Fluid Machines.
Professor Sankar Kumar Som.
Department Of Mechanical Engineering.
Indian Institute Of Technology Kharagpur.
Lecture-35.
Performance Characteristics of Centrifugal Compressors Part II.

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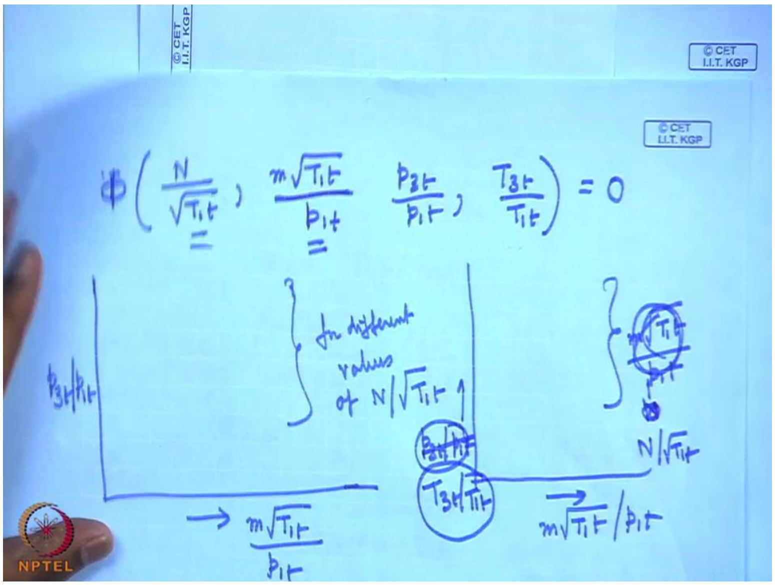

Good morning and welcome you all to this session of the course. Now we will try to solve some problems. Okay. Here it is. Now let us see a problem now. Here also I did a mistake, this will be not, this will be repetition of this, this will be M, sorry, this will be M we are writing, N by root over T1 T and this will be for T3 T by by T1 T, this I did a mistake earlier, this will be like this, the 2 curves. Okay.

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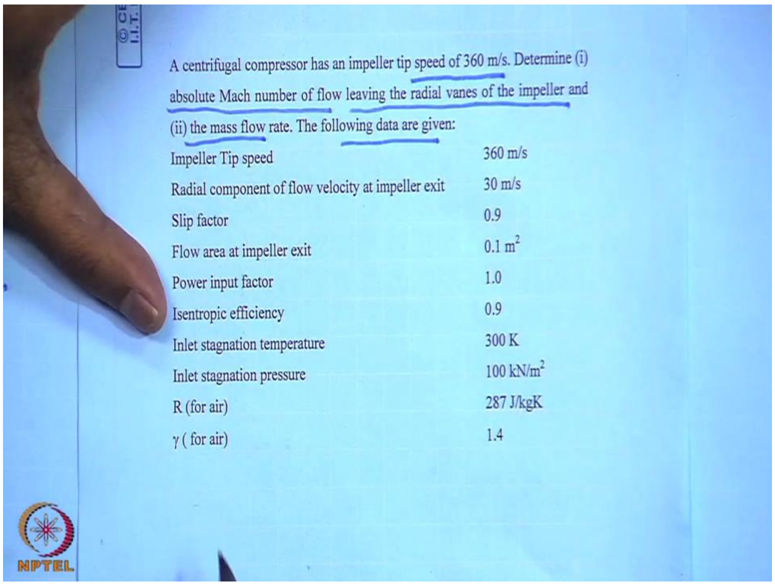

