Jet Aircraft Propulsion

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Lecture No. # 22

Radial Turbine Aerodynamics and Thermodynamics; Losses

We are talking about gas turbines; we have done Axial flow turbines in the last lectures. Today, we look at the Radial flow turbines. Now, chronologically the Radial turbines were indeed actually considered for application in aircraft gas turbines even before the Axial flow turbines. The reason is very simple Radial flow turbines the shape and the configuration of it is something very simple. As, we will see in a few minutes, it actually looks a very similar to a centrifugal compressor. Now, centrifugal compressor as you actually appear before the Axial flow compressors, because they were very simple to configure and also the very robust machines.

Similarly, Radial flow turbines are very robust machines and they are very easy to configure. As a result of that they were indeed considered for application even before the Axial flow turbines there is another reason just like centrifugal compressors, the Radial flow turbines have very high energy extraction capability in one single stage. Now, this is attractive simply because in aircraft gas turbines as we have discussed before you need to extract as mass energy per unit mass flow as possible. So, that the amount of work that is to be supplied to compressors can be done in minimum number of stages in the Axial flow turbine or gas Radial flow turbine used in aircraft engines.

Now, Radial flow turbines intrinsically has the capacity to extract a lot of work, whereas in Axial flow turbines that intrinsic capability was lacking to begin with and of course, now-a-days Axial flow turbines as we have seen can have very high energy extraction capability because of the high temperature input into the Axial turbines. Now Radial flow turbines, we will see even without high temperature input high energy gas it can still extract a lot of energy output or unit mass flow because of its intrinsic way the way it performs and the way it is configured. As a result it is a very attractive proposition even today for various gas turbine applications and we will see as we go along that there are certain areas in which Radial flow turbines are indeed, extremely useful and indeed the more preferred form of energy extraction than even compared to Axial flow turbines, especially in small engines.

We shall see that Radial flow turbines has another advantage or one may call it restriction, whichever way one wants to look at it: the Radial flow turbine rotor does not use aero foil sections, now Axial flow turbines use aero foil sections. As a result of which it its shaping is needs to be a very intricate for reproduction of those aero foils sections very accurately whereas, Radial flow turbine does not use any aero foil sections. As a result of which the rotor of Radial flow turbine has a shape as I said very similar to a centrifugal compressor and it uses the 3D shape for energy extraction and this 3D shape of course, is something which is become of great interest in the modern research. Again, as I mention the Radial turbine actually appeared before the Axial turbines, but for a long time they were not considered and most of the development indeed to place with Axial flow turbines.

Recently lot of people have taken a fresh interest in Radial turbines and have tried to give it more and more accurate shapes; 3D shapes and more and more new designs, which renders it is use to various kinds of applications in a modern small gas turbine segments. So, these are various advantages and one can say some restrictions of the use Radial flow turbines. Let us take a look at some of these Radial flow turbine configurations.

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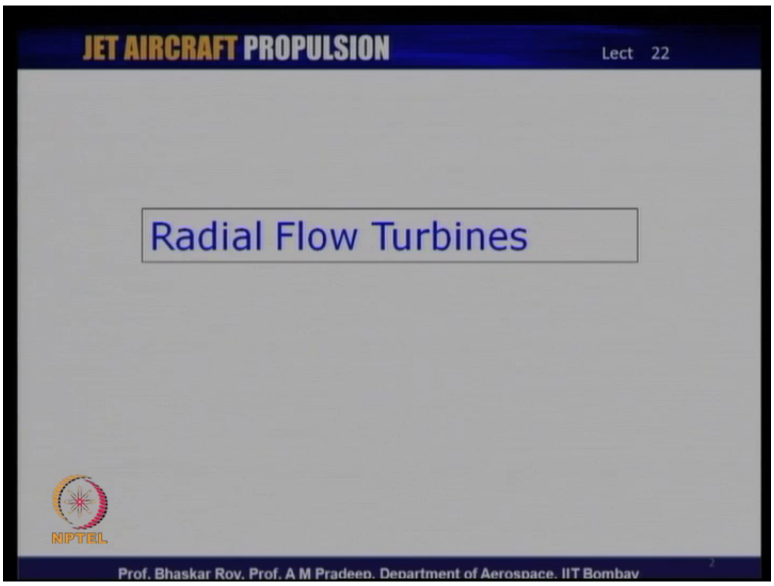

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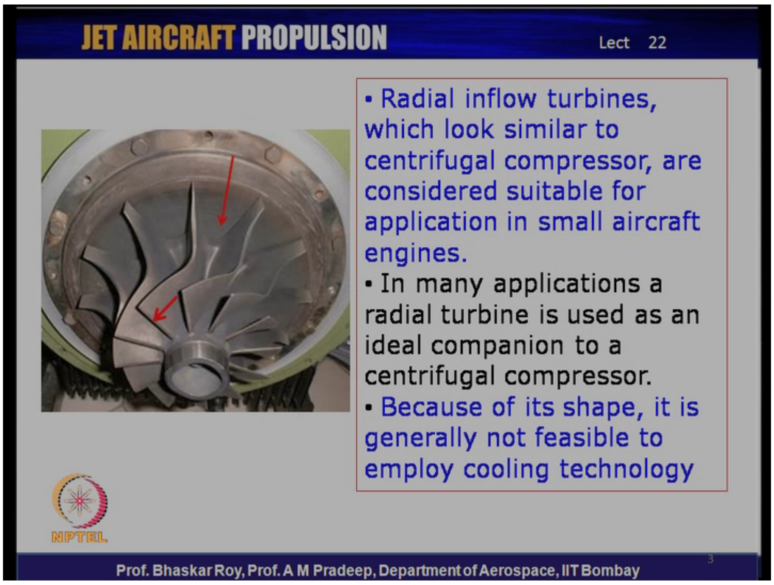

The Radial turbines that one uses can also be considered as some kind of mix flow turbines, if one compares that with, let us say Axial flow turbines there is a chance that. You may like to look at how the flow is actually executing its path to the turbines. Now, through the turbines are Axial flow turbine as we have discussed the flow essentially keeps its path along the line parallel to the axis in Radial flow turbine it quite often takes a path partly to begin with parallel to the axis and then goes out radially and that is why is often called Radial flow turbine.

Now, as I mention it looks very similar to a centrifugal compressor. As result of, which it is able to extract lot of work, just like centrifugal compressor in one single stage. That makes it very attractive for use in small aircraft engines, which means you can have the combination of a centrifugal compressor and a Radial flow turbine and this creates a very compact energy creator for gas turbine engines for aircraft usage. As one see in these diagram, this Radial inflow turbine centrifugal is typically out flow compressor and the flow comes in from the outer segment of the turbine through this volute shaped rotor this is the rotating element or impeller.

