Jet Aircraft Propulsion

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Lecture No. #23
Tutes – 4

We are talking about gas turbines, and we just had a look at the basic theories of axial flow turbines, and radial flow turbines. In today's class, we will take a look at how simple problems related to these two kinds of turbines can be solved using the theories that we have done. So, I will probably solve a couple of problems for you, and then I will leave you with some problems for you to solve for yourselves using the gas turbine theory that we have done in the last two or three lectures. Now, these problems are set out for you, so that one you can use the theory that we have done in the last lectures, and secondly you get a feel of the numbers.

In engineering, it is extremely important that you not only understand the equations and the theories, that you also get a feel of the numbers. What are the possible correct numbers under various situations for various parameters, that feel is extremely important for good engineers. So, hopefully in today's class, I will be able to expose to you some of these engineering quantitative issues, and you get a feel for the numbers. So, in today's class, we will do the tutorial solved examples, and tutorial problems on axial and radial flow turbines.

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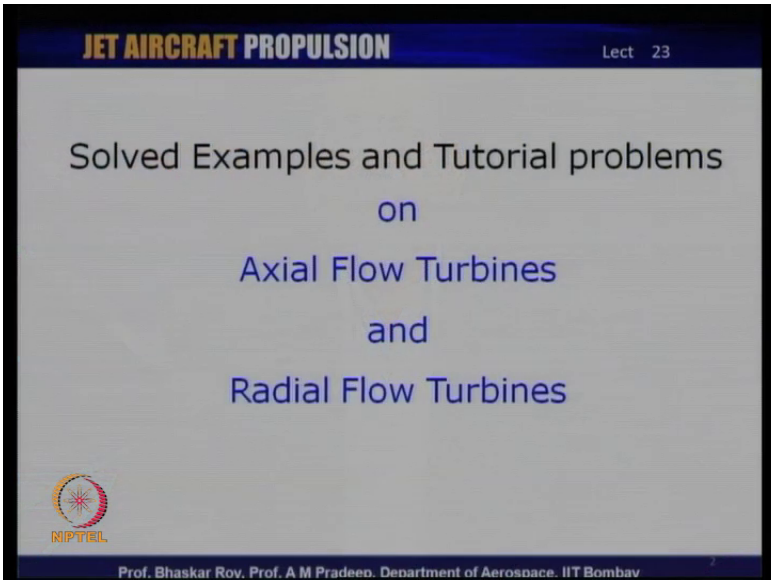

Now, the radial and axial flow turbine that we have done we know are slightly different kinds of turbines. Even though though they do the same kind of job basically that they perform work. So, first we will take on the axial flow turbines and take a look at a problem, which represents a typical axial flow turbine problem and then we will discuss some of the tutorial problem that you could possibly attack for yourselves and get a feel for the numbers.

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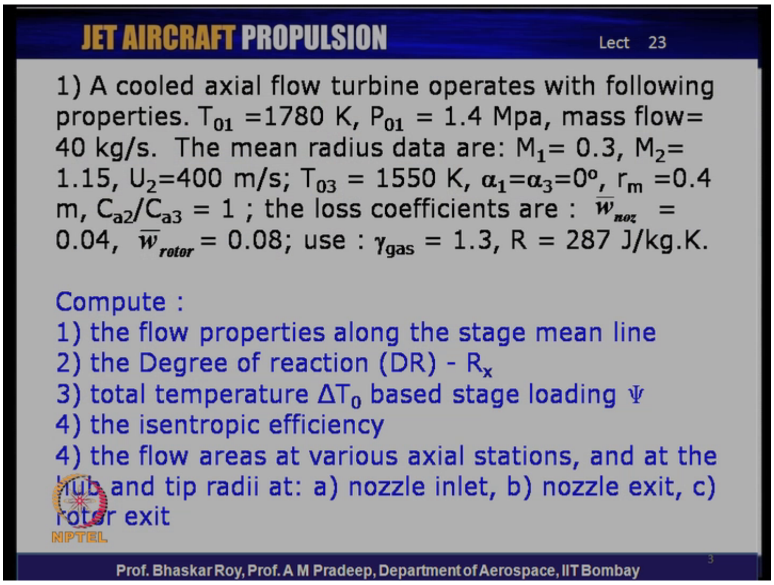

The first problem that we have is on axial flow turbine and this problem statement shows that if you have a cooled axial flow turbine, now we have discussed the cooling technology of axial flow turbines. So, if we have most of the modern axial flow turbines do tend to be cool turbines, unless it happens to be the last stage of a multistage turbine. So, let us take a look at a typical cooled axial flow turbine problem and the problem shows that it has properties such that its entry temperature is 1780 K and entry pressure is 1.4 mega pascals and carries a mass flow of 40 kg per second, which means it is a medium sized engine. The mean radius data; that means, mean is between the hub and the tip of a blade. So, the mean there is given as mach number.

The entry absolute mach number is given as 0.3. The exit from the stator is given as 1.15, which means the flow has indeed gone a little supersonic at the exit of the stator and the rotational speed at this mean radius is 400 meters per second. T 03 that is the exit temperature form the turbine is gives as 1550 K and some simplistic angular parameters are prescribed here; that is alpha 1 is equal to alpha 3 is equal to 0 degree; that means, flow is coming in and going out axially that ofcourse simplifies a problem. But it is also reasonably realistic. So, it is not just ideally simplified. But it does represent realistic flow situation and then at the mean, the radius is 0.4 meters and as I mentioned, it represents probably a medium sized engine.

The axial flow velocity ratio across the rotor C a 2 by C a 3 is equal to 1; that means axial velocity across the rotor is conserved. This is again a simplifying assumption; but also reasonably realistic assumption. It is not very ideal; it is a realistic assumption. The loss coefficients through the rotor and the stator… The stator is of course we have been calling it nozzle. So, the loss coefficient across the nozzle is given as 0.04 and that across the rotor is given as 0.08. So, these two are prescriptions. These numbers are realistic numbers and represent a reasonably real compressor turbine situation. Given are the thermo dynamic parameters. The specific rate heat ratio gamma is given as 1.3 and the gas constant R is given as 287 Joules per kg K.

Now, those are standard parameters and they have been prescribed for this problem also. Now, the problem asked for you to compute the flow properties along the mean line of the stage, the degree of reaction, the total temperature delta T 0 based on stage loading based stage loading. Now, this is something which we have discussed before. So, we will try to compute this and then the isentropic efficiency which was been defined and the flow areas at various axial stations and at the hub and tip radii at the nozzle inlet, at the nozzle exit and at the rotor exit. So, let us take a look at these problems, the parameters that are given and see what kind of solutions we can get out of this problem that has been stated here.

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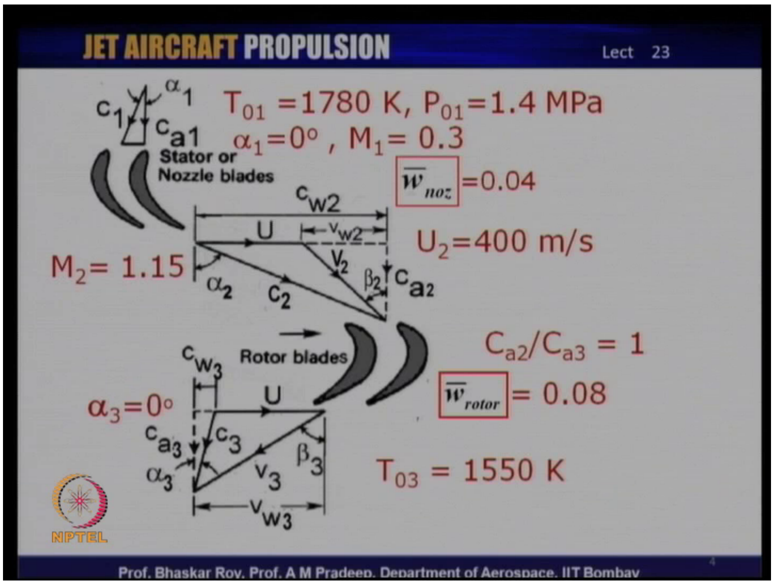

Now, we try to put the problems statement in terms of at the mean radius as it is been prescribed in terms of the velocity diagram that we have done before. And the problem statement now cast on to the velocity diagram that we are familiar with shows that the entry temperature at station 1 has been prescribed 1780 K and pressure has been prescribed. Now at the station 1, alpha 1 there is now prescribed as 0 degree and the entry mach number 0 3 corresponds to c 1 which is shown in the diagram. So, that c 1 corresponds to M 1 equal to 0.3 at that particular station. Now, at the exit from the stator nozzle, the mach number prescribed is 1.15 which is corresponding to the velocity c 2; that is the absolute velocity.

