Jet Aircraft Propulsion

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Lecture No. # 20

Axial Flow Turbines; Turbine Blade 2-D (cascade) analysis

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We are now talking about compressors and turbines, you have undergone a number of lectures on various aspects of thermodynamics, their cycle analysis and over the last few lectures you have been exposed to number of aerodynamic issues related to compressors. From today's lecture we will start issues, related to the aerothermodynamics of turbines. Now, we know that compressors and turbine, both are essentially aerodynamic machines. They essentially operate on number of aerodynamic or gas dynamic laws and laws of motions and of course, thermodynamics. Now, all of them put together create these machines help us create these machines which work turbines create work to run the compressors and compressors of course, work to create the compression which is required for operation of a jet engine.

So, today we will look at how the turbines actually perform? How they create work? What are the fundamental mechanisms, the aerodynamic mechanisms based on which turbines perform? And how exactly their performance is a quantified through various parameters? And of course, we know that the turbines in flight compressors use blades, use aerofoil sections to do the work and we will look at some of these issues related to turbine blades, blade section, the aerofoil sections and some of these issues are what we will be discussing over a period of next couple of lectures.

So today, we will do the fundamental issues related to working of gas turbine. The issues related to gas turbines as I just mentioned essentially pertain to aerodynamics of gas turbine the thermodynamics of gas turbine and in, so far as the fire that the flow is coming from combustion chamber. Now, the flow that is coming from combustion chamber is hot it is already compressed by the compressor to high pressure. So, it s high pressure and high temperature and that gas is now being released on the turbine with very high internal energy level.

So, the pressure and temperature that is contained in the gas essentially in the form of internal energy or what we can call potential energy and with this high potential energy gas is now released on to the turbine and that is how the gas turbines start operating with gas coming from combustion chamber. So, that is the general jet engine layout which we have done before and of course, you have done the basic thermodynamics in the cycle analysis now let us takes a look at how the turbines actually work? And what are the fundamental concepts of working of a turbine.

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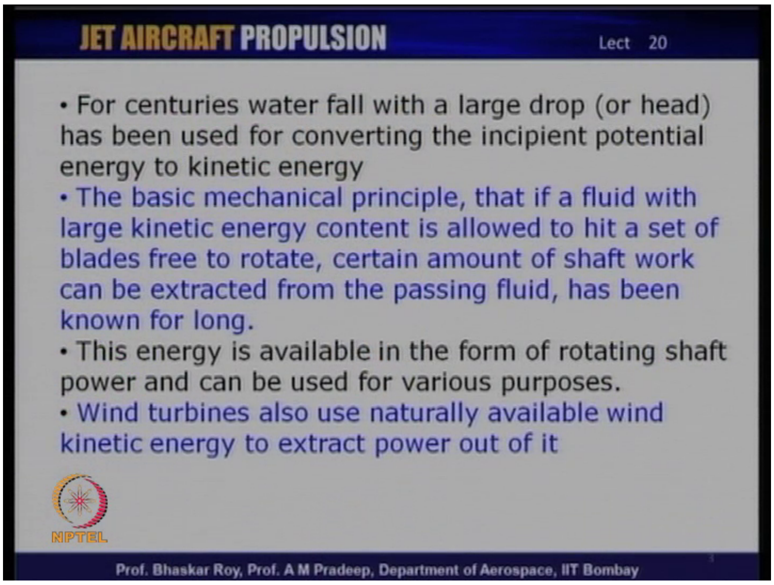

While you see, over a period of hundreds of years really the turbines work in a fashion that require the fluid to come with a high potential energy and then, there is a mechanism by which this high potential energy is converted to kinetic energy. Now, the concept of working of turbine is that: if this fluid or gas with large kinetic energy is allowed to hit or impinge on a set of blades, which are left free to rotate then the blades would do work they will rotate as they are free to rotate. As a result of which certain amount of shaft work or shaft power can be extracted from this passing fluid or gas. Now, this is something which is been known for a long time, because based on this concept people have been using making water turbines, wind turbines for many centuries now and the concept is fundamentally same that the potential energy that is available is often released for the working of turbine.

Now, in case of let us say hydraulic or water turbine quite often you would be looking for a water fall and if there is no water fall, you would need to create a water fall or a dam. To create the large head or drop that is required to create the kinetic energy of the water, which then hits the turbine and makes the turbine work. Now, same thing is true for wind turbines, where you have naturally available wind speed and that naturally available wind speed is made to pass through the turbine blades and then the blades are designed in such a manner. That the passing wind actually transfer certain amount of energy on to those blades, which are again free to rotate and then these rotating blades create power which can now be harnessed for any kind of work.

Now, these two kinds of turbines: water turbine and the wind turbine have been in operation for centuries now. So, the concept of how to harness a work out of a passing fluid with a certain amount of energy contained in it is known and this fundamental principle has been now used for gas turbines; however, we will see that in gas turbine these things need to be done with far greater intend and for greater accuracy and that is what we will be discussing over the course of this lecture.

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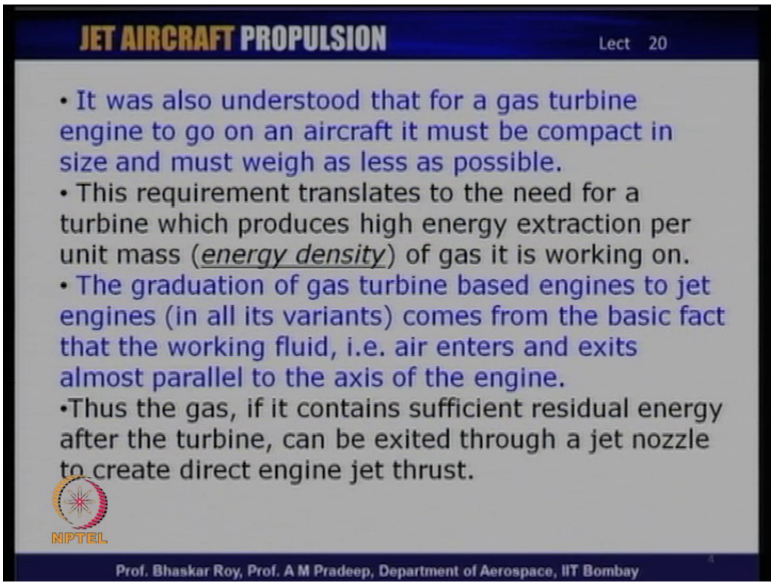

So, let us take a look at, how this can be done in a gas turbine. Now, for a gas turbine to work and that to go on an aircraft engine, it must be very compact in size and must have as less a weight as possible. Now this means, that in terms of the working of the turbine it must have very high energy extraction per unit mass flow. Now, we see that the air is flowing over the gas is flowing over the turbines and energy is extracted from it. What we need to do is create gas turbines which have very high energy extraction capability per unit mass flow and this is often in some books referred to as energy density extraction capability.