Then goes out through the impeller of a executing a rather complicated shape through this veins; this rotating veins and this passage through this veins is what transfers the energy from high energy gas to the rotor. So, transfer change of momentum in the lateral or rotating direction, what actually executes the transfer and the work transfer. Now, this how the work is transferred we will of course, have a look at this in some detail in a few minutes from now. Now, because of the fact that we have a shape here, we is as I mentioned not of aero foil shape and as you can see here the edge of these rotor is likely to be rather thin and not round head like an aero foil. The result is that it is generally considered not feasible; not employee cooling technology. As, we have done in Axial flow turbines in the Radial inflow turbines. There is no space for employing or deploying cooling technology here.

However, lot of research is going on these days to somehow employee cooling technology here. So, that the temperature of the Radial inflow turbines can also be increased in a manner, such that they can actually use high temperature gas from combustion chambers somewhat similar to that of Axial flow turbines. So, some of those things have now gone into research and it is hope that some of it will actually be used in future for Radial inflow turbine designs.

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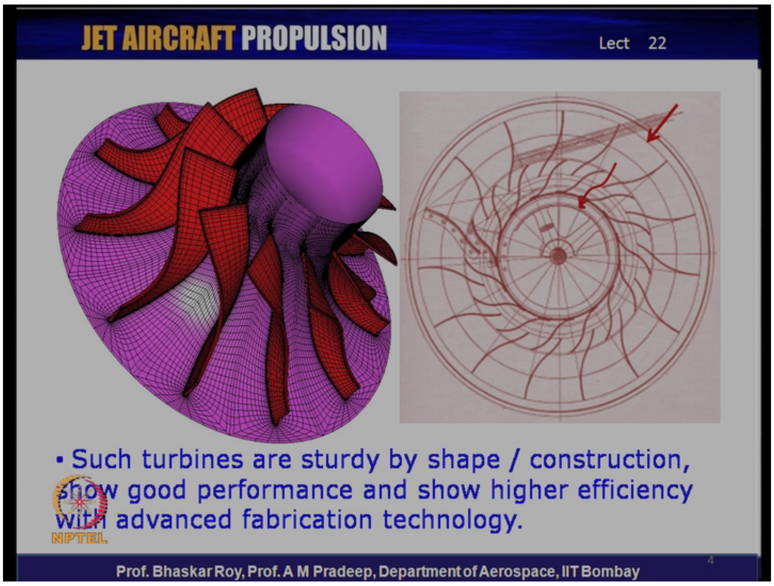

If you take a digital model of a Radial inflow turbine, it is seen that if you have the blades over here as one seen the flow coming through these blades indeed go through a passage. That is actually an expending passage and a result of which the flow comes in through the rotor over here. Then as you can see the passage here is essentially converging passage and then the converging passage takes a curve linear converging passage. So, this straight converging then gives into curve linear passage and then the flow indeed goes out actually. So, in Radial inflow turbine there is every possibility that flow will come in radically and go out actually. This is one of the reasons; why some people may like to call it a mix flow kind of a turbine, because part of the exit flow is indeed again actual.

Now, this something which people would you knows like to look into in more and more modern designs. One can see a digital model of such a Radial flow turbine over here. On the right inside you can see top view of modern Radial flow turbine, in which one can see that the flow is coming in and it is getting into converging passage and then a part of the rotor over here actually is overlapping the outer parts or the inner and outer parts are overlapping. One can see the number of veins in the inner part indeed different. As a result, the flow which is coming from the outer ring or outer rotor, let us say gets often spilt up in two passages and this flow then gets split up in two passage: one coming into this passage; another going into that passage.

As a result of which you have further convergence through the inner part of the rotor and this is one kind of a modern design that people have been trying to develop to extract more work from Radial inflow turbine. As, I mentioned Radial inflow turbines have intrinsically more work extraction capability and this is one way of trying to increase the Radial turbine a work extraction capability in some of the modern designs.

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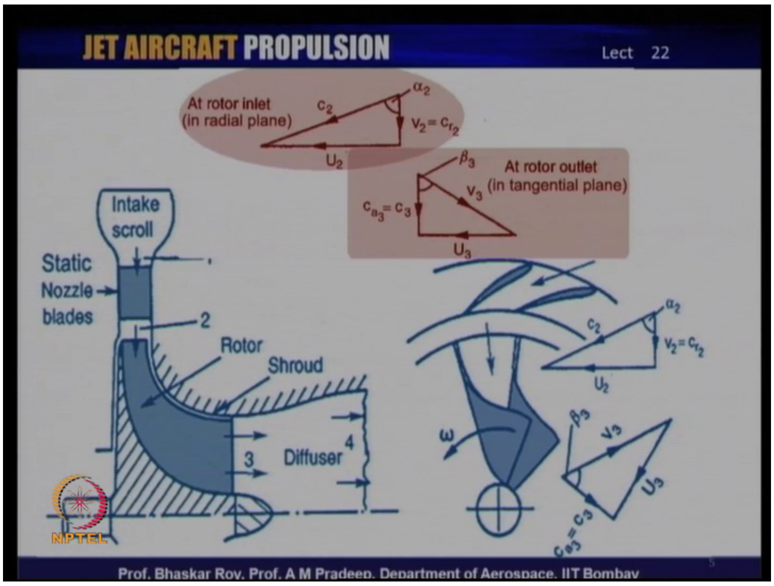

Now, let us take a look at: something of fundamental issues related to Radial turbine. Typically in a Radial turbine, you have a some kind of a collector or scroll whatever, one may like to call it, where flow is coming in. Let us say from the combustion chamber, which are hot gas high pressure gas; high potential gas and then this high potential energy gas is released through the static which is of nozzle stator, which is of nozzle shapes and these are blades. It is possible that these could be made of air fall sections. So, the stator blades or stator nozzle blades could indeed be aero fall section blades. Now the flow here, coming in actually in subjected to again converged passage between the two blades.

So, the passage here is converging and that creates the nozzle effect and then this nozzle effect creates the high velocity exit jet C 2. So, this coming in with small velocity may be small c 1 and it is going out from these nozzles with the very high velocity C 2 and then this c 2 is transform to V 2 which could be Radial going into to this Radial turbine rotor.

So, quite often especially in aircraft gas turbine even to this day the relative velocity V 2 that goes into the rotor could actually be Radial and quite often may be called C r 2 or V r 2 signifying that it is essentially a Radial flow going in the relative frame of the rotor itself. This flow goes through the rotor and as I was mentioning it takes almost a 90 degree turn through this rotor if one looks at this side diagram cutout diagram and comes out more or less actually.

So, when it comes out from the rotor over here it comes out more or less actually and it comes out with a velocity V 3.Now, it goes in with the velocity V 2 over here into the rotor and then it takes a large turn. Then comes out with the velocity V 3 and in a craft gas turbine as we shall see we will see probably that V 3 is likely to be significantly more than V 2, which means there is a clear increase of velocity r acceleration through this rotor. This kind of as we have seen in case of Axial flow turbines or essentially refers to as reaction turbines. So, aircraft Radial turbines indeed are often or most of the time reaction turbines, which means there is increase of velocity from V 2 to V3. Now, V 2 was essentially a Radial and hence we could call it C r 2 or V r 2. On the other hand V 3 is a neither Radial nor actual it comes out at an angle.