And that absolute velocity is prescribed in the form of mach number as 1.15 depending on the local flow condition; that is local temperature and the corresponding rotating speed U is given as 400 meters per second. So, in that velocity diagram, you can see the value of U and that number quantitative number is given as 400 meters per second. The other thing that is prescribed is across the rotor, the axial velocity ratio now you can see C a 2 and C a 3 in the velocity diagram here and that ratio is prescribed as 1 in this problem statement. Also prescribed as that the exit, absolute flow angle alpha 3 is 0. Now, this is something which is is similar to the entry absolute flow angle.

Now, corresponding to the to the prescription that has been given here, we have the loss coefficients. The loss coefficients prescribed for the nozzle or the stator nozzle blade is 0.04. The similar loss coefficient that is prescribed for the rotor is 0.08. Normally, you would see that the rotor losses are somewhat on the higher side; because it is a rotating blade. And in rotating blade, the losses are normally of various origin and this is something we have discussed a little and you would probably appreciate the fact that the number related to the rotor is on the higher side. Actually, it is almost double of that of the loss in the nozzle.

The other thing that is given is that the exit total temperature is 1550 K, which means it is undergone a total temperature drop of the order of 230 degree K across this turbine. That is the amount of what you can expect that this turbine would have probably accomplished in the process of functioning or in the process of transfer of energy from the gas to the rotor and then mechanical work. Now, this is something which is what the turbine exists for and the quantitative value prescribed here is 230 K; that is a pretty large number and you could probably quickly notice that, that number is substantially higher than what you can get in terms of temperature raise in any compressor stage. So, these are the prescribed values for the problem that has been put in front of us. So, let us go along and see whether we can complete the process of solution of this particular problem.

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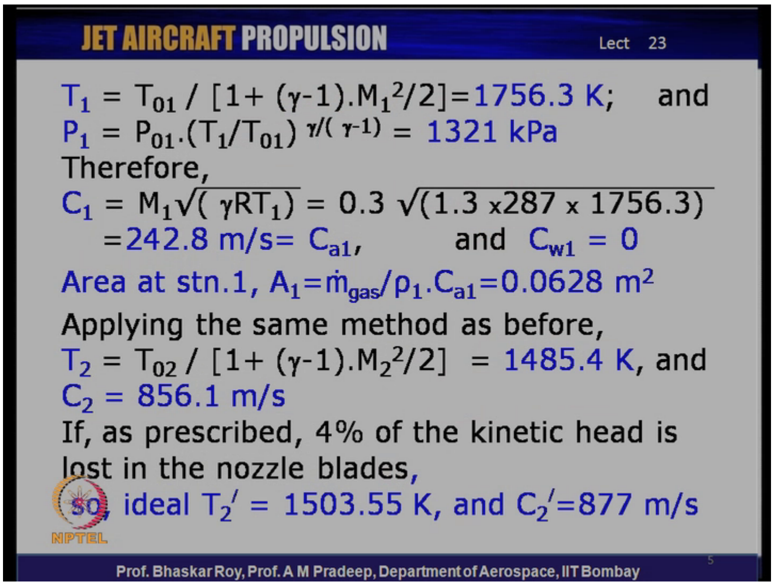

Now at station 1, if we look at the numbers that are given, and try to find the static parameters; if we can get value of T 1 and if we apply the isotropic flow conditions at station 1, we get T 1 is equal to 1756.3 K using the isentropic flow conditions. And P 1 correspondingly using the same isentropic conversion from total to static condition, we get 1321 kilo pascals converting from mega pascal to kilo pascals. Now, we are using isentropic flow condition, because as we you have done before in various thermo dynamics. That at any particular station, conversion from static to total or total to static can be simply by using the ideal isentropic relations.

Because at that particular station, it is assumed that the flow is undergoing isentropic conversion from total to static or static to total; that is an assumption; that is ofcourse the theory and we can always invoke that theory at a particular station. There is no process from 1 to 2; it is only at a particular station 1. So, we can always invoke the isentropic flow condition at that particular station in an ideal manner. So, that is what we have done and we have got the static temperature and static pressure at station 1. Now, we can find the velocity C 1. As I mentioned, M 1 that was given is corresponding to C 1 and that is dependent on the local temperature that we have just found.

And if we invoke the local temperature that has been just found, we get a velocity which is 242.8 meters per second corresponding to mach 0.3 that has been prescribed there. Now, since alpha 1 is given as 0, C 1 effectively becomes equal to C a 1 and corresponding C w 1 would be 0. So, if you keep your eye on the velocity triangle, you would see that we are trying to solve all the parameters (Refer Slide Time: 06:52) that are shown in the velocity triangle as far as possible. And the trick of solving such problems is that if you can find all the parameters that are shown in this velocity triangle, you would be able to calculate the performance of the turbine completely and fully.

So, one of the things that you may like to do while solving a problem is to compute all the parameters; that are shown in this velocity triangle. So, let us do that and we found at station 1, C w 1 would be equal to 0. Correspondingly then at station 1, we can say that the area A 1 would be equal to the mass flow m dot gas divided by the local density rho 1 into C a 1. Now, this ofcourse means that we are simply using the continuity condition at station 1 and simply using the continuity condition, we can find out the area at station 1. You could notice that you would have to calculate the density rho 1 corresponding to T 1 and P 1 that we have just calculated.

So, if you calculate rho 1 and plug in that value here, you would get an area that is a 0.0628 meters square at station 1; that is at entry to the turbine stator nozzle blade. Now, applying the same isentropic method of conversion from total to static, we can find the temperature at station 2. Because through the stator nozzle, a lot of acceleration has taken place and the total temperature as remain constant. But static temperature has undergone a large amount of change and that shows up here that the static temperature now is 1485.4 K substantially lower than 1756.3 K that we have found at station 1. So, that is a drop due to the large change from potential to kinetic energy through the stator nozzle.

And correspondingly, we find a C 2 using the same method again that is conversion from mach number to velocity using the local temperature, which we have found as 1485.5. And we get a velocity now corresponding to mach 1.15 velocity of 856.1 meters per second. Now, this is a very high velocity jet and intended purpose ofcourse is that this would now be made to impinge on the rotor blade to make the rotor rotate. Now, as prescribed, 4 percent of the kinetic head is lost in the nozzle blade. The nozzle loss coefficient was prescribed as 0 4 and that is corresponding to 4 percent of the kinetic head as per the definition of the loss coefficient.

And as the result of which, the we can sort of do a reverse engineering and back calculate and find that the ideal T 2 would have been T 2 prime would have been 1503.5 K and corresponding to that, ideal C 2 prime would have been 877 meters per second. Now, this is something we have discussed before in our lecture that through the nozzle; because of the real flow situation, the axial velocity C 2 is often a little less than what would have been the ideal velocity C 2 prime. Now, this change from real to ideal is quite often a situation that happens; because you see at the end of the nozzle, you are trying to achieve a sonic velocity. Sometimes as we seen this particular problem, you are trying to achieve a slightly supersonic velocity.

So, what happens is you end of getting a little less than what you prescribed or what you design for. And hence, the loss coefficient comes in to the picture over here and this slight loss of a performance through the stator nozzle needs to be accurately facted in your calculation. So, that you know exactly how much you are losing in terms of the acceleration that the stator nozzle is expected to achieve. So, that is what we see here that the ideal velocity could have been a little more through the stator nozzle and as it happens, we are getting a little less of the order of almost 20 meters per second, 21 meters per second. Now, this is something what every turbine design and needs to keep an eye on.