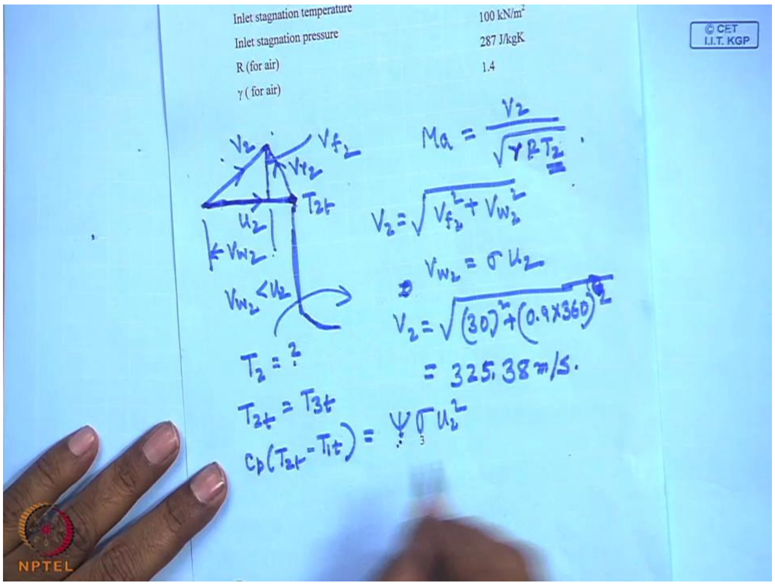

Now let us solve problems. So we have discussed the principal of, the characteristic curves, the concept of surge, the surge line, the maximum efficiency line and the choking line. Now let us consider this problem. A centrifugal compressor has an impeller tip speed 360 metre per second, this is the impeller tip speed. Determine absolute Mach number of flow leaving the radial vanes of the impeller and the mass flow rate. The following data are given, so data are given.

So let us see, the Mach number of flow leaving the radial vanes, absolute Mach number, means based on absolute velocity. If we recall the vane, now let me recall the vane like this. Sorry, this is the vane. It is not, oh oh , this is the vane, this is the vane. Now if this is the vane, then what is the diagram that the velocity diagram, let me better show the things which I earlier showed you. This is the thing, I think this will be better to show like this, you can make things like this. Can you see? Okay.

Please. Why I am writing that, I am not doing the radial one? Here one thing is important that slip factor is given 0.9. That means here, due to the slip, what happens, we have a, this is rotating in this direction, U2, so VR2 is not radial because there is a slip, so VW2, this is VW2, VW2. And VW2 is less than U2. What is U2, U2 is this one, this is U2. So this is the absolute velocity V2. And this velocity is VF2. This is VF2. So this is the diagram because there is a slip, so therefore this is the outlet triangle.

Now what I will do, I will write what has to be found out, then it has to be found out that Mach number based on absolute velocity at the outlet of the impeller. So therefore I have to find out Mach number V2 by root over gamma R T2, okay. Now how to find out V2? V2 is the absolute velocity. Now we to his root over, this is VF 2, VF 2 square + this is VW2, VW2 square. Now VW2 is not U2, okay, this is U2, this is U2. So VW 2 is Sigma U 2.

Okay, now U2 is 360 metre per second, V F2 is given, flow area, power input factor, impeller tip speed, flow area, mass flow rate, so VF 2 is not given, impeller tip speed is given, radial component of flow velocity is given, VF 2 is 30 metre per second. You will see that V F2 is 30 metre per second so therefore you get V2 is equal to 30 square +0.9 into 360 square. I will not do everything, calculations square. In this way you will get a value of V2 equals to, what is the value of, let me tell you the value of V2 here, the value of V2 is 325, you can check, 325.38 metre per second.

Now to find out the Mach number, you require this static temperature, here in the formula, it is gamma R T2, T2 is the static temperature at the outlet of the vane. Now how to find out T2? Now our main objective is to find out T2. Let us 1st find out the total temperature T2 T, we know that T2 T here is equal to T3 T, that means outlet total temperature from the compressor at the outlet of the diffuser. And we know that CP into T2 T - T1 T, that is the work done, that is equal to psi, Sigma, the power input factor, U2 square divided this is okay.