If you look at the plane over here, it comes out at this angle which is kind of parallel to rotor curvature that is given to the exit side of the rotor veins and then of course, it creates this vector diagram in which the rotational speed of the rotor at that station gets added up and when added up V 3 and U 2. You may probably get an exit velocity C 3 which could indeed be actual. As result of this the flow is coming in radially. It is going out in absolute frame actually. So, the Radial inflow is relative at the actual output is indeed absolute. So, this velocity could possibly be going out actually. So, this is a kind of intended Radial inflow turbine that could be typically used in aircraft gas turbines.

As a result of that the flow comes out here, actually at let us say station three and quite often after station three there is little bit of a diffusion of flow to station4. Now this allows the pressure, the static pressure to go up a little to a certain comfortable static pressure for a delivery to somewhere else may be to the exhaust system; this allows the pressure at the station 3 to be very low. Now, if you allow the station three pressures or static pressure more correctly to go rather low you would indeed be allowing the turbine rotor to operate under higher static pressure ratio. If you do that the work extraction capability of the rotor indeed goes up. So, this is a small bit of trick, which the aerodynamic designer often employee that you put a small diffuser over here. The exhaust of the diffuser matches the pressure that is required for the exhaust system, which may indeed ambient pressure where as the pressure at station 3 is actually lower.

This gives high pressure ratio across the rotor from two to three and this high pressure ratio as we know and as we shall see in a few minutes. Actually, allows more work extraction capability across the rotor. So, this is the kind of general fundamental principal based on which the Radial inflow turbines actually operate indeed. It is possible that the entry to the rotor, which we have shown here as essentially Radial V r 2 may not be exactly Radial it may be at some angle and the exhaust from the rotor may not be exactly actual it may indeed at small angle to that at actual direction. So, that may happen, but most of the aircraft gas turbines quite often stick to this principle because it is simple.

It also allows us; we shall see it allows maximization of the work extraction. So, maximization of the work extraction, typically in aircraft engines is very important because this allows you to supply more work to the compressor and do more compression work. So, this is the fundamental method by which a typical Radial inflow turbine works.

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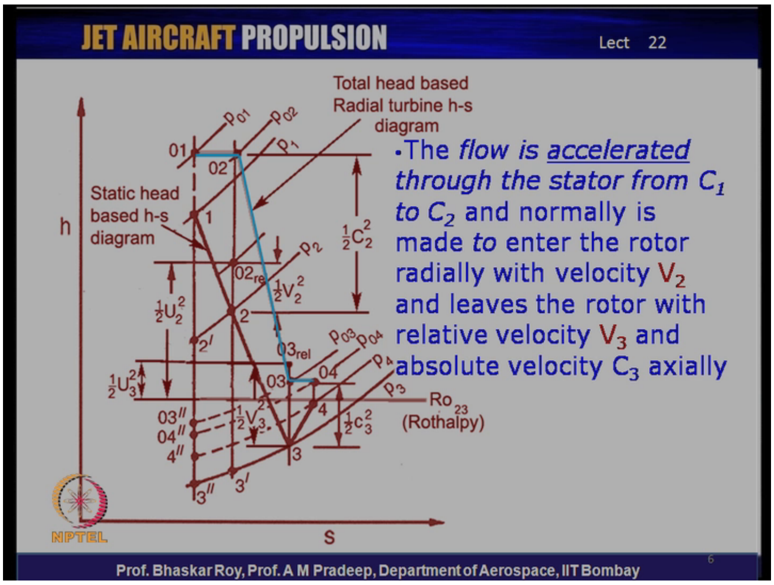

Let us take a look at a simple thermodynamic basis on which this Radial inflow turbine as to work, because as we have discussed before every component in the gas turbine engine has to confirm to the thermodynamic matrix on which this whole engine is working. So, let us take a quick look at basis Radial inflow turbine on its thermodynamics. Now, it starts from a station 0 1 from which the flow is indeed accelerated and it accelerates to 0 2. Now, we do in 0 1 and 0 2 there is no work extraction if there is only a change of velocity from C 1 to C 2 and it comes out with a high kinetic energy head. Now, this is what was intended for all turbine work that why very high kinetic energy head impinges on the rotor for work extraction propose. So, it creates this high kinetic energy and then of course, it enters the rotor with a velocity V 2 which is what I shown here and typically V 2 would indeed be much lower than C 2.

We shall that C 2 could indeed be a pretty close to sonic velocity it could be equal to mach one over there where as V 2 is like here to be much lower than that and then of course, it could possibly accelerate from V 2 to V 3 which is much higher and V 3 could be pretty close to sonic, but by design most people to avoid going sonic because in a rotor if you shafts it could create more losses and bring down. The aerodynamic efficiency of the blades hence quite often V 3 may not actually goes sonic and then finally, it goes out with the velocity V 3 at the exit station 0 3, now between 0 2 and 0 3 the work has been extracted.

So, the enthalpy h has come down from 0 2 to 0 3 because of the work extraction. That has happen it has come down from pressure line P 0 2 to P 0 3, it has come down from temperature t 0 2 to t 0 3 and all these downward parameters simply signify the work that is been given up two the rotor in form mechanical work. Now, what happens is at the station three as we have just seen quite often a small bit of diffusion is employed and this diffusion takes it from 0 3 to 0 4. This travel from 0 3 to 0 4 may involve a small loss of pressure from P 0 3 to P 0 4 no work is done is there and during this process the velocity may come down from C 3 to C 4.

This is what is intended that it goes out with a lower velocity and a higher static pressure P 4, which you can see here is a much higher than the static pressure P 0 3 and this is what is intended. So, this is how the thermodynamics of a Radial inflow turbine actually works. There are couple of other things, which we shall come back to this diagram what is this enthalpy we shall come back to that and the fact that U 2 square could possibly be higher than is indeed higher than U 3 square and what it means and will come back to this that those parameters in a few minutes. just one simple thing that, if you have a purely Isentropic turbine that flow comes out from 0 1 goes all the way down to 0 3 double prime and then 0 4 double prime. It is a vertical drop all the way and that signifies Isentropic turbine performance. That is of course, as we know the Ideal performance based on which real performance is often configured and hence the efficiencies are cost against this Ideal performances and efficiencies are indeed call high Isentropic efficiencies. we will come back to couple of these parameters in a few minutes.