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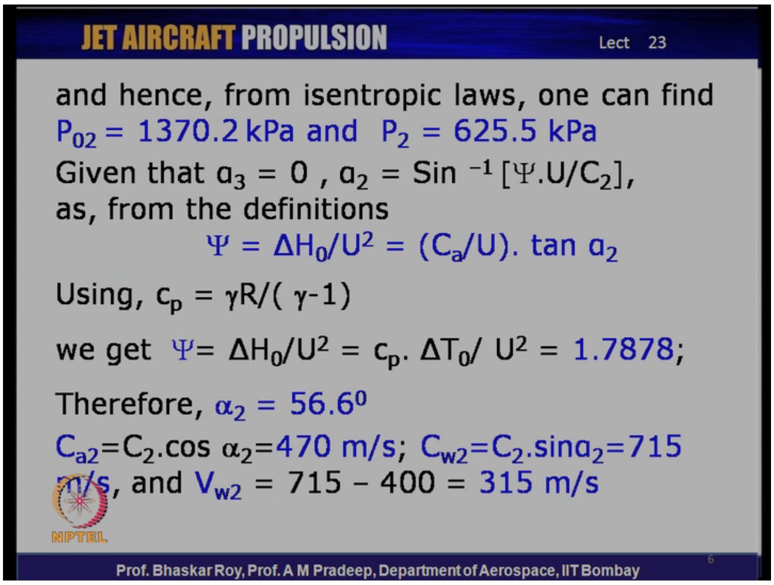

Now, from the isentropic laws, we can also find the value of static pressure P 2 at the end of stator nozzle and since P 0 2 is kind of only factors in the 4 percent loss, it tells us that P 2 would be 625.5 kilo pascals. Now, at station 3, it is given that exit angle is 0; alpha 3 is 0 and at station 3, it is prescribed that alpha 2 could be corresponding to sine inverse psi into U divided by C 2. Now, this is from the definition of the work done which we have done before; that is psi is equal to delta of enthalpy change across the stage divided by U square, which is the rotating speed.

So, it is used as a normalizing parameter and this is the definition of blade loading or the stage loading quite often used in case of turbines and also sometimes in case of compressors. Now, if you do that, you get a parameter that is C a by U into tan alpha 2; from which, we wrote down as above that you can get a parameter in terms of alpha 2. Now, c p ofcourse from thermo dynamics we know is gamma R divided by gamma minus 1. And if we plug in all those values, the stage loading psi can be computed as a 1.7878 and this is ofcourse often as a non-dimensional parameter and this number is often an indication of the amount of loading that you can prescribed for a particular stage.

Higher this number is higher the stage is being us to perform. And so, keeping an eye on this number tells you whether the stage has been sufficiently loaded or the stage loading has been maximized. And in case of aircraft gas turbine engines as we have discussed before, we would like to maximize this number without causing and U gas dynamic are structural problems. Now, from all these calculations what we get is alpha 2 is equal to 56.6 degree.

This is the angle at which the flow is coming out from the stator nozzle. Correspondingly, the C a 2 the axial component of this velocity is before 170 meters per second.

And C w 2, that is the old component or tangential component of the absolute velocity that would be 715 meters per second. And ofcourse, your V w 2 that is the relative tangential component would be 315 meters per second. So, some of these are numbers which you would probably like to get used to. Because as you see these numbers are substantially different from what you found in station 1, where C w 1 was ofcourse 0 and hence the change across the stator nozzle only. Even when no work has been done, a substantial change in the velocity field has been achieved through a large acceleration and this is what was ofcourse intended by there so called stator nozzle.

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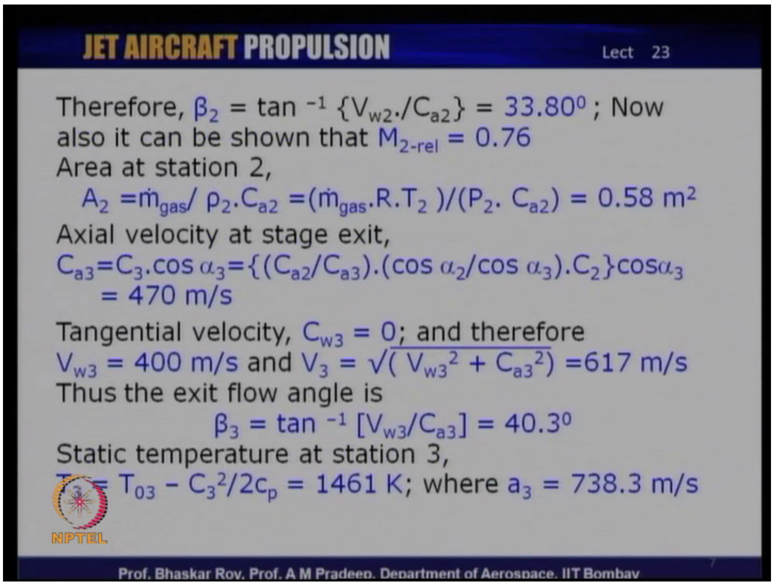

If we move forward with these numbers and move on to the rotors, what we find there is that at the entry to the rotor, the relative flow angle beta 2 can be now found from the tangential velocity V w 2 and the axial velocity C a 2 and if we plug in those numbers, we get beta 2 is equal to 33.8 degrees. Now, it can be also shown that corresponding to this, that the M 2 relative at the entry to the rotor that is relative mach number to the entry to the rotor would be 0.76, which is subsonic. Now, we just saw that the exit from the stator M 2 is actually supersonic; that was prescribed as 1.15 and we see by conversion through velocity triangle, the M 2 relative is now subsonic.

(Refer Slide Time: 06:50) Let us take a quick look at the velocity triangle; you see corresponding to our calculations, c 2 has been prescribed clearly as supersonic. We got the velocity value and we got the v 2 velocity value. When we converted v 2 to M 2 relative, this is clearly subsonic by the local flow conditions and this is exactly what is been achieved through this velocity vector transformation that the exit velocity here can be clearly supersonic. But the entry here would be subsonic and as I have been mentioned earlier, this is done deliberately that in most of the modern turbines today. Still admit flow in to the rotor which is subsonic.

It is indeed possible to admit flow into the rotor which is supersonic; that means you can indeed have supersonic rotors. But normally in aircraft gas turbine, even today it is not a done thing. Supersonic rotors have been used in other applications notably in termission the applications in space craft; but they are normally not used in aircraft gas turbines. So, in aircraft gas turbines, we still keep the v 2 value subsonic. This is deliberate and very done very consciously for the turbine designs; so that, the losses through these turbines are somewhat under control. As you can see, the loss to the rotor is already little on the higher side and through the shocks, it would have gone even higher and hence, most of the aircraft gas turbine even today are essentially subsonic rotors.

Let us get back to the calculations that we were doing. Through the rotor, we can now find the area at the station 2 which is at the entry to the rotor and that is again found by using the continuity condition. And the continuity condition tells us that value of A 2 can be written down in terms of the various flow parameters there and it comes out to the of the order of 0.58 meters square. Now, axial velocity acts at the exit of the stage can be found simply by using the velocity triangle that we were looking at and this comes out to be 470 meters per second. Now, we have seen that this axial velocity is constant across the rotor. So, the value of C a 2 would be exactly same. So, that is how this velocity has been computed.

Now, at the exit again it is been prescribed that alpha 3 is 0. So, C w 3 would again be 0. And therefore, the value of V w 3 would be equal to the rotating speed of the rotor and that is 400 meters per second and corresponding relative velocity leaving the rotor would be 617 meters per second. Now, this is ofcourse the relative velocity. So, as we can see that the relative velocity here is also essentially subsonic and we will see that it is a little on the higher side compared to V 2. Now, the exit flow angle beta 3 can be computed and this comes out to be 40.3. This is invoking the fact that alpha 3 is indeed 0 and static temperature at station 3 now can be computed again invoking the isentropic laws as we have done in station 1 and 2.

And if we do that, we find the temperature to be 1461 K. The total temperature ofcourse was prescribed. So, it is it is easy to use the isentropic laws and find the static temperature that is 1461 K and the sonic speed at that particular station is 738.3 meters per second and we can very well see that this velocity V 3 would be subsonic. So, the exit velocity from the rotor also is subsonic. So, both the entry and the exit velocity from the rotor are deliberately kept subsonic to avoid shock losses, which again would reduce the efficiency of the turbine; increase the losses and reduce the efficiency. And most of the designer presently designers are extremely sensitive to efficiency of the turbines and hence they try to keep the turbines subsonic even today.