We shall see how this can be done in gas turbines that have to go on an aircraft. So, that they are small and compact and still produce a very large amount of power. You have already been told that one turbine can produce sufficient power to run a number of compressor stages and we will try to see how that is indeed actually done. Now, this requires that as we have discussed in the last slide that the gas turbines, which have to produce this high power then would need to be fed with gas; with very high kinetic energy. This kinetic energy has to be created, because the flow that is coming from combustion chamber is indeed at very high potential energy of pressure and temperature, but it still does not have the high kinetic energy. So, that is one thing that needs to be created, the another issue is in a gas turbine engine, which goes on an aircraft or a jet engine the flow remains, essentially parallel to the axis of the engine or axial flow.

So, this kind of gas turbine is referred to as axial flow turbine and the flow going into the turbine also comes out of the turbine, more or less axially and then goes into a nozzle which creates the jet and that creates a thrust of the jet engine.

So, one of the issues is that the axial turbine operates with air coming in axially exists, axially and is released or delivered to the nozzle axially. So, we need to perform everything keeping in mind that the flow would indeed be more or less axial. Of course, we shall see very soon that as the flow gets into the turbine, it indeed cannot really remain axial it has to get into the blade it has to turn, to the blade and then it has to perform the work. So, a large amount of turning would be required to be axially executed and hence it cannot really remain axial, what it means is that the flow going through the turbine would essentially remain parallel to the axis of the engine. So, in that sense it can be kept more or less axial, but in that particular plane it will execute a number of turns and that is essentially a requirement for operation of the turbines.

So, we will see that when we put in the blades to actually do the work, the flow will have to execute non axial path through these blades. Now, let us take a look at what can be called a fundamental turbine unit.

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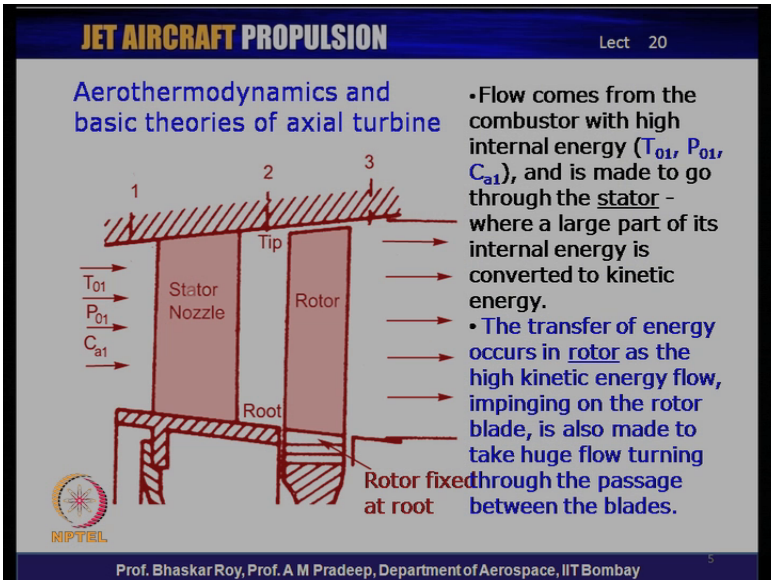

Now, we have done the fundamental thermodynamics of these kinds of units before, Let us take a look at: how it works, essentially aerodynamically or gas dynamically and some are at the back there will be always a little bit of thermodynamic. So, quite often many people would like to call it, aerothermodynamics of a flow through turbines or indeed flow through compressors and turbines. Now, what is happening here is the flow is coming from the combustion chamber, combustor with very high temperature, very high pressure and not so high velocity in a combustion chamber. As you probably have some idea, we will be doing it in detail later on operates with rather low velocities for the sake of stability of the combustion process and hence it delivers the flow through the combustion chamber to the turbine with somewhat modest velocity with which it now enters the turbine.

Now, as we have just seen that it has very high internal energy, very high potential energy, but it does not have very high kinetic energy which means that; we need to create the kinetic energy before the old fashion concept of turbine working can be executed. So, rotor of course, if the unit which will do the work in the old fashion concept of turbine doing work, but we need to create a high velocity jet to impinge on this rotor as it is done. Let us say it for centuries, in a water turbine or it is available to wind turbines. Now, this jet needs to be created artificially inside the axial turbine; it is not available naturally. So, the stator are often referred to also as a nozzle is there to create this high velocity jet artificially inside the turbine body before it hits the rotor.

So, this internal energy is to be converted to kinetic energy inside the stator nozzle, we call it stator because it is stationary row of blade. So, we will see that they are made of also of aerofoil sections, they are also called nozzles because this is a flow through them is essentially a through a nozzle kind of passage, which means there is a huge conversion of this potential energy. High potential energy to high kinetic energy and that high kinetic energy is then a made to impinge on the rotor for doing the work. As we have just seen the rotor has do a large amount of work to probably run a number of compressor stages and we can do that large amount of work only if the flow is impinging on the rotor with very high kinetic energy.

So, creation of kinetic energy is a crucial element in the operation of turbine and in creation of high amount of work through this rotor now this transfer of energy from the gas to the rotor occurs through the blades of the rotor and then this high kinetic energy as it passes through the rotor. It is also made to take a huge flow turning. So, there are two important issues here: one is the high kinetic energy that is to be created inside the stator nozzle; another issue is creating a high turning flow inside the rotor. So, we have to have a high kinetic energy creation inside the stator nozzle and then the rotor must allow the flow to take a huge flow turning through its own passages for doing the work.