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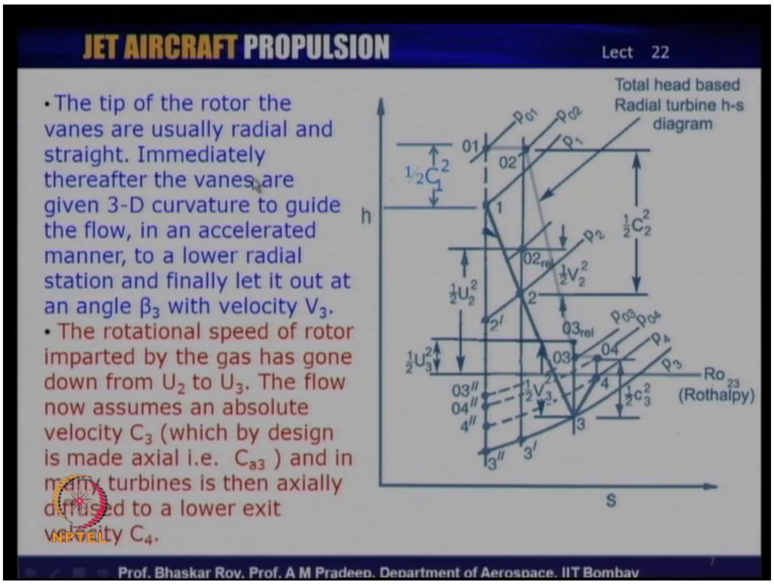

Now, if you look at the way it works, typically the tip of the rotor the veins are usually Radial and straight and there after it takes a 3D curvature, as we have just seen which guides a flow from Radial to actual. In the process also does a lot of acceleration and it accelerates the flow to a lower Radial station and it finally, let it out at an angle beta 3 with a velocity V 3. Now, lower Radial station indeed creates the lower velocity U 3 square. So, the gas velocity along with rotor velocity in the tangential direction comes down from U 2 square to U 3 square. So, the exit gas tangential velocity component is much lower than the entry at the tip. This is one of important issues related to Radial turbine, which is quite different from actual turbine. In a typical actual turbine U 2 would have been equal to U 3 the entry and exit.

Hence, there would have been very little differential available there here we see that there is a large differential available between U 2 and U 3 and in terms of energy half U 2 square and half U 3 square the difference is indeed quite large. The flow goes out with their absolute velocity C 3, which most of the time are quite often by design is made actual. So, it becomes c a 3 and then this is actually diffuse to a lower exit velocity C 4. So, the C 1 square is what it comes in with and C 3 square is what it goes out with and finally, it exited a small velocity C 4. So, this how the thermodynamics of the Radial flow turbine may be cost.

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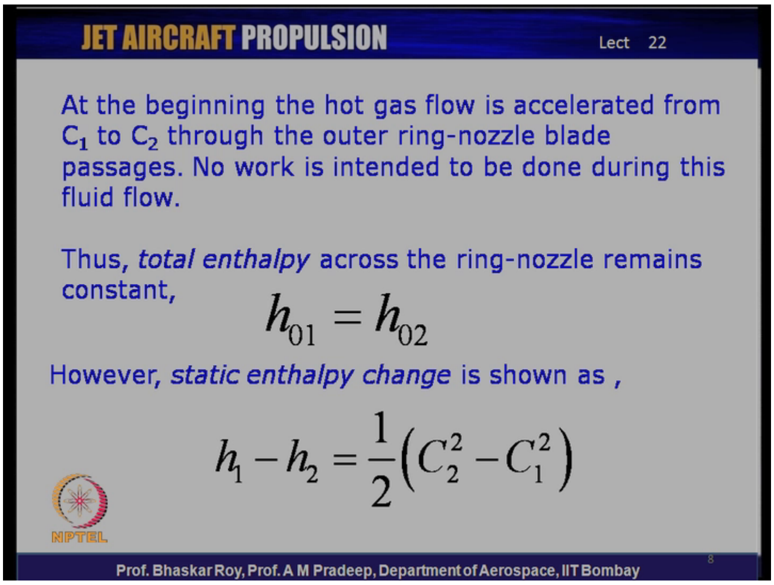

Now, let us take a look at some of the parameters that we would like to discuss at the beginning of the gas flow. It starts with a velocity C 1 goes on to velocity C 2 which I mention is indeed quite high in the ring nozzle or stator nozzle and this creates the high velocity jet that impinges on the rotor. Now, total enthalpy change across these nozzle is constant no work is being done. So, the total enthalpy remains constant and the static enthalpy change is shown here, in terms of the change in the velocity form C 1 to C 2 now this is a larger change and hence there is large change in the static enthalpy that can be quantitatively written down.

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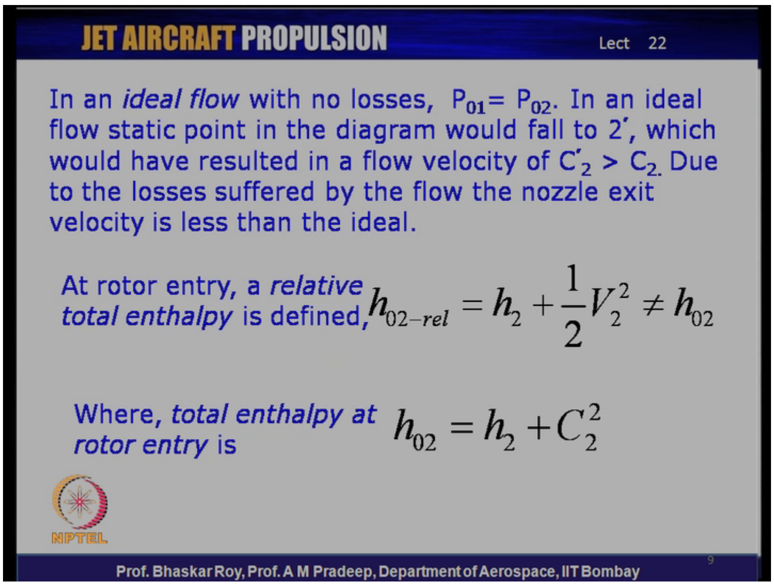

Now, if you go across in an Ideal flow then there is no loss of pressure, but we have just see that the indeed would be a loss of pressure from P 0 1 to P 0 2. Now, what happens is this difference between Ideal flow and real flow means that there would be a difference in the velocity C 2 that is finally, achieved at the end of the stator nozzle. The real velocity C 2, the Ideal velocity could be C 2 prime and it stands to reason that Ideal velocity would have been higher than the real velocity C 2 and this difference between the two or the ratio of the ratio of the two is an important issue of the performance of stator nozzle, how much is the difference between Ideal flow through the stator and the real flow across the stator.

The losses suffered by them needs to be them quantified in actual terms. at the rotor entry the relative total enthalpy is defined in terms of h 0 2 to relative and it is equal to h 2 plus half row V 2 square. Now, this is of course, different from h 0 2 this is relative enthalpy that we are talking about and h 0 2 was absolute enthalpy. Now, at the station 2 the total absolute enthalpy is indeed h 0 2 is equal 2, h 2 plus C 2 square.