And the other thing is most of the work done is being accomplished higher level of work done is being accomplished by increasing the turbine entry temperature. And this increase of turbine entry temperature is quite often the focus of attention of modern research and more and more cooling technologies applied. And we have prescribed that this particular problem actually applies blade cooling and that is how, that high entry temperature was admitted and hence we see that we have a turbine here, which is a cool turbine. The entry temperature is very high and that allows the designer to keep the rotor subsonic and hence, the rotors are not under any compulsion to go supersonic to get more work done.

Rotors can be kept subsonic. Another reason, why modern designers would like to keep the rotors subsonic is because many of the modern rotors are also subjected to cooling technology. Some of these cooling technologies as we have seen are extremely intricate and if we have supersonic flow over them, it will be an extremely complicated fluid mechanic situation. And most of the turbine designers would like to avoid that kind of complication in their turbine design; because it would impact on the efficiency or aero thermodynamic efficiency or what we call isentropic efficiency of the turbine quite adversely. So, as we see by the numbers that they are deliberately kept subsonic.

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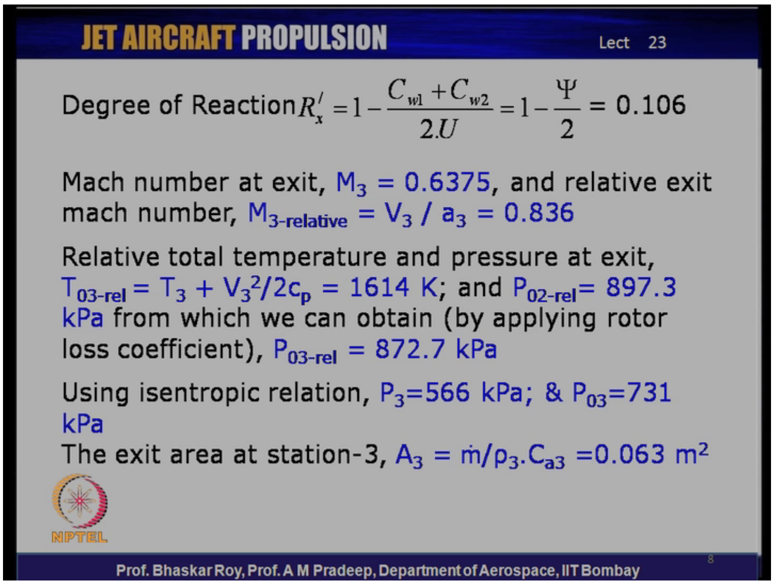

Let us proceed with this problem and see whether we can complete it. The degree of reaction that we have prescribed before, as we see now if it is computed using all the parameters, comes out to be only 0.106. And as we have discussed in many of the modern turbines, the degree of reaction value are of that order much lower compared to what you have done probably in your compressor chapter why the degree of reaction values are somewhat much higher than these numbers. So, you got to get the feel of these numbers. The degree of reaction in turbine is substantially lower than that of compressors and these are the numbers you would need to get used to.

The mach number at the exit then the absolute mach number is 0.6375and the relative exit mach number as we just saw in subsonic and it is 0.836. It is slightly higher than what it came in with in to the rotors. So, the rotor is clearly a reaction turbine. It has accelerate the flow a little and has produced a reaction and hence it is a reaction turbine. The relative total temperature and pressure at the exit can also be computed to compute the calculation and we get T 0 3 relative as 1614 K and P 0 2 relative as 897.3 kilo pascals by applying the rotor loss. I need to mention here very clearly here that the rotor loss coefficient that was prescribed should be applied across the rotor relative frame.

So, the 8 percent loss that was prescribed should be applied to P 0 2 relative and if you do that, you get P 0 3 relative at as 872.7 kilo pascals. Now, this is something you need to again very clearly understand. That the loss prescription that is normally given should be applied in the absolute scale in the stator nozzle and should be applied in the relative frame in the rotor and when you are calculating the pressure losses respectively across these two rows of blades. So, losses in the rotor take place in the relative frame; in the stator, it takes place in the absolute frame. So, you need to take note of this and do your future problems accordingly. Using the isentropic relation, we can now find the stator static value that is P 3 as 566 kilo Pascals and the total pressure is 731 kilo Pascals.

Correspondingly, now we can find the exit area at station 3 and this exit area is now A 3 equal to… Again using the continuity condition and using m dot which is constant across the stage; the local density rho 3 and C a 3, the local axial velocity C a 3. If we apply all those, we get at station 3 the area is equal to 0.63 meters per second. You can see that the area across the stage is going slightly higher; because the flow is axially losing its pressure and temperature and it is losing its density and hence the area requirement would be higher, as you go through the stage. So, these are the numbers you need to understand and made and try to make it clear that when you get these numbers when you are solving a problem, certain numbers would tell you whether your solution is proceeding along the right path and you get the feel of the number that you are probably okay, when you get the numbers in hand.

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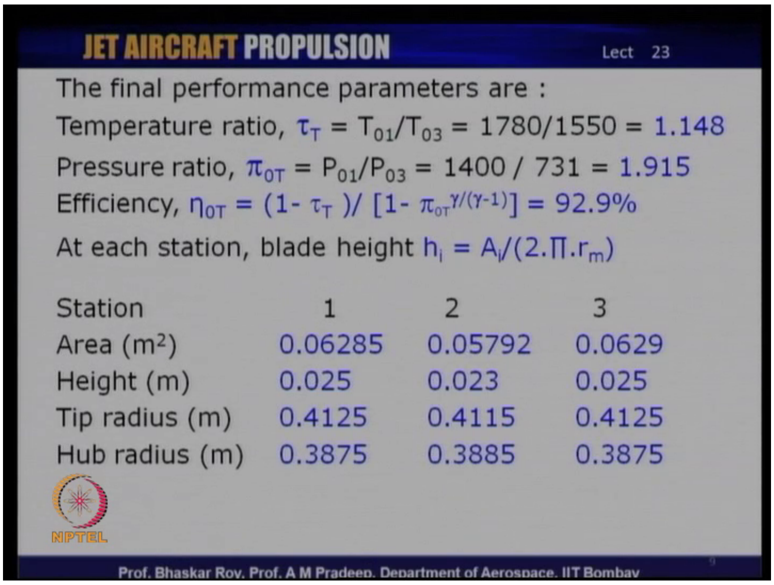

Let us finally put them altogether; the performance parameters that we get from this in in terms of temperature ratio. The total temperature ratio is 1.148; the total pressure ratio or the pressure drop across the stage is 1.915, which is a modest total pressure ratio across turbine stage. Many of the modern turbines could possibly have much higher pressure ratio across its stage. The efficiency of this particular turbine can now be computed using the thermodynamic laws that we have done before and it is simply is 92.9 percent, which is a fairly good efficiency. Many of the modern turbines can have efficiency slightly higher than these; but 92.9 nearly 93 percent is definitely good efficiency.

At each of these stations, the blade height can also be calculated simply using the geometry at that particular station; that is h i equal to a i divided by twice pi or a mean at the particular station. And if we put them all in table in station 1, 2 and 3, we get the areas which we have computed before and these areas are now shown over here. And then across the rotor, as you can see there is you know increase in area and across the stage indeed, there is been a slight increase in area. The height as you can see again has change across the stations. Correspondingly, the tip radius and the hub radius can be found using the geometry that is available with us. So, this table gives us an idea about the changes that typically occur across a stator and the rotor. This may vary from one kind of turbine to another.

If you go from HP to LP, these variations could be slightly different. If you were crossed to last stage of the LP, it will again slightly different. It depends on the turbine design and as I just mentioned that the pressure ratio 1.95915 is a modest pressure ratio. Many of the modern turbines could indeed have pressure ratios quite higher than this. And if they are, then all the values that you see here in terms of area, height and the tip radius and so on would indeed change from station 1 to 2 to 3. So, it depends on turbine and every turbine would have unique such numbers except that if you get the feel of the numbers, you would know whether the numbers are coming out in a correct trend and that trend is what you can get the feel of when you are solving a problem. But the numbers for every turbine would be quite different from each other.