So now here you see T1 T is given where because the inlet stagnation temperature, 300 K is given. psi is given, power input factor is given, one, now slip is given 0.9, Sigma is given 0.9, psi 1, U2 is given 360 metre per second, T1 T is given, the inlet stagnation temperature is 300 K, so everything is given except T2 T from which we can find out T2 T equals to what? T2 T becomes equal to, ultimately if you calculate T2 T will be 416 K. I am not writing every step because everything I know, power input factor is given in the problem, slip factor is given in the problem and T1 T is given the problem, U2 is given in the problem.

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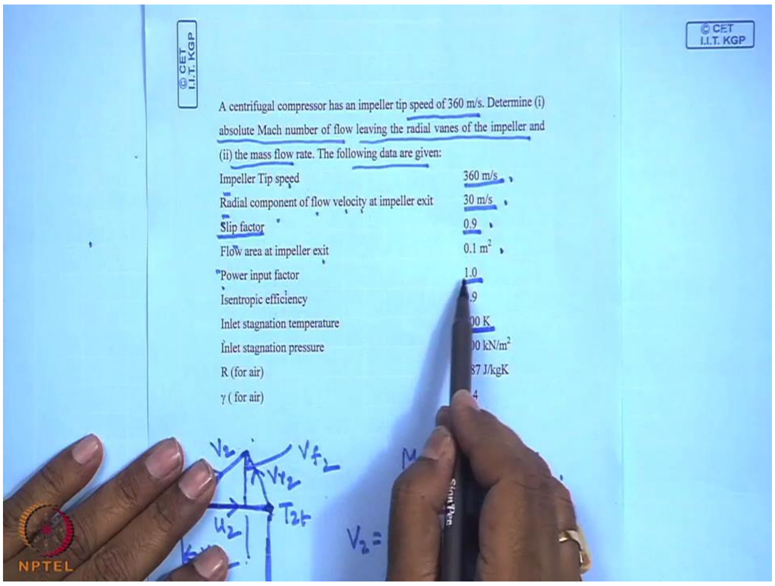

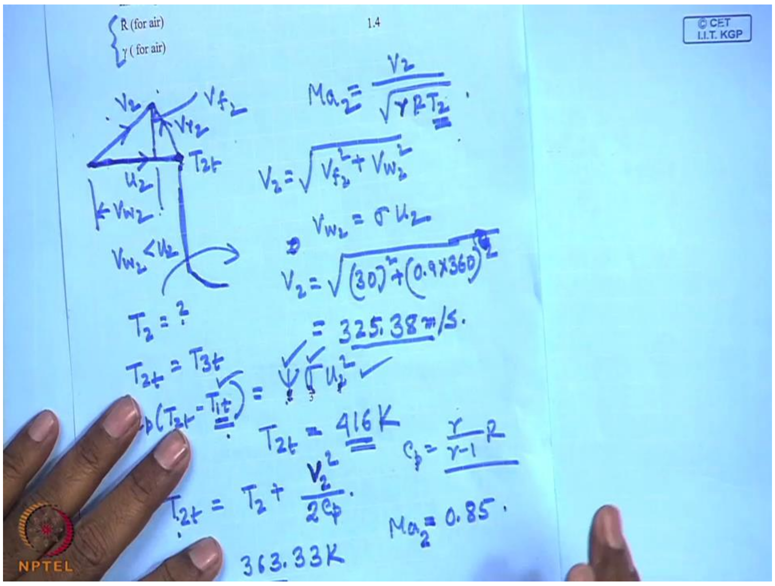

Again I will show you the problem that impeller speed 360 metre per second, radial component of flow velocity 30 metres, slip factor is 0.9, flow area at impeller exit 0.1 square, it is not now required. Power input factor is given, isentropic efficiency given, inlet stagnation temperature, inlet stagnation pressure, then R and gamma. So here what is required, power input factor which is given as 1, the slip factor which is given is 0.9, U2 is 360 metre per second and T1 T is 300 K, we get T2 T.