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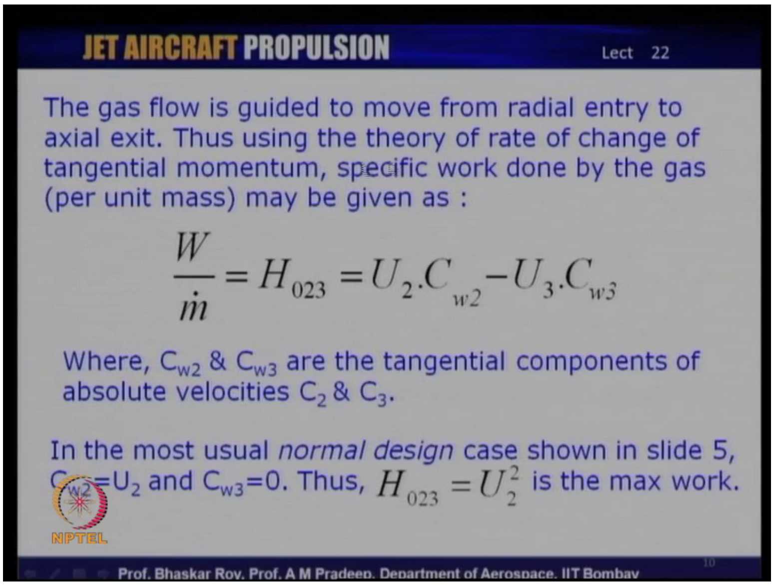

Now, this actually means that the work extraction capability is can be now written down in terms of W by m dot and that is the enthalpy change across the rotor total enthalpy change across the rotor from h 0 2 to 3 and this could be written down as change of a angular momentum from station 2 to station 3 and this is something we have done before with earlier compressors and turbines and that particular theory is still valid and change tangential momentum is indeed equal to specific work and that is U 2 into C W 2 minus u into C W 3.

This differential is what gives us the work extraction capability of the turbine. So, C W 2 and C W 3 are the Radial components of the absolute velocity C 2 and C 3.

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This what we had seen in the diagrams earlier that if you take the tangential component of C 2 this is what indeed it will come to be equal to U 2.Whereas a few take tangential component of C 3 it will come out to be zero from this diagram. So, the kind of Radial turbine that are normally used.

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we see that C 2 C W 2 comes out to be equal to U 2 and C W 3 comes out to be equal to 0 and as a result of which the total work that is possible to be extracted from a typical Radial turbine is simply equal to U 2 square and this represents the maximum work that the Radial turbine can do. So, this is the kind of work that people would like to extract from a Radial turbine.

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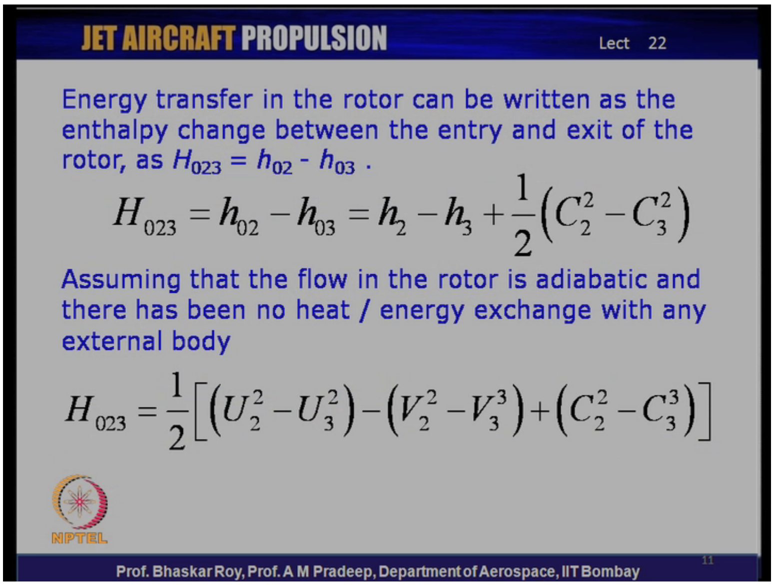

We shall see that the work extraction capability h 0 2 3 is indeed written down in static enthalpy change and the kinetic energy change across the rotor from station 2 to station 3.So, the differential between the two states of enthalpy written down as h 0 2 3. Now, this can one also be written down now in terms of all the velocity components. So, this comes out to be U 2 square, minus U 3 square, minus V 2 square, minus V 3 square, plus C 2 square minus C 3 square now take a good look at this equation in terms of all the velocity components; if we look at the first term U 2 square minus U 3 square. We see that in Radial flow turbine there is a clear difference between these two terms. So, the this term is going to be positive and its going to be quite large depending on the size of the Radial turbine and depending on the rotational speed of the Radial turbine.

So, you because as you know is omega r, omega is the angular velocity and. So, higher is the r difference of radius between station 2 and station 3 higher would be the difference between U 2 and U 3 on the other hand if omega very large even if r is not very large again the different between U 2 and U 3 is going to be quite large. As a result of, which in a typical Radial turbine, this term; the first term is going to be contribute significantly to the work extraction capability of Radial turbine now if you remember in actual turbine U 2 was indeed equal to U 3. Hence, this first term had no contribution to make in Axial flow turbine sand this is the difference that Radial turbine as intrinsic capability to extract more work, because of this first term, which shows up here.

The second term is indeed V 2 square minus V 3 square now, if we have a situation where V 2 is equal V 3 then this term is going zero which means the rotor is essentially more or less some kind an impulse turbine; however, if V 3 is more than V 3 we see that this term would become additive it will become positive and hence it would add to the work done capability of the Radial turbine and in an aircraft gas turbine most of the rotors indeed reaction turbines and this then became a positive addition to the work extraction capability of the Radial turbine. The third term is different between C 2 and C 3 this could be very small.

Or it could be some positive value it depends on the designer he would rather like to make it such that C 2 at least equal to C 3 or slightly more than C 3 and as a result of which one can get a positive contribution and settle not negative contribution quite often small positive contribution is extracted from third term also. So, in a typical Radial turbine all the three velocity components indeed contribute to the work extraction capability and this is what makes a Radial turbine a better work extractor intrinsically than let us say an actual turbine working under same operating conditions.

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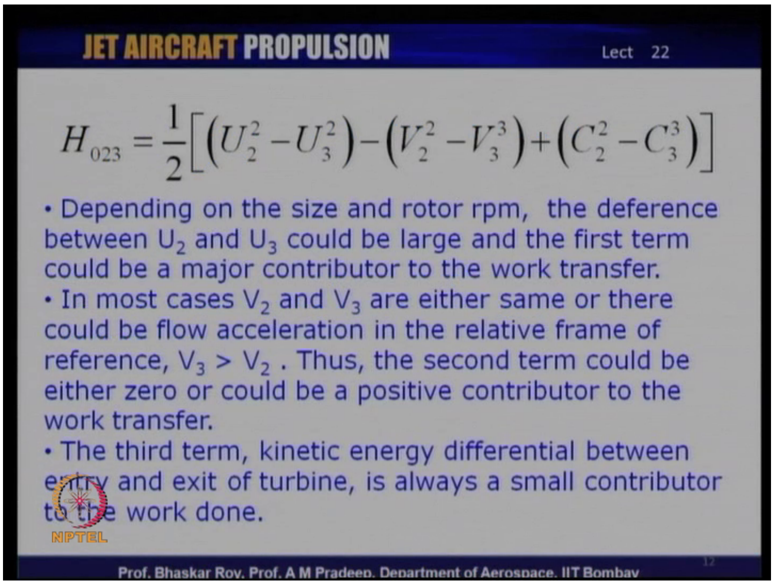

If we look at this equation, this work extraction capability specific work extraction all over again; it depends on the size and the rotor r pm and as I was saying the different between U 2 and U 3 can be manipulated during their time of design to ensure that you have maximum work extraction from the first term itself ; the second term is a question of how much reaction you can render through the rotor and this reaction capability also has to be built into the rotor shape design; the vein shape design and then this vein shape will ensure that you have V 3 which is higher than V 2 and the third term again by design could be made such that a small contribution is main to the work done. So, this is how the work done capability of a Radial turbine can be built into it by design.