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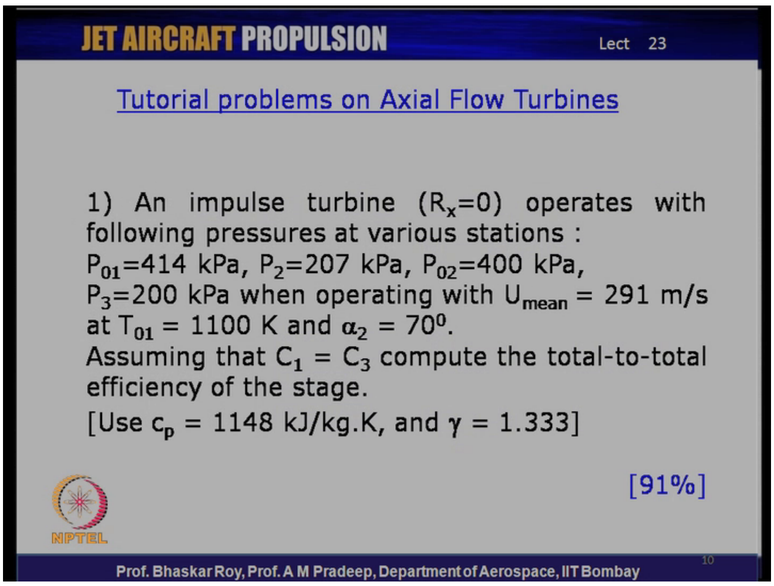

What I will do now is I will prescribe a few problems for you to solve for yourself using the methodology that we have just solve the problem. So, the first problem is actually that of a impulse turbine, where reaction is 0. And if we do that, we prescribe that it has a entry pressure of 414 kilo pascals, static pressure of 207 and exit pressure of P 0 from the stator nozzle of 400 kilo pascal. So, it is lost about 14 kilo Pascals across the stator nozzle. The exit static pressure from the whole stage is given as 200 kilo Pascals. Now, when operating with a rotating speed U mean at the mean of the rotor blade, 291 meters per second.

The entry temperature given is a modest 1100 K and alpha 2 that is exit from the stator nozzle is prescribed as 70 degrees; that is from the exit of the stator nozzle. Again it is assumed or prescribed that C 1 that is entry velocity is equal to the C 3, which is exit velocity from the stage. What is asked for is compute the total-to-total efficiency of this particular stage prescribed or the values of C p and gamma, which are the normal values. The C p is 1148 k g per kilo joules k g per k and gamma is 1.333. So, if you use those numbers, you would probably get an answer close to 91 percent as efficiency of the stage. I hope you can sit down and solve the problem using the method that we have adopted before.

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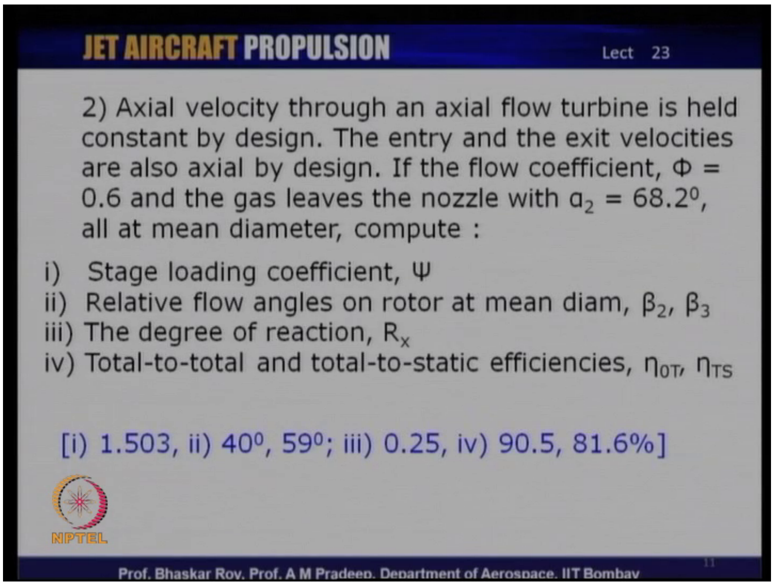

Let us go on to the next problem which corresponds actually now to not a impulse turbine. Let us look at the problem and we will see that the axial velocity as prescribed through the axial turbine is held constant by design; that means, C a 1 is equal to C a 2 is equal to C a 3. And this entry and exit velocities are also axial; that means, C a 1 is equal to C 1; C a 3 is equal to C 3. It is a simplified problem and the flow coefficient that is C a by U through the rotor is 0.6. Now, if you do that, the gas leaves the nozzle with alpha 2 equal to 68.2; that is at the exit of the stator nozzle.

Now, at whole mean diameter that means, across the stage if you if you just travels through the mean diameter from the stator entry to the rotor exit, you are required to find the stage loading coefficient, psi; the relative flow angles at rotor mean diameter, beta 2 and beta 3; those are the relative flow angles; the degree of reaction, R x and the total-to-total and total-to-state static efficiencies that we have prescribed in our lecture earlier. And you are required to find both the efficiencies and the answers given are that your stage loading coefficient is 1.5, the relative flow angles are 40 and 59 degrees, the degree of reaction is 0.25 and the two efficiencies the total efficiency is 90.5 and the total-to-static efficiency is 81.6. As we have discussed during the lecture, the total-to-static efficiency is normally lower than the total total-to-total efficiency. So, these are the answers you would get by solving the second problem.

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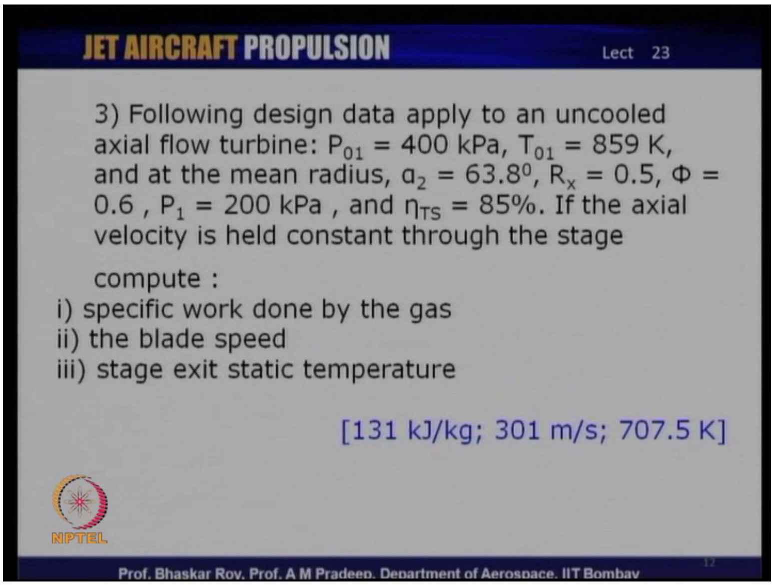

Let us look at the third problem. This is following the design data applied to an uncooled axial flow turbine. You get P 0 1 equal to 400 kilo pascals; T 0 1 equal to 859 K and at mean radius alpha 2 equal to 63.8 degree; degree of reaction is 0.5 and phi, the flow coefficient as 0.6; P 1, static temperature at the exit at the entry is 200 kilo pascals and total-to-static efficiency is now prescribed in this problem as 85 percent. If the axial velocity is held constant as in the last problem, through the whole stage you are required to compute the specific work done by the gas, the blades speed and the stage exit static temperature. Now, these are the numbers that you would get. You would get 131 kilo joules per kg and the blade speed would be 301 meters per second and the stage exit static temperature would be 707.6 K.

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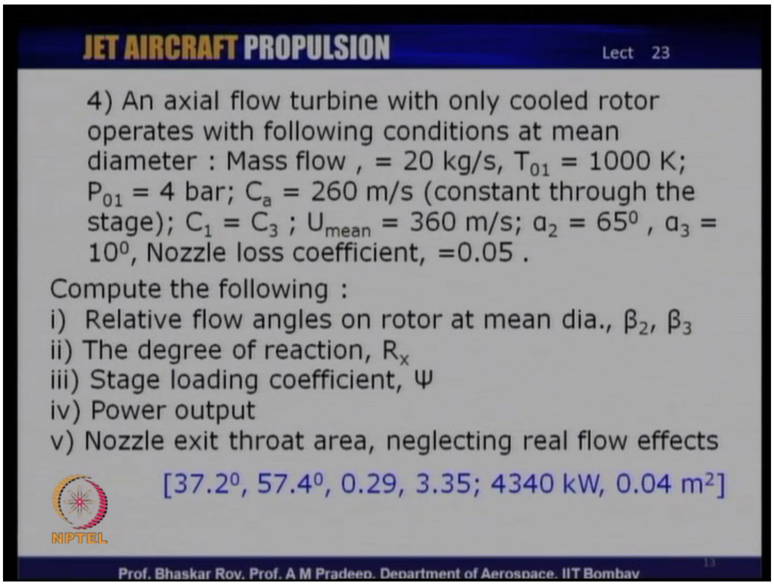

If you look at the fourth problem, it is an axial flow turbine now again with a cooled rotor. Now, as I mentioned, you could have cooled rotor. So, you have a problem here which says that the mass flow is 20 kg per second; the entry temperature total temperature is 1000 K and P 0 1 is 4 bar; C a is 260 meters per second and this is assumed to be constant through the entire stage. Again it is prescribed that C 1 is equal to C 3; U mean is 360 meters per second; alpha 2 that is exit from the stator nozzle is 65 degree; and alpha 3 at the exit to the stage is 10 degree and the nozzle loss coefficient is prescribed as 0.5.