Now, both of these need to be done very efficiently and this is what is crucial to the operation of high work output of gas turbine engines and this is what is a crucial issue that if you can do that you have a gas turbine engine or axial flow turbine that then goes into an aircraft fulfilling, the needs of requirement of an aircraft jet engine.

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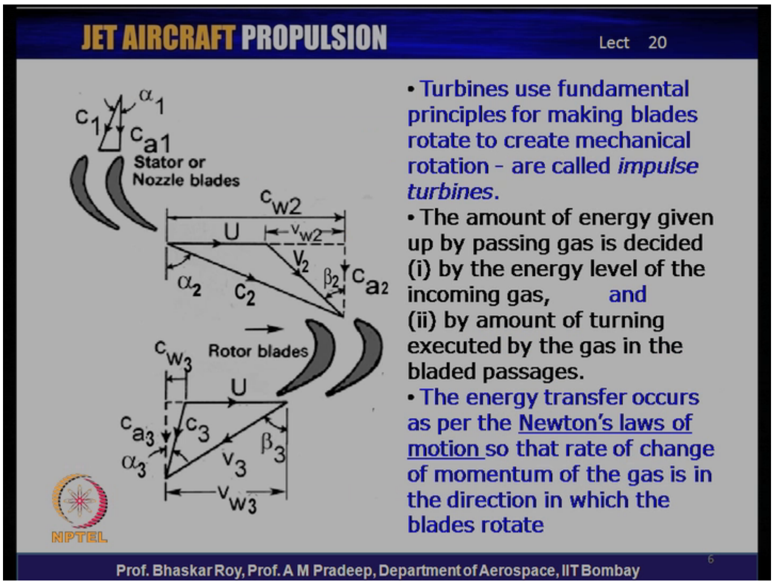

Let us go forward and take a look at; how this kind of turbine indeed tries to work? Now, what we are doing? Here is something you may have done already in the course of your lecture through the compressors that we are looking at what is known as a cascade picture of a turbine. In which one particular section of the turbine, let us say the reference or the midsection of the turbine is been viewed at on a sectional basis. Now, what is happening here is that the flow is coming from the combustion chamber as we just saw with a modest velocity c a 1. Let us say and it may have or may not have a small angle alpha 1 depending on how the flow is been released from the combustion chamber.

And depending on that, the stator or nozzle blades are set there or positioned there and the passage between this stator or nozzle blades is indeed a highly converging passage, which of course creates the nozzle effect; very strong nozzle effect. This is crucial, as we just mentioned that we need to create a situation, where by the incoming velocity C 1 is hugely accelerated to a high velocity, C 2 as it is coming out of these stator nozzles. This will of course, be coming out at a different angle that is alpha 2 and then this high velocity jet is to be then released on to the rotor. Now as soon as the rotor starts rotating, let us say it has reached its full rotating speed as and when it has reached its full rotating speed it will acquire a tangential or rotating speed of U.

Now, if we have the vector diagram here of the C 2 and U put together, what happens is a result in velocity V 2 is created artificially, which is what is impinging on the rotor. This is now at an angle beta 2 with respect to again the axial direction and with this angle the flow is now impinging on the rotor which means, that the rotor would have to be set at this angle; that means, a rotor leading edge would have to be set in such a way that it accommodates the incoming flow V 2 into the rotor. So, notice here that the C 2 velocity at an angle alpha 2, which will release from the stator nozzle, is not the velocity that is indeed impinging on the rotor. What is impinging on the rotor is the velocity V2 at an angle beta 2? And that is what the rotor would indeed feel rotor would never feel the velocity C 2 at angle alpha 2. It will only feel the velocity V 2 at an angle beta 2.

So, it is necessary that this velocity is what the rotor accommodates. The rotor blades, we see here a cut or a section of the rotor blades, the aerofoil sections of a particular cut of a rotor blade and that is indeed set or positioned or set at a state stager angle, which accommodates the incoming of this flow velocity V 2 into the rotor. Then this rotor makes the flow to take a huge turn this turning is quite often very large and then this is what we talked about, this is crucial to the working of the turbine. It lets the flow go at a velocity V 3 at an angle beta 3 and this is the exit velocity from the rotor. Now, what happens is, if the rotor essentially is involved in making the blades rotate simply by the virtue of turning of the flow from beta 2 to beta 3 and during this process, there is no change in the velocity V 2 to V3 this kind of blade is simply refer to as impulse turbine.

That means, the flow is simply taking a turn through these rotors and as a result of this turning as per Newton's laws, it imparts certain amount of energy from the gas onto the rotor, which we saw is free to rotate and this free to rotate blade, then way the energy from the passing gas and converts this energy to mechanical rotating work. Now, if that is so, then this kind of turbine is simply referred to as impulse turbine and as I mentioned earlier over the years this mechanism has been used in working of turbines, notably the water turbines or hydraulic turbines. So, most of the hydraulic turbines work on the principle of impulse turbines, because there the water is incompressible fluid. So, it can only take a large turn through these rotors and give up the energy for the rotation of the rotor blades.

Now, the amount of energy this is important here especially in case of aircraft gas turbine engines, the amount of energy given up by passing gas is decided by the energy level of the incoming gas. So, we need to have very high energy level coming from the combustion chamber. It is also decided by the turning executed by the flowing gas in the blades. So, we have to make sure that its coming in with a very high energy level and that is at the station before the stator nozzle and only if it has very high energy level, it can execute a very high expansion or acceleration through the stator and nozzle blades to create this high velocity jet C 2.

So, that is crucial to the operation of high working gas turbines. Now, the energy transfer that occurs in the rotor is as per the Newton's laws of motion. So, that the rate of change of momentum of the gas is in the lateral direction or we may say is the rate of change of angular momentum that occurs inside the rotor. Now, this occurs in the rotating direction or the lateral direction or the direction in which the blades are free to rotate. You see the blades are free to rotate in nearly one direction and we have to ensure that the blades accommodate the gases and allow the gasses to pass through them in such a manner, that the rate of change of angular momentum occur in a particular direction and this direction is pre decided by the design of the turbine blades.