Now what happens, T2 how to find out T2? Now T2 has to be found out from the concept of the stagnation temperature. What is that? T2 + the temperature, then the velocity equivalence, temperature equivalence of the dynamic head, that is V2 square by 2 CP. That is the temperature equivalent of the kinetic energy, V2 square by 2, that is total, this + this is the total temperature, from which we can find out T2 is, T2 T is now found out 416, now V2 already we have found out 325.38 metre per second, the value of CP has to be found out from R and gamma.

Which you have read at school level that the specifically, the constant pressure is gamma by gamma -1 into R. So you know this is CP, so therefore from here you can find out the static temperature as 363.33K. Everything is known, so we know this static temperature. When we substitute this static temperature here, we get the Mach number equal to, the Mach number 2 for example, the 2 suffix I am using equals to 0.85 all right. Now the next is to find out the mass flow rate.

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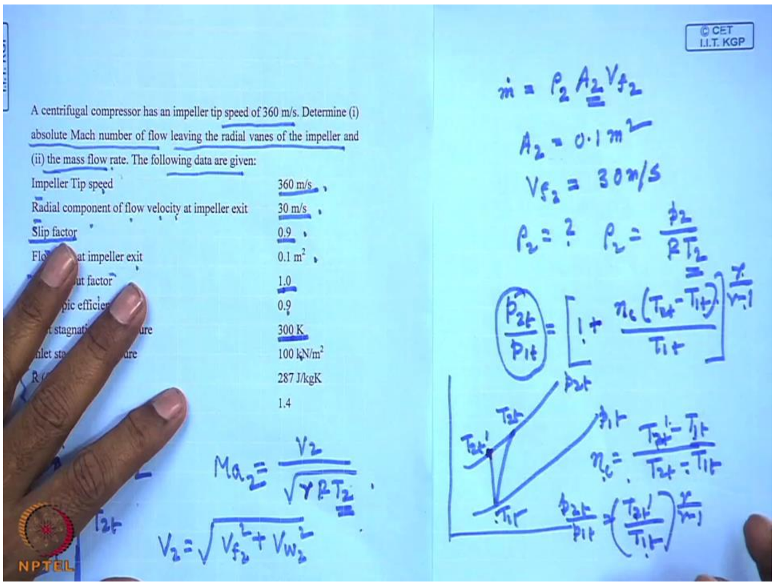

How to find out the mass flow rate? We will see the mass flow rate. Let me keep it here so that you can see. Now mass flow rate to find out, mass flow rate, let us write the mass flow rate. Mass flow rate is same throughout the machine. Let us write the mass flow rate based on the condition at the outlet of the diffuser rho2, A2 and the flow velocity. Now here A2 is the flow area at the outlet of the impeller which is given you see here. Flow area is given, radial component of flow velocity, the mass flow rate, impeller speed, flow area at impeller exit, that means A2 is already given, 0.1 metre square.

So what is not given, V F2 is given, the radial flow velocity coupled with the impeller exit is given, V F2 is given, VF 2 is what, 30 metre per second. It is alright, 30 metre per second. What is not given, rho 2. So how to calculate rho 2? Now rho 2 is P2 by R T2. Now T2 I know, the static temperature, already, T2 already is calculated here, so I do not know P2, how to calculate P2? Now before calculating P2, you have to calculate the stagnation pressure, then if you calculate the stagnation pressure, then you can calculate the static pressure.

So how to calculate the stagnation pressure? So stagnation, stagnation pressure you can calculate P2 by T1 T from your this earlier formula 1+ Eta C into, you can calculate, write like that, T2 T - T1 T divided by T1 T to the power, this has been told earlier, gamma by gamma -1. So you remember this one that is the pressure, this comes from where, this comes from the isentropic relationship and then using the isentropic efficiency of the compressor.

Well, so using these relationship, we can find out, this relationship you remember, this was derived in the class, that means I find out this way that if these are the 2 pressure lines, then what happens. This P2 T, P1 T, then this is the thing, this is the T2 T, T1 T and this is the T2 T dash. So P2 T by P1 T is T2 T dash by T1 T to the power gamma by gamma -1. Now this T2 T dash by T1 T is found out by expressing this Eta C is T2 T dash -, I repeat again, this was done earlier, - T1 T.