You are required to compute the relative flow angles at the rotor mean diameter beta 2 and beta 3 at the mean, the degree of reaction R x, the stage loading coefficient psi, the power output of this working turbine and the nozzle exit throat area, neglecting the real flow effect; that means, you assume that is an isentropic ideal flow and you can still find the nozzle exit throat area. And if you adopt all these prescriptions, the answers that you would be getting as the relative low angles would be 37.2 degrees and 57.4 degrees respectively. The degree of reaction would be 0.29; the stage loading co efficient would be very good 3.35; power output correspondingly would be 43.40 kilo watts and the nozzle exit throat area would be 0.04 meter per square. This is the throat area at the exit of the nozzle, which is typically at the end of the converging channel that is prescribed or normally used in the stator nozzle.

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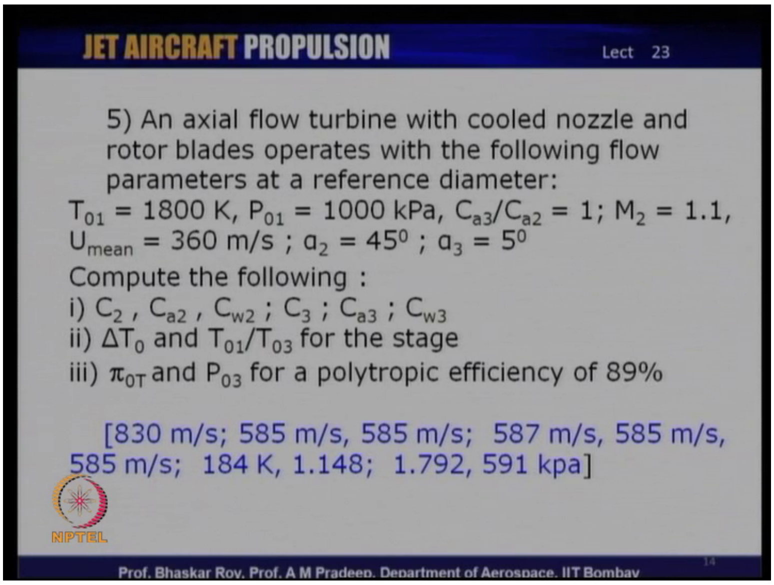

The fifth problem that is prescribed to you is the axial flow turbine with cooled nozzle and rotor blades; that means, both nozzle and rotor are prescribed to be cooled operates with the following flow parameters at the reference diameter, which is the mean. The entry temperature is a respectable good modern temperature that is 1800 K. The entry pressure is 1000 kilo pascals; C a 3 by C a 2 as we have done in all problem is equal to 1; that is axial velocity across the rotor is conserved mach number at the exit of the stator nozzle is 1.1; that is it is allowed to go slightly supersonic and U mean is 360 meters per second. Alpha 2 prescribed is 45 and alpha 3 at the exit of the rotor is prescribed as 5 degree.

You are required to compute the following that is C 2 at the exit of the stator nozzle; C a 2, the axial velocity between the stator and the rotor; C w 2, the absolute tangential component of the velocity at station 2 between the stator and the rotor; C 3, the absolute velocity at the exit of the rotor; C a 3, the axial velocity and C w 3, the tangential velocity at the exit of the rotor. So, all these velocities that is you are required to complete the velocity triangle that we have seen before; the total temperature drop across the stage and correspondingly ofcourse the total temperature ratio across the stage, the pressure ratio across the stage and then P 0 3 for a polytrophic efficiency of 89 percent.

And if you adopt all the prescriptions that are given and the velocities that are another parameter that asked for, you get those numbers. The velocities are 830 meters per second; 585 meters per second and 587 meters per second for C 3 and 585 meters per second for C a 3 and C w 3. You get a temperature drop of the order of the 184 K; corresponding temperature ratio is 1.148 and the corresponding pressure ratio or pressure drop across the turbine is 1.792, which gives you exit pressure of 591 kilo Pascals. So, those are the answers you are likely to get, if you adopt the prescriptions that are given in this problem. Let us now take a look at a problem of radial flow turbine; this radial flow turbine which we have done in the last class. Using the simple theories that we have done in the last class, we can try to solve this problem.

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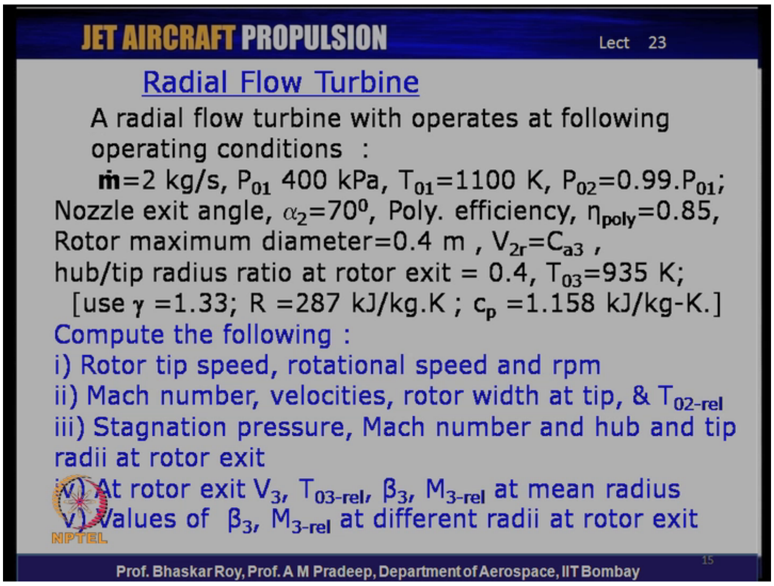

What is prescribed here is that the mass flow is 2 kg s per second, which means it is a small turbine. The entry pressure is 400 kilo pascals; the entry temperature is 1100 K and the entry pressure undergoes 1 percent loss; that means, the pressure at the exit of the stator nozzle is 0.99 times P 0 1. The nozzle exit angle alpha 2 is 70 degrees; the polytrophic efficiency is prescribed as 0.85 for the turbine. The rotor maximum diameter that is at the tip of the radial turbine is 0.4 meters. The radial flow entry in to the rotor is prescribed and that is assumed to be or allowed to be assumed to be equal to the exit of the rotor, which is C a through and it is supposed to be axial. So, the axial velocity at the exit is to be taken as equal to the radial velocity relative radial velocity at the entry to the rotor.

The hub to tip radius ratio is 0.4 and T 0 3 at the exit is 935 K. The thermo dynamic parameters prescribed here gamma equal to 1.33; R equal to 287.287 kilo joules per kg K and C p as 1.158 kilo joules per kg K. The problem asked you to compute rotors tip speed, rotation speeds and rpm of the rotor; the mach number velocities, the rotor width at the tip of the rotor and T 0 2 relative; the stagnation pressure, mach number, hub and tip radii at rotor exit; at the rotor exit plane, the relative velocity V 3, T 0 3 relative, relative flow angle beta 3 and the relative mach number M 3 at mean radius; ofcourse, they are all connected to each other; the values of beta 3 are the relative flow angle and M 3 relative at different radii at rotor exit. Now, these are the answers that are expected out of this problem statement.