We have to ensure that the release of the energy from the gas to the rotor occur in a direction in which the blades are indeed free to rotate. This is crucial and very important for working of the turbines; if we can do that then we have the work extraction performed by the rotor from the passing gases. We see here now in this diagram that as the flow comes out it comes out with velocity V 3, which has a whirl component or tangential component V W 3 it is coming in with a tangential component V W 2 and we shall see that the flow which came out of the stator had a velocity C 2 which itself has a tangential or whirl component of C W 2 as the flow comes out of the rotor, it now has a very small whirl component C W 3 and an angle alpha three which makes the flow nearly axial all over again and that is why we would like to call it an axial turbine.

So, it comes in with a very small angle or almost axial direction and it goes out with a very small angle to the axial or nearly axial direction and hence we can conform to the name that it s an axial turbine. So, that the flow comes in and goes out nearly axial. We shall see later on very soon that just as you had seen in case of compressor these whirl components C W 2, C W 3 and indeed V W 2 and V W 3 have a crucial role to play in quantifying the amount of work that is being done by this rotor and we shall write them down in a few minutes from now.

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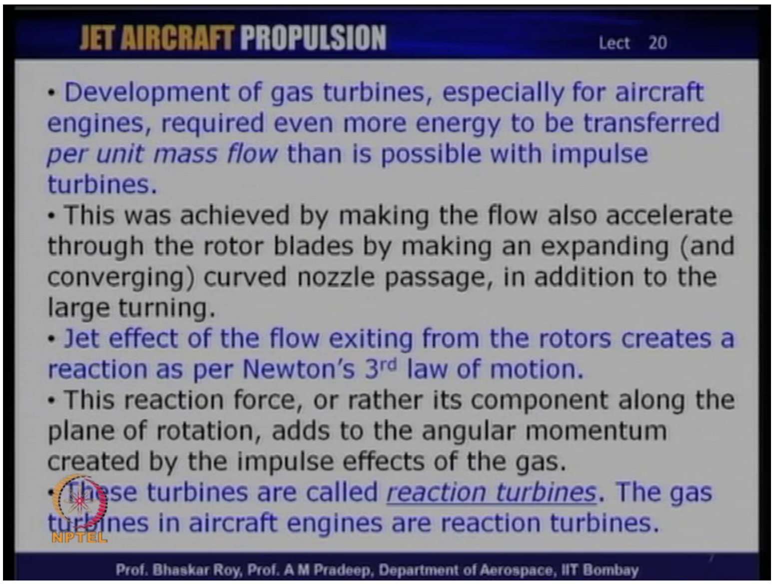

Let us quickly summarize what is happening here, the development of gas turbines especially in aircraft gas turbines it requires very large energy transfer through the rotor per unit mass flow. Now, this is normally a requirement for aircraft gas turbine and this is much more than what a typical impulse turbine can do. Now, which means that the requirement of aircraft gas turbine is more than that of what a normal impulse turbine would be able to do through with the same gas if you have the same gas with the same potential energy coming in impulse turbine can do so much?

Anything more than that you have to go beyond the capability of a normal impulse turbine and that is what is indeed required in a typical aircraft gas turbine. Now, this is done by making the flow also accelerate again through the rotors. We have also seen that it accelerates a lot through the stator that is of course, to create that high velocity jet impinging on the rotor. Now, what we are trying to do is make it accelerate more through the rotors by expanding it or through the converging nozzle passage through the rotors in addition to the large turning.

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Let's go back to the diagram quickly the flow is now coming into the rotor, it has already executed a large acceleration flow is come out with C 2 and it has a large velocity V 2 which as you will see is much larger than C 1 and with this fairly large velocity it is coming into the rotor.

Now, of course, normally you would see V 2 would be a little lesser than C 2. So, which means that the V 2 is now a quantifiably in terms of actual value lower than C 2 with which it is now going into the rotor? Now, what we propose is that through the rotor it goes through another round of acceleration. It is expanded again from V 2 to V 3. So, V 3 is larger than V 2 and as a result of this acceleration the flow comes out of the rotor with a nozzle effect. Now, as we know from Newton's laws of motion anything that has an accelerating flow through a nozzle creates a reaction. Now, this reaction is now felt on the body of the rotor and the reaction now creates a reaction force, which if we say has a component in the direction of the rotor movement or the rotation; that means, in the lateral direction or the direction in which the rotor is free to rotate then the force is now acting in a direction in which the rotor is free to rotate and this is an additional force in addition to the force that is created by the turning of the fluid now.

Turning of the fluid as per again Newton's laws of motion gives you the force that creates the basic force or the impulse force and that is why it is called impulse turbine. That impulse force makes the turbine rotate to begin with and then the reaction force is the additional force that is now available by virtue of acceleration through the rotor. So, we have two forces now acting on the rotor the impulse force due to the turning of the fluid through the turbines; the reaction force due to acceleration of flow through the turbines and two of them together create, what is known as reaction turbines.

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So, all the aircraft gas turbines are indeed reaction turbines and these reaction turbines now operate in conjunction with the impulse action and as result of which the jet affect that is exiting from the rotor is a creation of this reaction. The whole thing is operating as per Newton's law: third law of motion, we have seen that the rotor operates as per Newton's first and second law of motion and now we have the Newton's third law of motion also in addition available to us for creating an additional force called a reaction force.

This reaction force are the component of the reaction force along the plane of rotation adds to the angular momentum, that we have talked about earlier, which is what we call earlier the impulse force and these turbines, hence are called reaction turbines. All gas turbines in air craft engines are indeed reaction turbines, because we desperately need these turbines to create a lot of work per unit mass flow and that is why we need to have reaction turbines just impulse turbines would not do we need to have more work done out of these turbines to meet the requirements of a compact and light weight gas turbine inside an aircraft.

