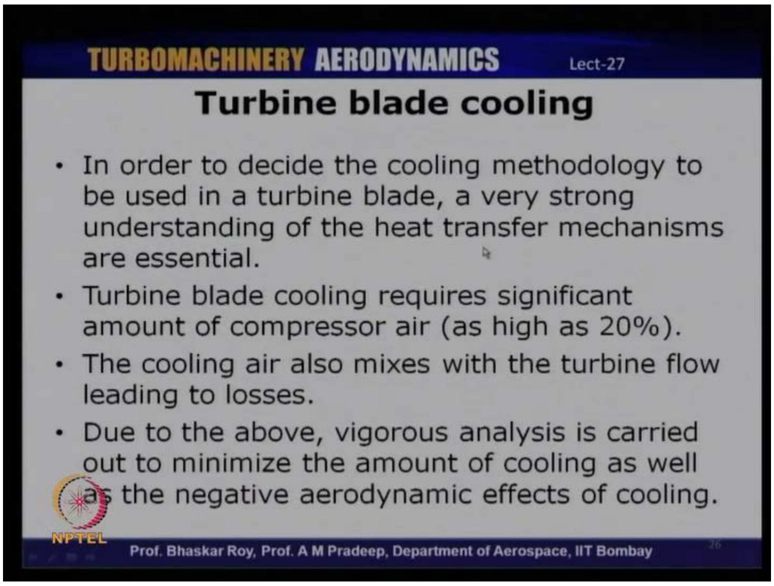

So, just to summarize the various points regarding with reference to blade cooling methods, needless to say of very strong understanding of the heat transfer mechanisms is essential because cooling a turbine blade is essential heat transfer problem, of course, there is also strong coupling of heat transfer with the fluid mechanics here.

Turbine blade cooling obviously requires the significant amount of compressor layer which might firstly lead to losses in the turbine leading to poor a lower efficiency of the turbine, and also it leads to a loss in overall loss in thrust, but that of course, is compensated by the fact that you can actually a get higher turbine inlet temperature with cooling probably that kind of compensates, but the effect of cooling on the aero dynamic performance is something that will need a greater attention and analysis to be able to achieve have cooling methodology which does not significantly affect the turbine performance.

Let me just conclude today’s lecture with an overview of what we are discussed. We had discussed about two distinct aspects of turbine blade cooling. We began our lecture here with an overview of wide turbine cooling is required, and what is the significance of turbine blade cooling and why I said that one needs to employee elaborate methods of cooling a turbine blade.

We also had very quick overview of the heat transfer Fundamentals which are required in analysis of turbine blade and some of the concepts which are used in turbine blade cooling analysis. So, we will be continuing discussion on turbine blade cooling and also the different types of turbine blade cooling methods which are used in modern day gas turbine engines and this, these topics of course we will be taken up for discussion in the next lecture.