So therefore T2 T dash, that means P2 T by P1 T is T2 T dash by T1 T to the power, this is the isentropic relationship, PT relationship. So this thing is taken from here, T2 T dash by T1 Eta C into this +1. So Eta C into this by T1 T +1. So therefore we can write this, this is the thing done earlier. Now T2 T - T1 T you know, already you know T2 T, you already know T2 T, T2T is found out, T2 T is 416 K. You know T1 T, T1 T is 300 K, given, Eta C is given in the problem, Eta C is what?

C is 0.9, so therefore T1 T is known, everything is known, you find out the P2 T. Now after knowing the P2 T, you have to know the P2 because how, because rho 2 is P2 by R T2. I rotate earlier, so you have to know the static pressure.

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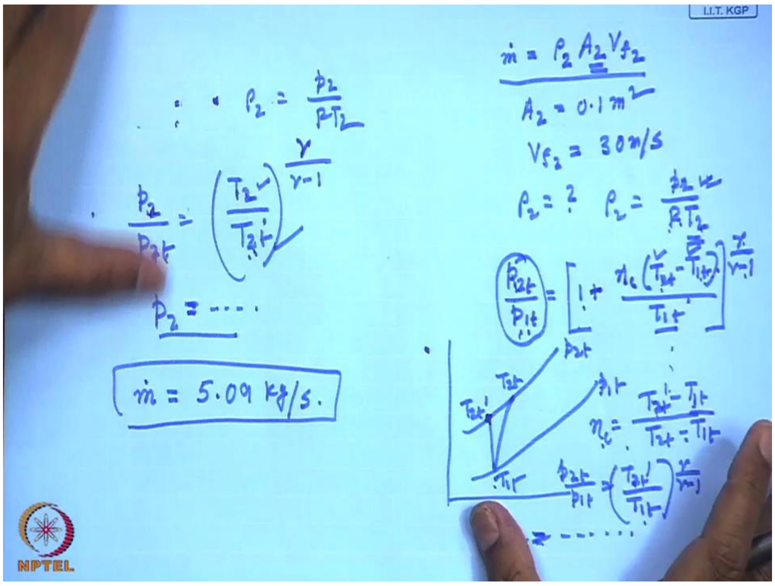

Now how to know the static pressure? By the concept of stagnation pressure, P2 by P 2 T is T2 by TT to the power gamma by… Wherefrom it comes? That means the static pressure is changed to stagnation pressure, that means when this is brought rest isentropically. That means this process of changing from P2 to P2T is obtained by bringing the fluid isentropically to this. That means therefore the gain in temperature T2 T from T2 is made isentropically, so that the pressure ratio will be related to the isentropic relationship with the temperature ratio. This is the relationship between total stagnation pressure to the static pressure.

So therefore T2 T2 T is known, therefore we get P2. So we can find out P2. You understand. So from here we find out P2 T, P2T is known, here we find out P2 T, P2 T is found out here and here we find out P2, because P2T is known, so finally P2 is found. 1st we find out the ratio of the total pressure in terms of this, you know everything, P1 T you know, you know P2 T. When you know P2 T, you know P2 from this equation. So P2 is find out.

So when P2 is found out, then you can find out rho 2 from P2 by R T2 and you can find out the mass flow rate. So I am not doing things by putting the numerical values but I tell you the way, so this values you check, 5.09 KG because this will take more time to solve this by putting these values. So that is I am not doing, so if you put these values, you will get the results. I think there will be absolutely no problem. Now only substitute the numerical values and get the result and check the results with this.