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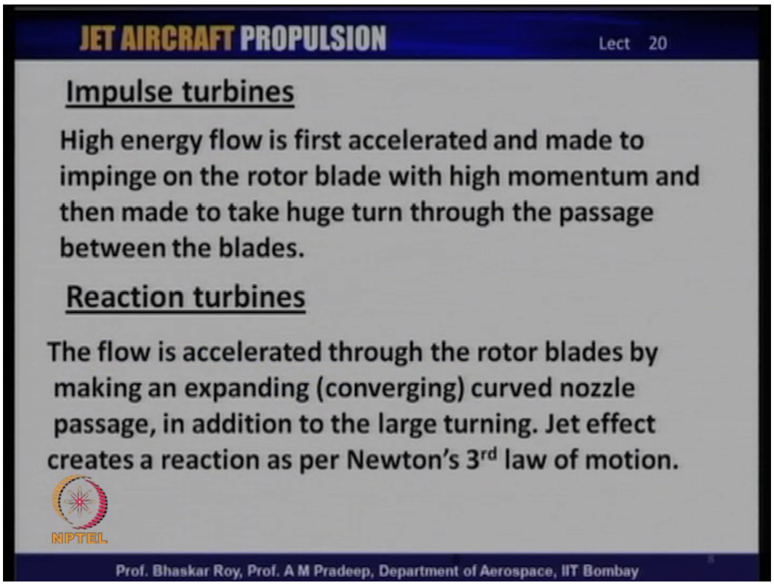

Hence, we have two kinds of turbines: the impulse turbines, in which the high energy flow is accelerated and made to impinge on the rotor blade with initially high momentum and then it takes a huge turn through the passages which are created between the blades. The aero foils create the passage and then we the impulse action; the reaction turbines on the other hand not only take a huge turn but, in addition they execute a large acceleration through this converging curved nozzle.

So, we have this curved passage through which the flow of course, takes a huge turn, but they are not only hugely curved they are also converging passages and as a result of that we have a jet effect that is created by these nozzles rotating nozzles really and then we get the reaction in rotation and then the reaction of course, creates a reaction force as per the Newton's third law of motion and hence we have reaction turbines.

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Let us take a look at the diagram all over again. The reaction turbines that we know now as a post impulse turbines, where the V 2 is equal to V 3.In reaction turbines V 3 is more than V 2 and that is crucial to the operation of reaction turbines; obviously, it stands to reason more V 3 in comparison to V 2 we have more of reaction.

So, how much reaction is dependent on how much more is V 3 compared to V 2, which means how much of acceleration you can indeed execute in between the passage of two blades and that is what creates the reaction. In air craft gas turbines typically the exit Mach number form the stator nozzle m 2 that is corresponding to c 2 is pretty close to one indeed, its deliberately made pretty close to one which means the flow coming out of the stator nozzle has as actually has gone sonic.

In gas dynamics, you would say that the stator nozzle has gone chocking. So, quite most of the time an aircraft engine, when it is operational the stator nozzles specifically the first stage of the turbine in a multi stage turbine the stator nozzle almost invariably would be chocked, which means the c 2 would be equal to the local sonic speed. Hence local m 2 would indeed be 1. On the other hand the relative exit Mach number from the rotor that is m 3 relative corresponding to V 3 is indeed going to be a little less than 1 is deliberately kept subsonic. Essentially, to avoid the shock related issues moment, you are allowed flow to go sonic you are likely to have shocks around the blades.

Now, when you have shocks around the blades the trailing edges of these blades are curved quite often. They are not very sharp and as a result of which you have literally shocks flying around. Now, rotor is a rotating body now, if you have shock at the rotor trailing edge the whole rotor would be rotating with the shocks attached to the trailing edge. Now, that is not a very desirable phenomenon both in terms of the efficiency of the rotor as well as in terms of various other disturbances that the flow would be experiencing, because the flow would be delivered later on to the next turbine or to the nozzle. It is not a good idea to deliver flow with lot of disturbances.

So, the rotors most of the rotors even as of today are indeed deliberately kept subsonic, which means the flow coming out of the rotor is still very much subsonic expect that the velocity V 3 is more than the velocity V 2 both of which now are subsonic. So, in the process of this velocity vector that you see here the flow c 2, we have just seen has gone sonic it may be you know after living the stator. It may be slightly supersonic, but the velocity V 2 is actually subsonic and this conversion happens due to this vector diagram here that c 2 gets converted a supersonic or definitely a sonic c 2 gets very naturally converted to a subsonic V 2 with which the flow is going into the rotor.

So, this conversion happens very naturally by virtue of the vector diagram or the vector transference that occurs through this velocity diagram and the flow coming out here is V 3 the c 3 here is again purely subsonic the flow normally is kept subsonic through the turbines essentially. As, I mentioned to avoid shocks and remember, if you have a multi stage turbine as we shall see later on this flow is going into the next turbine again with lot of potential energy and hence it is necessary that you try to keep the losses down because shocks are associated with losses.

Now, we see here that the work done in a gas turbine is fundamentally dependent on the potential energy with which the flow is coming into the turbine. Now, the potential energy is partly dependent on the pressurization created by the compressor and it is partly dependent on the temperature created by the combustion chamber. Now, pressurization of course, is a business of compressor and that will be dealt with separately the question of combustion chamber creating temperature is a crucial, because higher the temperature higher is the potential energy assuming that it already have sufficient pressure. Now to create high temperature, you have to burn more fuel or you have to have a bigger combustion chamber. Now, if you create higher and higher temperature it is necessary that the turbines with stand the temperature.

Now, we understand that if it has higher temperature inlet temperature it will produce more work that stands to the thermo dynamic that we have done it stands to the fundamentals that we are discussing right now and we shall see later on that if you create high temperature,it can indeed do more work and we shall see later on that to do that you need to probably create cool turbines. We see that some fundamental issues, you can get a lot of work out of one stage of turbine and indeed one rotor of a turbine; if you take care to do a few things carefully; that means, you create a reaction turbine you create expanding nozzle or a converging nozzle in the first in the stator and then again in the rotor which is rotating and then of course, you are allowing flow to come into the turbine with high temperature in addition to high pressure; if you do all that you can have turbine, which can do a lot of work in one single rotor.