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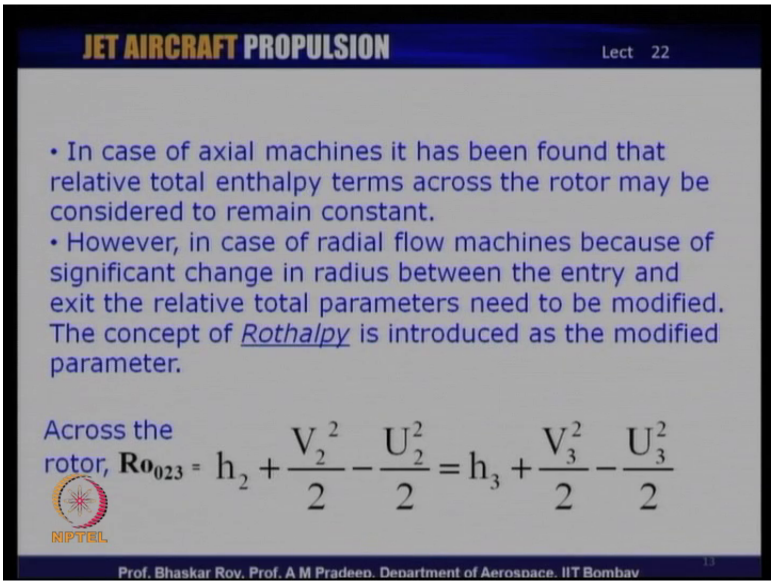

Now, we have seen that in Axial flow turbine this total enthalpy term of the first term is quite often constant and incase of Radial flow or Radial inflow machines, because of the significant change in radius the total parameters quite often in need to modified. now in case of an Axial flow, turbines what we would normally assume is that T 0 2 relative T 0 2 is equal to T 0 3 and P 0 2 relative would be more or less equal to P 0 3 relative and we would assume that h 0 2 relative would be equal to h 0 3 across an Axial flow turbine incase of Radial flow turbine you cannot do that because the station from 2 to 3 has as large change in radius.

this means that you need to create a new parameter and this parameter is refer to as Rothalpy or a short form of rotational enthalpy which is introduced to the Radial flow turbine performance usages and it is simply defined as Ro 0 2 3 that is across the rotor and h 2 plus V 2 square by 2 minus U 2 square by 2 and this would be considered as equal to h 3 plus V 3 square by 2 minus U 3 square by 2. So, combination of the static enthalpy the relative velocity and then the tangential or rotational energy component at the two stations at station two and station three if all of them are put together then get a term which is called Rothalpy.

And that is a terminology or Rothalpy which is expected to ideally remain constant across the rotor and this term then allows you to compute parameters across the rotor because that is a constancy that is useful in terms of computation of parameters from station 2 to station 3. So, Rothalpy is a very useful parameter while computing the performance of rotors of a Radial flow turbine.

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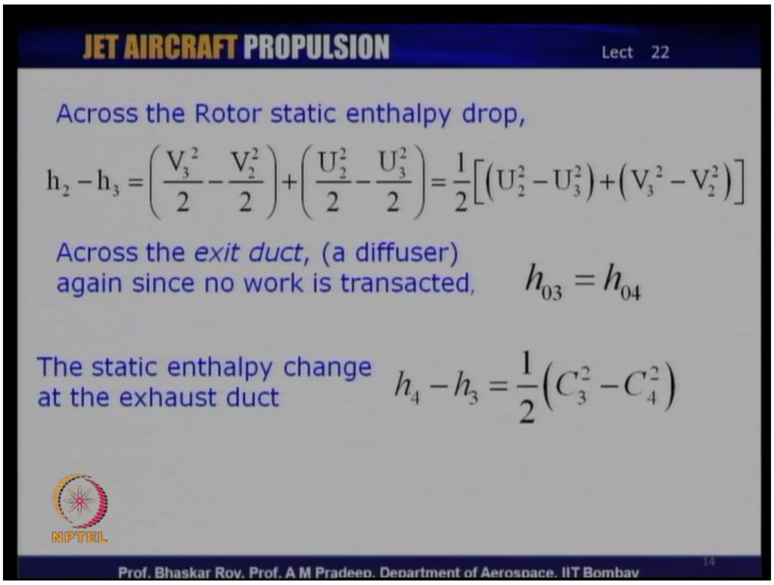

So, if you look at the whole thing the static enthalpy change can be written down in terms of the relative velocity change and the rotor speed changes, which is at the movement as the gas speed and if write all that down this is what you get across the rotor at the exit duct as I mentioned quite often there is a small exit duct.

This exit duct is actually not doing any work, hence the enthalpy; total enthalpy across this is constant and the static enthalpy change shows up in the form of change in velocity, which is what is indented and the C 3 is normally higher then C 4 it diffuses from C 3 to C 4. So, this exhaust duct is quite often a diffusing duct that is the only diffusion that is taking place in this Radial turbine.

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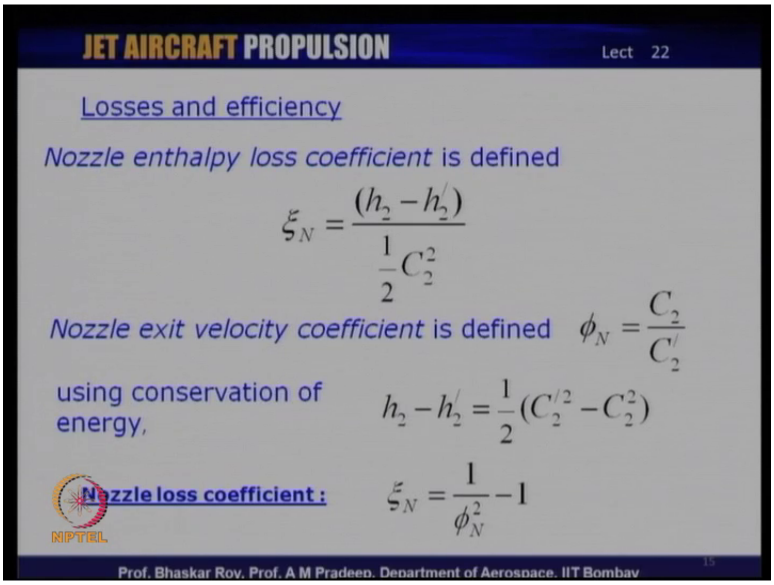

If we now look at: the other parameters that we would like to quantify for Radial flow turbines these are losses and correspondingly the efficiencies that come out and we will look at losses and the efficiencies now if we look at the nozzle or stator nozzle enthalpy loss coefficient across this ring nozzle that we had called ring nozzle.