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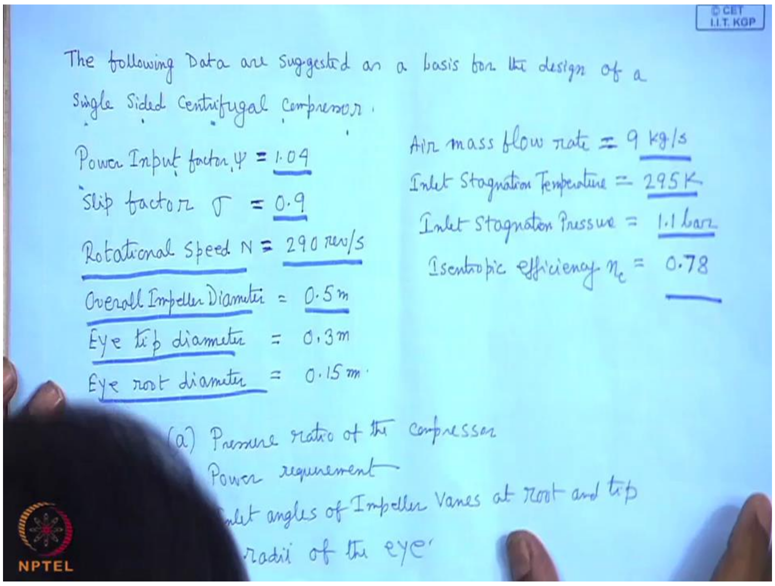

Now next another problem I will discuss before I leave you, so another problem is this one. Let us consider a problem like this. The following data are suggested as a basis for the design of a single sided centrifugal compressor. Single sided. Power input factor is 1.04, slip factor, 0.9, almost the similar problem which we discussed earlier, rotational speed is 290 revolutions per second, overall impeller diameter 0.5 metre, eye tip, eye root diameter. Air mass flow rate is given, in less stagnation temperature is given, in that stagnation pressure, isotropic efficiency.

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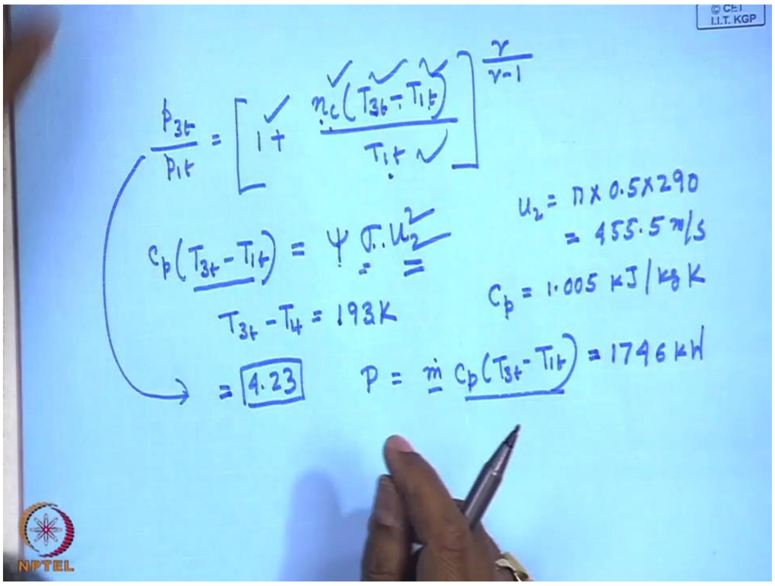

Now what is to be found out, determine pressure ratio of the compressor, power requirements, inlet tangles of impeller vanes at root and tip radii of the eye. Now let us find out the most simple thing, the pressure ratio. How to find out the pressure ratio? Now pressure issue to find out, what we have to do, let us again write the pressure ratio formula. If you write the pressure ratio, now I write P3 T by P1 T is equal to come in terms of this stagnation temperature rise, I think this you know, again and again I am writing. Just now I have discussed this, just now I have discussed this that the stagnation of total pressure ratio.