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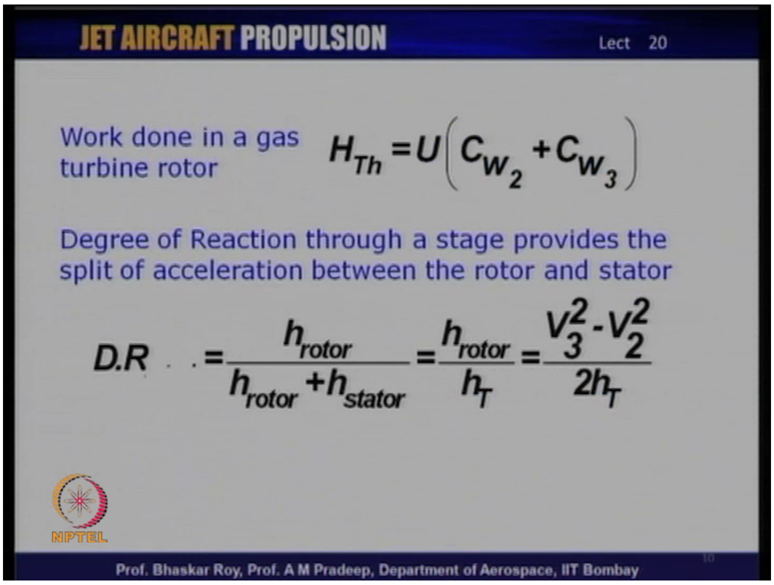

Let us try to quantify the work that these people can do the turbines; can do the work done in a gas turbine rotor; can be simply written down as U into C W 2 plus C W 3, U of course, is the rotating speed of the turbine at a particular section as we have just seen and C W 2 and C W 3 are the tangential velocity components or the whirl velocity components of the flow coming in and exiting from the rotor. Just, let us have a quick look at the diagram all over again, C W 2 is indeed the velocity with which the flow is coming into the rotor and we called it the absolute tangential velocity component in so far as c 2 is the absolute velocity with, which the flow is coming in and it is going out with absolute velocity c 3 and the absolute tangential component C W 3.

So, those are the two absolute components which are measurable components going in and coming out of the rotor the virtual or the relative components are the V 2 and V W 2, V 3 and V W 3 those are the velocity components felt by the rotating blades, but you cannot measure them with the help of any probes. If you put them inside the turbines, because what you would be measuring indeed are the values c 2 and C W 2 and c 3 and C W 3, because those are with reference to the stationary bodies of the rotor. We use those components which are measurable components and which are easily referred to the stationary components of the engine and not the virtual or the relative components which are understood by the designers h but, they are not easily measurable quantity.

So, we express them in terms of the measurable quantities indeed, you can express them in terms of the relative components also. In fact, if you replace C W 2 plus C W 3 with V W 2 plus V W 3 you would numerically get exactly the same amount.

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So, they are replaceable quantities, U is the speed with which that particular blade section. We looked at is rotating U indeed is omega r, r being the radius of this particular section from the axis of rotation of the entire rotor which

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we had looked at earlier this rotor and if you take r from the axis of rotation any section or a mid section that you are taking would have a rotating speed U which is omega into r omega b in the angular velocity of this rotor and r is the station or radius station at which this particular section we are looking at is rotating hence we can say that U is representative of this particular section and it stands to reason that U is variable from the route of the rotor to the tip of the rotor indeed this entire velocity diagram vector diagram that we are looking at is variable from the route of the rotor to the tip of the rotor.

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You need to reconstruct them every time you are looking at any section of the rotor or stator or the whole stage from the route to the tip of the stage. Now, let us take a look at the other important parameter that we have looked at the degree of reaction which is often used to essentially split the acceleration between the rotor and the stator we have just seen that we like to have acceleration split between the rotor and the stator and this is often qualified through this degree of reaction.

Now, what you can do is if you if you can quantify then you know how much acceleration you can do in your rotor and how much acceleration you need to do in a stator in the stator we have seen that we need to accelerate to the extent that the flow goes sonic at the exit of the stator and then we can do a lot more acceleration in the rotor all over again and this differential tells us how much of the potential energy is convertible through the whole stage. we saw that auto fit is converted in the stator and then we saw the part of it is also convertible in the rotor. Typically in a reaction turbine any impulse turbine of course, it is not converted in the rotor is done only in the stator.

So, the split of acceleration or conversion of potential energy to kinetic energy is done through this degree of reaction parameter and typically the degree of reaction values that, we would see later on or indeed much lower than the values that you may have encountered in case of compressors because in compressors typically much more of this conversion is done in a stator in a in a rotor, where as in a turbine much more of these conversion is normally done in a stator before it comes into the rotor.

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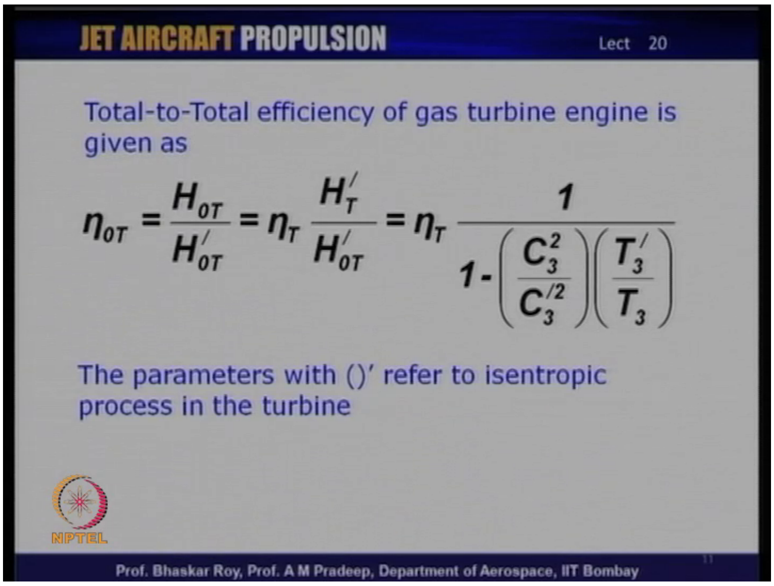

The important parameter that one looks at in case of a typical working of a gas turbine is the total efficiency this is with reference to, so called total parameters. Which we will be talking about or we have talked about a little in case of a when we discussed thermo dynamics of turbines and this is simply the ratio of the actual work done divided by the isentropic or the ideal work done. This is can be also expressed in terms of the static efficiency and the static work done related to the ideal total work done quite often the static efficiency are simply referred to as eta T as suppose to eta 0 T, which is the total efficiency because static efficiency is again easily measurable quantity.