The zeta nozzle or zeta N can be defined in terms of loss of enthalpy as I mentioned the Ideal flow is often give in terms of h 2 prime and h 2 of course, is a real amount and differential of the two can be considered to be the loss and this when normalize by half C 2 square indeed gives the loss coefficient now this loss coefficient is what we would like to quantify or no now one way of a numerically configuring this loss coefficient is nozzle exit velocity coefficient which we had defined described earlier and we can define a parameter pi n here which is C 2 by C 2 prime. Now, C 2 prime is the Ideal exit velocity from the stator nozzle.

C 2 is a real exit velocity and as one can expect the real velocity would be indeed a little lower than C 2 prime. Ideally as I mentioned the flow they are in a typical aircraft gas turbine would like to go sonic. So, if the real velocity is sonic, the Ideal would be slightly less than sonic. So, if this is Mach one this would Mach 0.96 and 0.97 or their about and this differential can be written down in terms of the nozzle loss coefficient, if we use a conversion of energy of the static enthalpy. It can be written down that zeta N is simply equal to one divided by pi N square minus 1 and these gives us a handy simple good first cart idea about what could be possibly the nozzle enthalpy loss coefficient. So, this is as good starting value for the designers to understand what the nozzle loss could possibly be.

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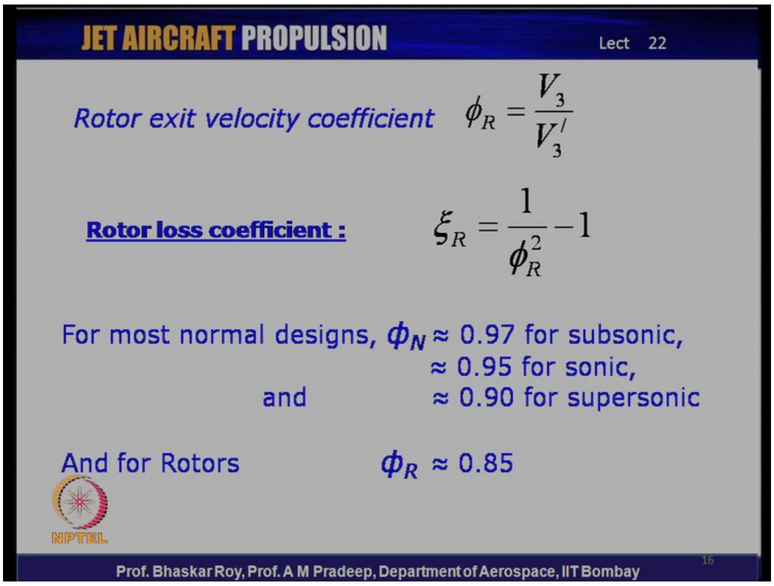

Now, similarly we could have a look at the rotor loss coefficient and connected to the rotor exit coefficient in terms of the actual velocity V 3 as oppose to the Ideal velocity V 3 prime and the ratio of the two is referred to as pi R and then this pi R can be used to write down the rotor loss coefficient zeta R in terms of one by pi R square minus 1. Now, in many of the normal Radial turbine designs these values are normally of this order, if it is subsonic its of the order of point nine seven; if it is sonic its of the order of 0.95 and if it is supersonic; if the flow indeed goes supersonic one could go down to about to point nine for rotors this value is quite often of the order of 85 as there are all kinds of losses in the rotor due to the rotation of the rotor veins and hence this parameter is likely to be somewhat on the load side compare to that in case of stator nozzles.

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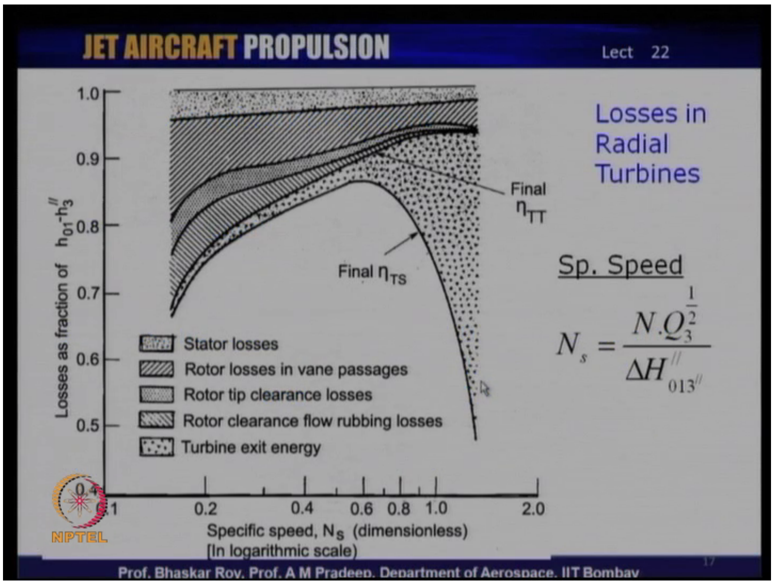

If, we put together all of them in terms of how they vary the losses shown here, in terms of the total enthalpy parameters with reference to the Ideal value, one can see that you have at the top losses related to the stator and then you have the losses that have related to the rotor vein passage. Now, these are of course, purely aerodynamic losses mostly connected to the friction of the flow on the surfaces of the blades and veins. Then you have this dotted area, which is the rotor tip clear encloses when the rotor rotates you have to leave a small tip clearance.

The flow of a move from one side to another and tip clearance of an entail set amount of small loss. You have done that in case of Axial flow compressors and exactly saying concept applies here and then there is a small bit of loss over there and then the rotor clearance flow creates a winding or rubbing loss. That is the another kind of loss that appears over here and then of course, you have the loss which is related simply to the turbine exhaust the flow goes out of the turbine with a certain amount of energy. You cannot use that any more once it is gone out are you cannot hardness it any more for work extraction. Now, that amount goes up as the specific speed of the turbine goes up the specific speed is defined here it is a non-dimensional parameter and this non-dimensional parameter is often useful in characterizing theses turbine performances.

That is what I shown over here and as the speed goes up; more and more exhaust energy goes out on used and we have to find some other way of using it either through a nozzle of a jet engine or some other usage and hence the losses connected to the exhaust goes up tremendously. As a result of which one can see that total amount of losses indeed are increasing. So, these are various loss parameters that one sees in a Radial flow turbine and each of these components would have to be looked into by the designer to ensure that the turbine finally, as a reasonable efficiency parameter during its operation. We can looked at the efficiency definitions.