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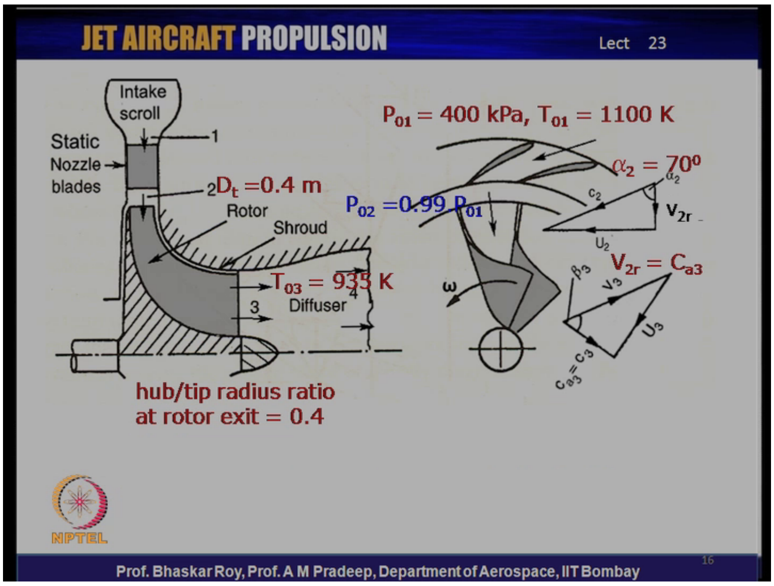

Let us look at the radial flow turbine diagram that we have done before. What is prescribed is the tip diameter of the rotor is prescribed as 0.4. At the entry to the turbine, what is prescribed is .0 P 0 1 equal to 400 kilo pascals, T 0 1 equal to 1100 K and alpha 2 over here is prescribed as 70 degree. V 2 r is that means this V 2 r here is to be equal to this C a 3. So, this radial component which is equal to V 2 here in this diagram as is normally often done in many gas turbines would be taken as equal to C a 3; that is this C a 3 that is coming out of the rotor; the absolute component of the velocity and its axial direction. The T 0 3 prescribed is 935 K and the hub to tip radius ratio of the rotor at the exit station, you see there is a hub here station and there is a tip of the rotor at the exit and this is prescribed as 0.4. So, these are the prescriptions with which we go forward the loss across the stator nozzle is 1 percent.

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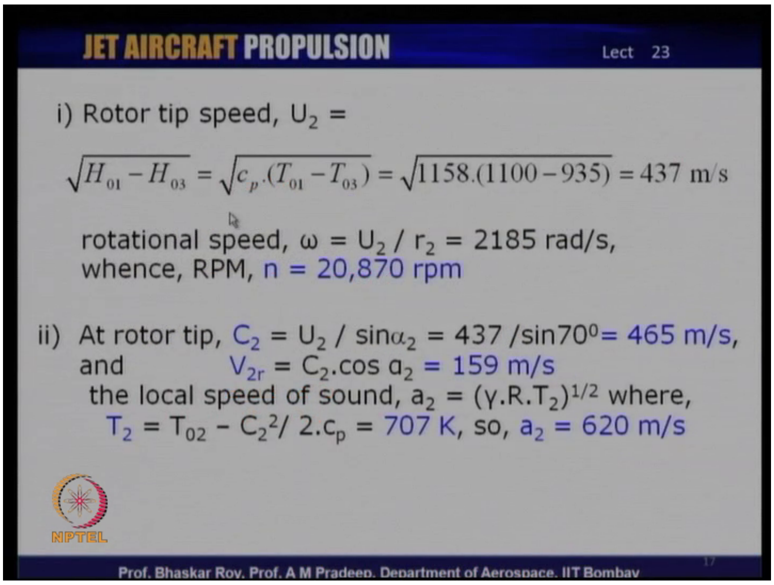

So, with this we move forward to solve the whole problem. The rotor tip speed can be simply found by using the isentropic laws and that tells us that if you use the enthalpy drop, you get a rotor tip speed of 437 meters per second. Now, this rotational speed then can be found simply by dividing this U by r and that gives us to 2185 radians per second. Corresponding to which, you would get the rpm equal to 20870 rpm. So, as you can see here, typical radial turbine would be running at very high rpm compared to an axial flow turbine. The corresponding at the rotor tip, the value of C 2 would be 465 meters per second using the velocity triangles that we have just seen. The corresponding V 2 r would be 159 meters per second. The local speed of sound using the local temperature T 2, you have to do that and if you do that, you get T 2 equal to 707 K and corresponding sonic speed as 620 meters per second.

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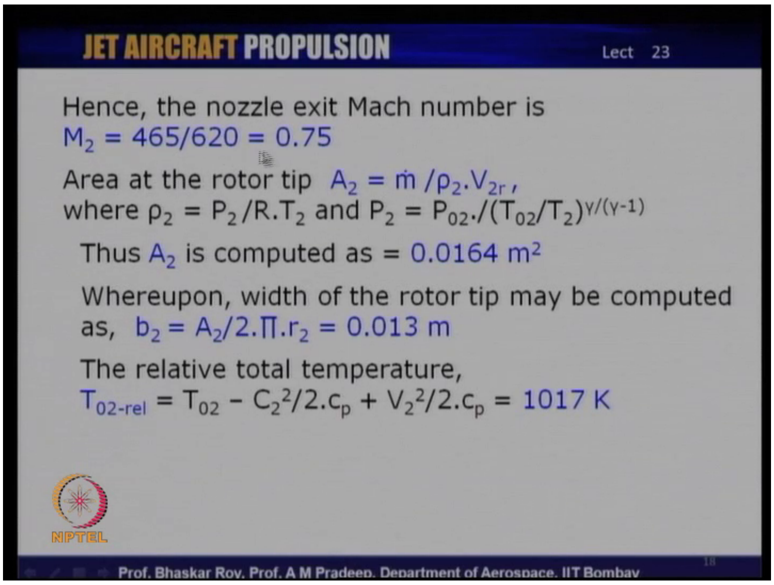

And then the nozzle exit mach number M 2 comes out to be 0.75. So, as you see here it is not sonic; it is still subsonic. The area at the rotor tip now is can be found using the continuity condition, as we have always done before and this comes out to be .0 0.0164. You have to find the local density and before that, the local pressure. So, if you do that, you get this area at station 2. Using this area at station 2 which is the entry to the rotor, you can find the width of the rotor tip; that is the axial width of the rotor tip. Using the geometry, you can find the rotor tip width to be 0.013 meters. This is simple geometry and then you can find the relative total temperature using the flow conditions that we have used before; that is T 0 2. You take out the absolute flow kinetic energy and plug in the relative kinetic energy and if you do that, the T 0 2 relative is 1017 K.

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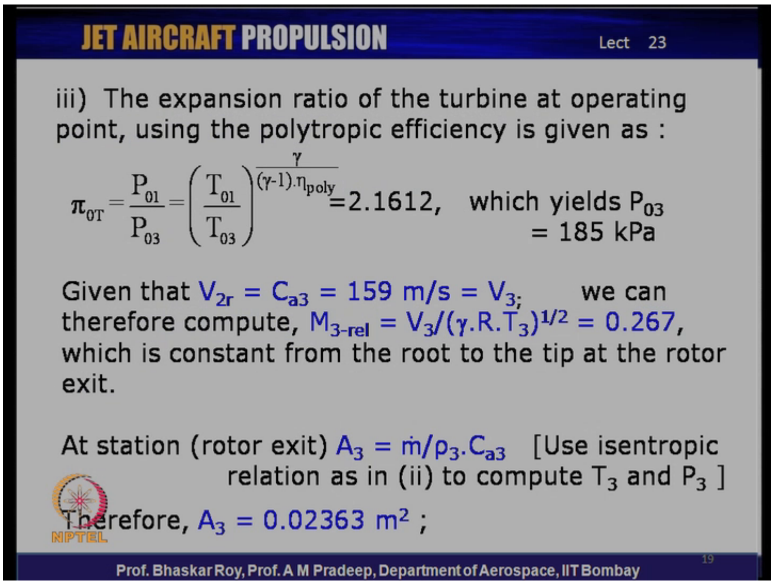

The expansion ratio of the turbine at this operating point using the prescribed polytrophic efficiency can be found by using the relation that we have done before and it gives you a velocity a value of 2.16, which ofcourse gives us a P 0 3 of 185 kilo pascals. Now, given that V 2 r is equal to C a 3 which would be then equal to 159 meters per second and this ofcourse is same as V 3. That we can therefore get M 3 relative that is the relative mach number at the exit of the rotor as 0.267. You would ofcourse need to find T 3 over there; so, which is taken to be constant from root to tip at the rotor exit. Now at station 3, A 3 can be found as using the continuity condition as m dot divided by rho 3 in to C a 3 and this yields rotor exit area to be 0.02363 meters square. So, that is the area you would get at the exit of the radial turbine rotor.