These are expressed in terms of the parameters; we just talked about the C 3 square divided by C 3 Prime Square multiplied by T 3 prime by T 3. Now, these prime parameters that we are mentioning here are all the isentropic parameters; that means, referring to the isentropic process or the ideal process in the turbines. The flow, as it goes through the turbines; if it is assumed that the flows purely isentropic, you would get one value of T 3 prime and correspondingly you will get a value of C 3 prime, where as in a real process. You would get a values c 3 which is different from c 3 prime and you would get a prime T 3 which is different from T 3 prime. So, these parameters are referred to the isentropic process and hence we know the total to total efficiency that we are talking about is indeed actually an isentropic efficiency definition, which we have talked about and described earlier in various thermodynamic discussions.

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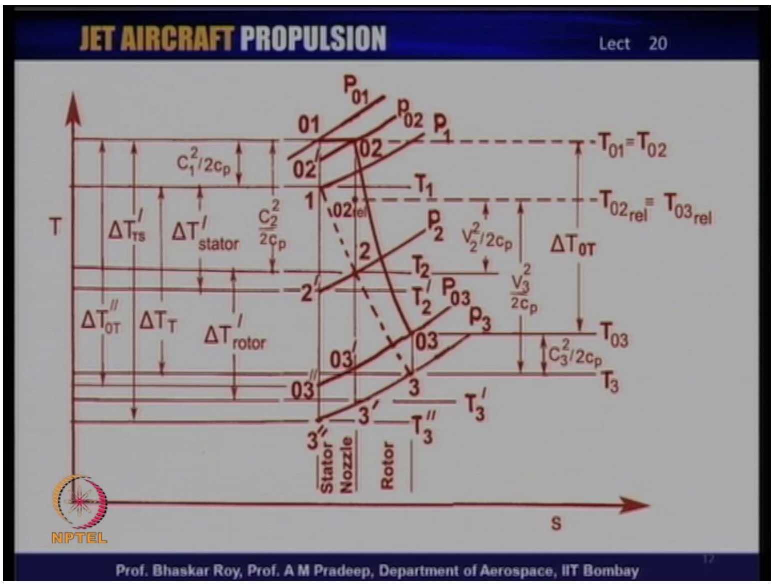

Let us take a quick look at the overall turbine process that can be shown thermodynamically. We know that everything that is happening inside a turbine must correspond to the thermodynamics of the flow, indeed we are talking about aerothermodynamics of flow through the turbines what we see here is flow coming into the stator with a velocity c 1 and that is the kinetic head it has then it goes from 0 1 to 0 2 in the process of which it losses the pressure from P 0 1 to P 0 2 that is the frictional and other losses no work is being done in the stator. So, there is no change of total temperature from 0 1 to 0 2 it simply losses a little pressure from P 0 1 to P 0 2 at 0 2 as we have just seen it has acquired a very high kinetic head.

So, c 2 square is the kinetic head at station 2. So, it is a static parameter 2 is down here and corresponding temperature would be T 2 and then it comes through the rotor to T 3 0 3 where the work is actually performed and it is down here at 0 3, it is at a different pressure. It has lost a lot of pressure in the process of doing work; it has also lost a lot of temperature in the process of doing works.

So, lot of pressure and temperature, potential energy has been given up in the process of doing the work and then this work shows up in the form of temperature differential delta T 0 totals and this is the work that is being done by this turbine in the process of drop in this temperature. It has a very low kinetic energy now; we have no use for very high kinetic energy more. So, it comes out with a modest kinetic energy feel with lower temperature and pressure. So, the exit of the turbine is now, at a not only at a lower temperature and pressure. It also comes out with a modest kinetic energy which is may be of the same order as the kinetic energy with, which it came in we can see the static parameters in terms of at station 0.3 the corresponding isentropic parameters are down all the way vertically down.

If you come down from one you will find 2 prime which is what we call the isentropic drop through the stator. So, through the stator it has come down from 1 to 2 prime. If you take it through the rotor, it comes from 2 to 0 3 prime, if the entire turbine is taken as isentropic. It will come down from 2 prime to 3 double prime or 0 3 double prime. So, if it is vertically coming down all the way that is an isentropic turbine. You can have isentropic rotor, which then only in the rotor it comes from two to 0 3 prime and then of course static parameter at 3 prime.

So, these are the fundamental changes of state that are occurring as it is going through the turbine and you of course, see the corresponding delta T values the isentropic values the real values this is the static parameter change that is occurring, this is the isentropic parameter change that is occurring. So, these are the change that is occurring first through the stator nozzle and then through the rotor the temperature drops, the pressure drops and then the energy is given up in the form of work. That is not shown in this diagram here, it only shows up in the form of loss of temperature or if you cast this diagram in the form of HS diagram. It will show up in the form of drop of enthalpy. So, this is how a typical gas turbine indeed works.

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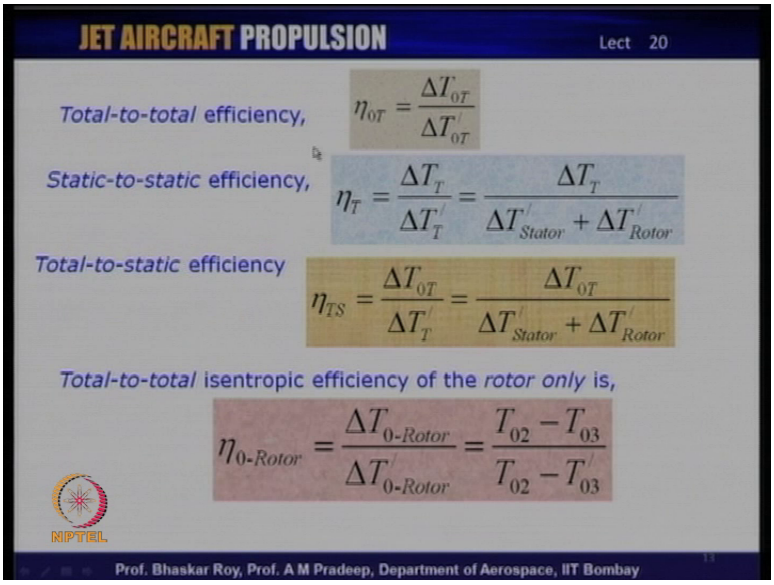

we can quickly now say that, the total to total efficiencies of these turbines can be cast in the form of efficiency parameters in terms of total efficiency drop through the turbine as opposed to the isentropic total efficiency drop. So, the turbine, the static sub, static efficiency is the static temperature drop through the turbine as a pose to the static temperature drop Isentropically through the turbine which is equivalent to static temperature drop through the stator and static temperature drop through the rotor which as you know are connected through the acceleration of the flow through the stator and rotor.