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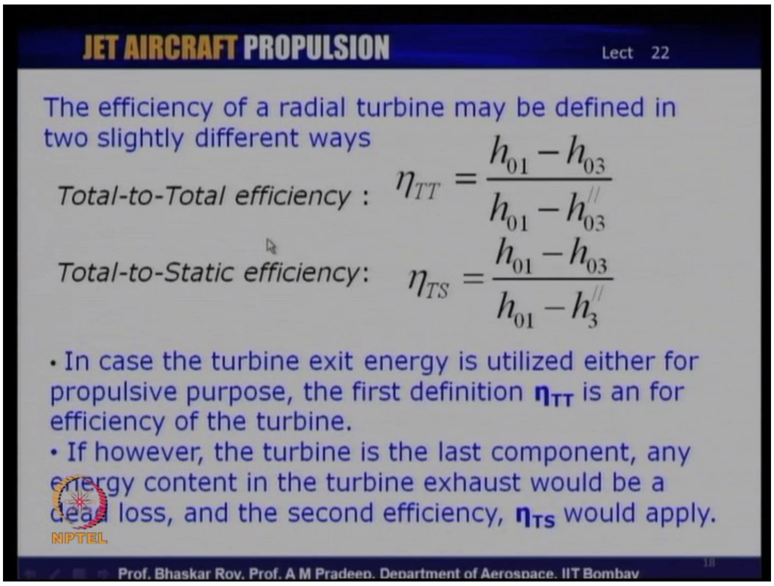

Now, that would need be created by that turbine designer then we have to two different efficiencies one is referred to simply as a total to total efficiency which takes the parameter from 0 1 to 0 3 total parameters as compared to 0 1 two 0 3 prime, which is the Isentropic parameter across the enthalpy entropic diagram that we have done before. This numerator denominator comparison gives us what is known us total to total efficiency parameter. The other efficiency definition is the total to static efficiency definition and that is often simply given as eta T S for turbines and this is again the work done; the total work done as oppose to h 0 1 minus h 3 double prime as oppose to h 0 1double prime which means the denominator now takes it from h 0 1 two h 3 double prime.

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Let us quickly go back to the h s diagram once more, now if see here the flow ideally or Isentropically drops all the way from h 0 1 to h 3 double prime. That is a vertical drops straight from h 0 1 to h 3 double prime, on the other hand h 0 3 double prime is somewhere over here, which contains the kinetic energy of the exhaust flow. So, typically h 0 1 minus h 0 3 double prime would be much lower than h 0 1 to h 3 double prime and hence we have two different denominators: one for total efficiency; another for total to static efficiency.

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So, let us go back those efficiency definitions and we can see now that intrinsically the total to total efficiency numerical value will always be higher than the total to static efficiency numerical value. Hence, both of them are useful typically in aircraft gas turbine in a jet engine the total to total efficiency is often used, because the exhaust gas would being used further through the jet engine nozzle; whereas in a land based application or in applications; where the aircraft engine has no jet thrust creating capability the efficiency of the turbines that should be used to signify its utility or indeed efficiency is the total to static efficiency, because by design then the total to static efficiency needs to be maximized.

Where as in a jet engine, which creates jet thrust total to total efficiency needs to be maximized. So, where these turbines are going to be used is important consideration in the design of the turbines. Accordingly, either the total to static efficiency or the total to total efficiency would need to be maximized by design. This is what is stated here that we need to consider the two efficiency is depending on where the turbine is indeed going to be used.

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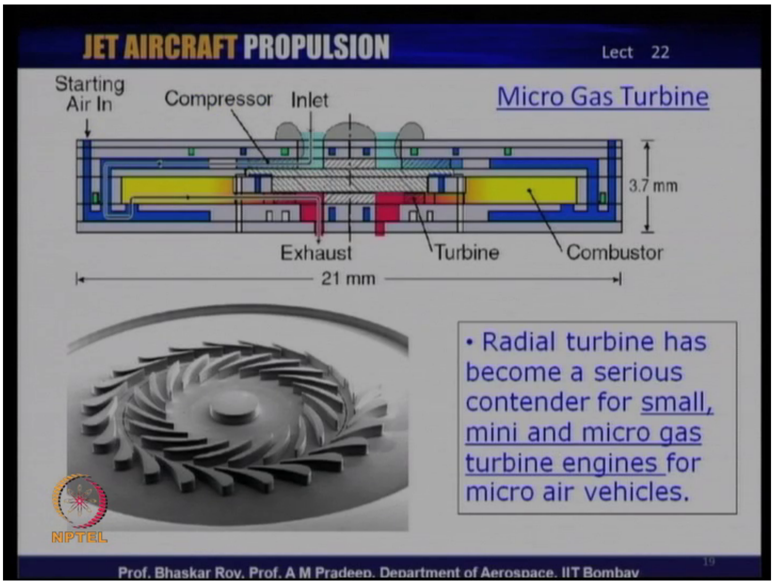

We take a quick look at a very modern usage of Radial turbine which is in micro gas turbines; the Radial turbines are indeed being very seriously considered for small mini and micro gas turbine engines for various kinds of usages. The small gas turbines may be used in small aircraft; the mini gas turbines may be used for various kinds of one mind aerial vehicles, on mind aircraft vehicles and micro gas turbines going used for various kinds of power generations, which are portable power generating units. We see here a micro gas turbine, which is credited to the development of which credited to MIT in US. It simply shows how Radial turbines have been put together with centrifugal compressors to create a very small micro gas turbine.

As you can see here, the dimension of this the diameter which is only 21 millimeters, the thickness of entire gas turbine is only 3.7 millimeters and how is within that you have combustion chamber you have the compressor and this is rather flow comes in through the inlet it goes through the compressor. It gets supplied into the combustion chamber. Then you have the turbine over here: the red part is the turbine flow and it goes out through the exhaust at the it comes out from the top. Let us comes in from the top and let us say goes out from the other side which is red flow the turbine here is shown. You have the ring blades, which are the stator nozzles and the inner ones or the designed rotational once, which create the work or the energy that is extracted from fluid to run the compressor.

So, this is how typically micro gas turbine is expected to perform and these micro gas turbines are mentioned are portable units. They can be as small as indeed the button of this jacket and that is how small they can be and they create power in terms of quite a few volts in terms of five tens fifteen volts. That can actually replace a battery. So, typical Radial flow turbines as found all kinds of usages these days and these usages indeed start from small aircraft engines to on mind aerial vehicles and then to portable generating units. So, Radial turbines have new lives of life in the last five ten years and all kinds of new designs are coming up connected to usage of Radial flow turbines in the next class we will take a look at all the theories that we have done for actual turbines and all the theories we have done for Radial turbines will put together all these theories to first solve a few problems connected to actual turbines and Radial turbines.

Then I will leave you with a few problems to solve on your own using the simple theory that we have done in the last few lectures. So, the next class will be some kind of we will have a tutorial in which I will first bring you some solved problems and then I will leave you with some unsolved problems for you to solve to all by yourselves that would be in the next class.