Here also the pressure ratio of the compressor, total pressure ratio P3 T by P1 T has to be found out. Now therefore what we require, we require T3 T - T1 T. How to find out T 3T - T1 T? Again the same formula we know, the work done to the fluid per unit mass or the energy added to the fluid per unit mass, it is psi power input factor, Sigma U square, U 2 square. Now this thing can be found out provided psi, Sigma, U2 square is given. What is given in the problem let me see.

This problem gives rotational speed at overall impeller diameter, 290 revolutions per second and overall impeller diameter 0.5. So U2 is equal to pie into the overall diameter 0.5 into 290 is equal to the rotational speed, that means the tangential speed is 455.5 metre per second, that means U2 is known. Sigma is given in the problem, if you see the slip factor is 0.9. Sigma is power input factor is 1.04, so if you put everything, you get the value of T3 T - T1 T which becomes equal to T3 T - T1 T is 193K.

Here the value of CP is not given in the problem. In the problem is the value of CP is not given in case you can use for air, the value of CP is 1.005 kilojoules, this is a specific speed, per KG K. So therefore you can use the value of CP and get T3 - T1 T. Eta C is probably given in the, where is Eta C, there is this isentropic efficiency, 0.78. So when you get the isentropic efficiency 0.78, the surface, T1 T is given, T1 T is the inlet stagnation temperature, inlet stagnation or total temperature, whatever you call, to 95K, so everything is known and this T3 T equals to, what is the value, equals to 4.23.

This you can check, so you can find out. So pressure ratio of the compressor is found. Power requirement, power requirement is mass flow rate into the CP, this work done per unit mass, T1, either this or this, both the things are same. So anyway you find out, the mass flow rate is given probably, otherwise power cannot be found out, air mass flow rate, 9 KG per second. So work per unit mass into mass flow rate is a power, you know everything, the power requirement is now 1746 kilowatts.

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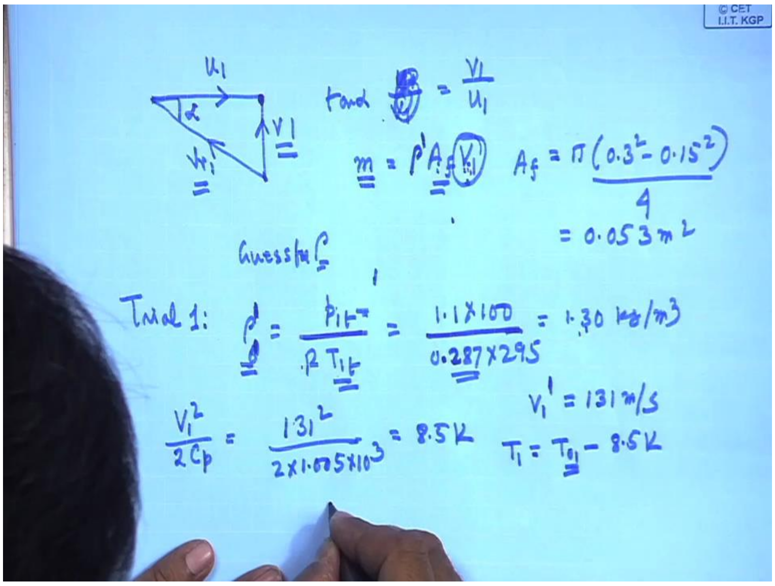