We also have a total to static efficiency definition typically used for turbines, often referred to as eta T S and that is the total temperature drop through the turbine as supposed to the static temperature drop Isentropically through the turbine and as a result of this you have the denominator very similar to the earlier definition but, the numerator here is same as the first efficiency definition. And this is what is indeed shown in the diagram that the drop through the entire isentropic drop is here and that is a large drop and as a result of which you can well imagine that your total to static efficiency value the numerical value will indeed always be lower than the total to total efficiency numerical value, because denominator here is much larger than the denominator over here and the numerators being same.

We can also have a total to static efficiency definition for the rotor only and that of course, is the total temperature drop through the rotor as opposed to the total temperature drop isentropically through the rotor, as again given in the earlier diagram. So, one can define a isentropic efficiency on the basis of total to total parameters for the rotor only

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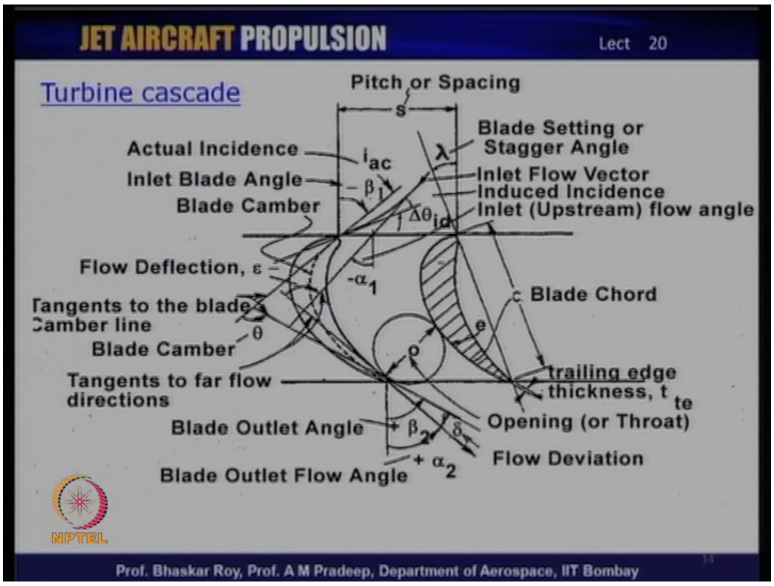

we have a quick summarization of what the turbine cascade would look like; we will come back to this diagram later on again may be, we have the flow coming into the turbine with a certain incidence you have the rotor blades over here and typical turbine cascade would aerofoil; would look something like this. The blade code is defined over here, the flow comes in with a velocity, as we have seen beta 1 and it goes out with a velocity beta 2, the flow often has an incidence of the order of I and it goes out sometimes quite often with a value flow deviation; that means, it does not stick to the flow surface exactly, it slightly goes off the flow surface and goes out with, what can be called a deviation.

All angles that, we have talked about in the earlier vector diagrams are also is shown here. The turning of the flow is executed or created by the blade camber. So, if you want a high turning flow, you have to put in there a blade, which has a very high camber and you have to look for blades, which are of very high camber indeed; that means, that the turbines require very highly cambered blades, which you need to put in there and indeed the turbine aero foils are very different from any aerofoil that you might have seen anywhere else. They are different from the aerofoil that a use in compressors; that are indeed different from any aerofoil used in aircraft anywhere else. So, turbine aero foils are completely different breed of aero foils; different family of aero foils and at some point of time we may have a look at them. So, that is a fundamental exposure to the working of a turbine.

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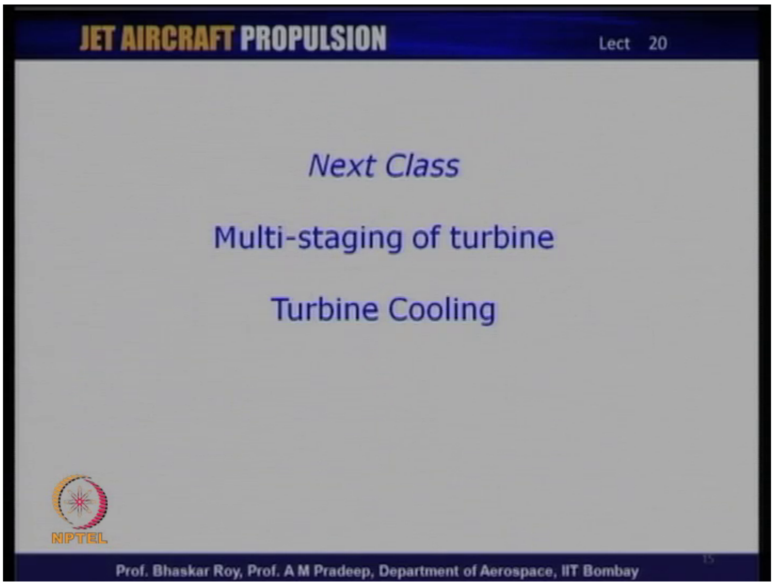

In the next class, we will take a look at: how the turbines operate; the turbine characteristics as a machine and we shall take a look at: how we can multistage this machine to get more and more work done. In the early stages of aircraft, most of the aircraft engines had only one turbine that was sufficient to run the compressor. Today more the aircraft engines bigger the aircraft engines you need more of these turbines and hence we need to have multistage turbines. We shall have a look at: how the multi staging is done and we shall also see, how these turbines if they are to do more and more work they have to encounter higher and higher into temperature, then we need to cool these turbines.

We shall have a quick look at this cooling technology that is employed in the modern aircraft gas turbine engines. So, that they have a reasonable working life otherwise these turbines would not last long. All this, we will do in the next class.