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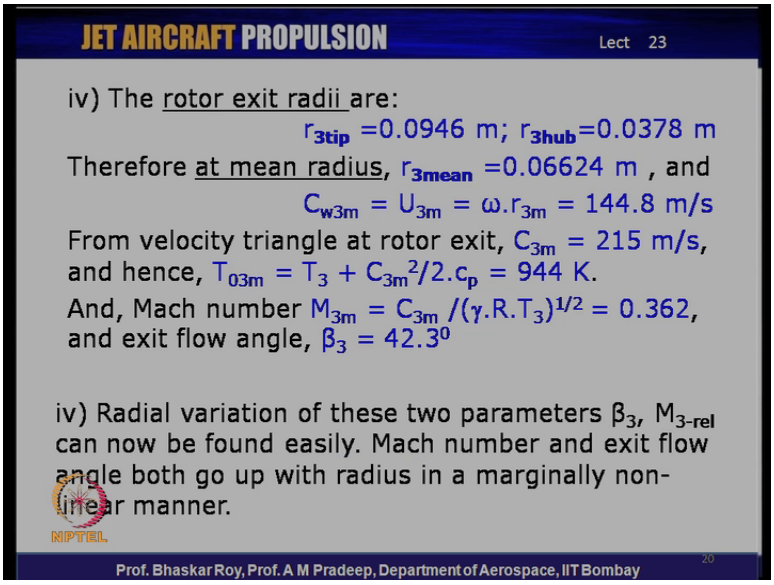

At the rotor exit area, if you find the radius using the area that we have found, we get the tip area using 0.4 as the ratio; tip radius to be 0.0946 meters and hub radius to be 0.0378 meters. And hence, the mean radius would be 0.06624 meters; corresponding to which, they are C w 3 the tangential velocity which is equal to U 3 would be 144.8 meters per second. The corresponding velocity triangle at the rotor exit would yield that C 3 at the mean of the rotor exit between; that is mean between the hub and the tip of the rotor exit is 215 meters per second and the T 0 3 at that mean would be 944 K. The corresponding mean mach number would can be now computed and you would get a value of 0.362 as the mean mach number at the exit. The corresponding exit flow angle would be 42.3. The radial variation of these two parameters that is beta 3 and M 3 relative can now be found and a mach number and the exit flow angle is go up with radius in a marginally non-linear manner.

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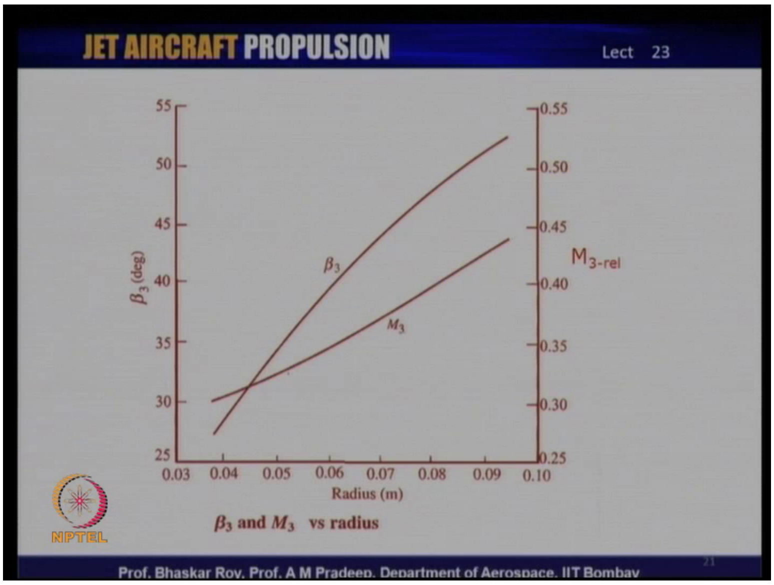

So, let us look at the solution in a graphical manner. Beta 3 is shown over here and M 3 relative on the other y axis and the change of radius across as we can see M 3 varies along this line path and beta 3 varies in a slightly different manner. Both of them ofcourse going up from hub to the tip of the exit of the turbine; so, this is what the solution of a radial flow turbine is.

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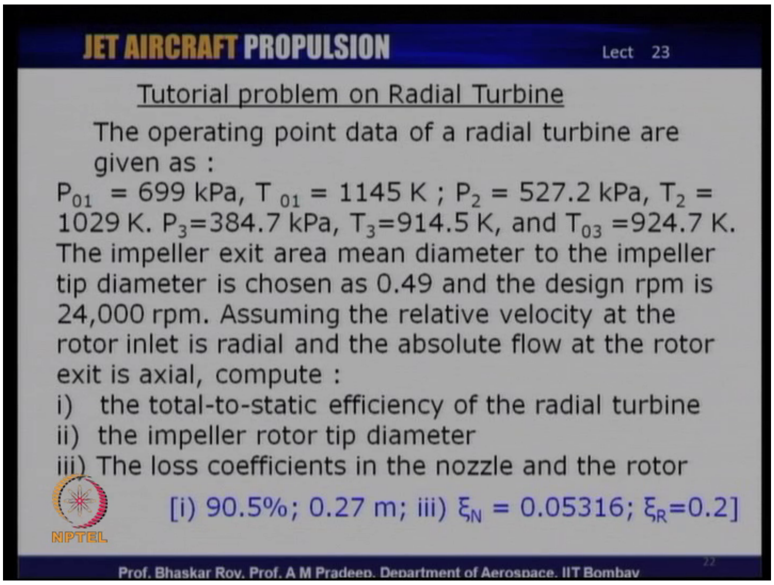

I will leave you with tutorial problem which you can solve on your own. The radial turbine problem prescribed here is that the operating point data are given to you P 0 1 is 699 kilo pascals, T 0 1 equal to 1145 K; the prescribed nozzle exit pressure is 527.2 kilo pascals and the nozzle exit temperature is 1029 K. The stage exit static pressure is given as 384.7 kilo pascals and static temperature there is 914.5 K. The T 0 3 value correspondingly is prescribed as 924.7 K. If it is given that the impeller exit area mean diameter to the impeller tip diameter is chosen as 0.49 that is ratio between tip and mean, the design rpm is prescribed as 24000 rpm.

Assuming that the relative velocity at the rotor inlet is radial as we have done before and the absolute flow at the rotor exit is axial again as we have done before, you are asked to compute the total-to-static efficiency of the radial turbine; the impeller rotor tip diameter and the loss coefficients in the nozzle and the rotor using the definition of the loss coefficient that we have done in the lecture. If you do those things, you would get answers; the total-to-static efficiency would be 90.5; the impeller rotor tip diameter would be 0.27 meters and the loss coefficients would be for the nozzle stator nozzle 0.05316 and for the rotor 0.2. As we see, the rotor loss coefficient is substantially higher than that of nozzle loss coefficient.

So, these are the numbers you would get and as you can see, these numbers are quite different from that of axial flow turbine. So, we have done two solved two problems. So, one on axial flow turbine; one on radial flow turbine and we have give prescribed some problem for you to solve. And as you can see, you can get the feel of the numbers that the numbers corresponding to radial flow turbine are quite different from that of axial flow turbine. If you talk in terms of efficiency; if you talk in terms of rpm; you talk in terms of the mass flows, the numbers of axial flow and radial flow turbine are quite different from each other. And by solving the problems, I hope you would get the feel of these numbers and that is very important for engineering people to get the feel of the numbers. We will leave the turbines with these problems and we will proceed in the next class.

We will proceed on to the combustion chamber, and that is what we will be doing in the next class. So, we have finished the turbine chapter, and from the next class we will proceed on to the combustion chamber, which actually spatially in a gas turbine you remember comes before the turbine. So, we will now look at how the hot gas is created that is applied to the turbine, and that is what we will be doing in the next class.