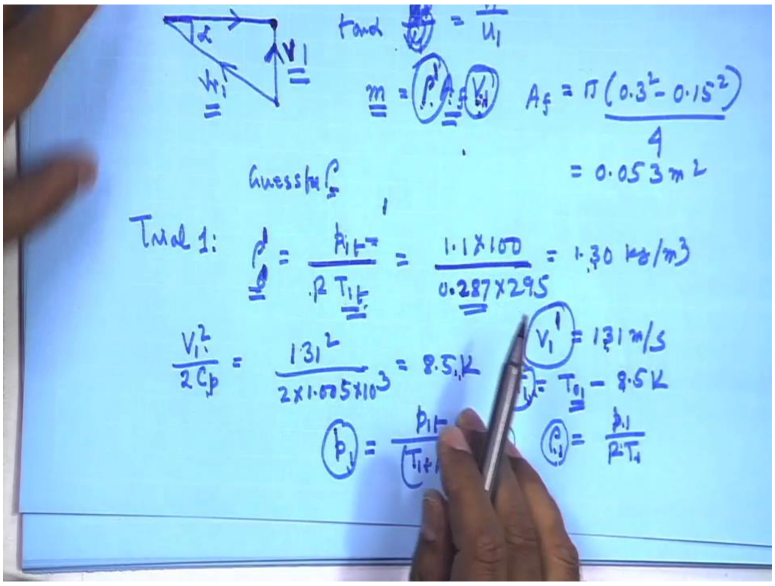

Alright, now the 2nd part is the inlet angles of impeller vanes at root and tip. Now at root and tip if you want to find out the impeller angles, then what will happen, let us find out root or tips anywhere at any representative section, it may be root, it may be tip. Okay, that means it may be root or it may be tip, that either it is, this is the root and this is the tip, so root and tip, axial flow velocity is constant, the normal flow velocity is constant, it is given there.

Okay, we will assume that, however, now what happens is that if we know the U1, the speed in V1, and VR1, if this is this, Alpha, just I wrote, I draw the right grams. So tan Alpha is U1 by V1. So I have to know the flow velocity or the relative velocity, tan Alpha is oh, V1 by, sorry, tan Alpha is V1 by U1. So this is, if I know the, at root this velocity, then this will be root, angle at the root, at the trip, it is angle at the tip. So root and tip, U1 will be found out based on the root and tip diameter, that I know, because I know the rotational speed.

I know the rotational speed, I know the eye tip diameter, I know the eye root diameter, but here I know, I do not, I know neither V1, nor VR1. So how can I find out? So this type of problem is based on a trial. What trial, how to find out V1? So V1 is not known, so if you see from the mass flow rate basis, mass flow rate is given. Rho AF V1. Okay, now AF is given, how AF is given, AF is given because the eye tip diameter, eye root diameter is there. The one can find out AF as pie into 0.3 square - 0.15 square by 4 and this becomes equal to 0.053 metres square.

So I know AF, so I have 2, these 2 I know, so what is that, I have to make a trial, guess for, guess for rho and find out V1. How to guess for rho? This rho, for example trial 1, this is the trial method. I guess rho from the total pressure, P1 T R T1 T, at impeller eye I know T1 T, I know P1 T, based on this I find out in this value is given 1.1 bar into 100 by 0.287 into 295. This is the value given here, yes, 1.1 bar.

So this in terms of kilojoules, kilo, this Newton per metre square, converting this unit is there, that is why I have written 0.287 which is, it should be 10 to the power 5, then another 10 to the power 3 and then it will be 287, the characteristic gas constant, you see the consistent unit it is written and it becomes 1.30 KG per metre cube. Now if you know this rho 1, 1st trial, this rho 1, trial 1. You put that thing rho 1 and if you know the mass flow rate is known, mass flow rate is already given in the problem, what is the mass flow rate? Mass flow rate is 9 KG per second, you get a value of V1.

Now when you get the value of V1, how to iterate, there should be a base on which you will iterate. When you get the value of V1, you can calculate the corresponding temperature, dynamic temperature by V1 CP. For example 1, this density you get, from this density you find out the V1. So with this density field find out the V1, then V1, for one trial will be 131 metre per second. So when you know the V1, then what you do, with this V1, you calculate gamma for 131 second V1 square by 2 into 1.005 into 10 to the power 3, the corresponding temperature.

So if you know this temperature, you can calculate the static temperature, T0 1 - this, 8.5 K. T0 1 we know, so therefore we can find out this static temperature and at the same time, we can find out, this is a little labourious calculation I know but this is usually done in the design. The static pressure as, as I told you the formula earlier, the static pressure and static, total pressure is related to the static temperature and total temperature to the isentropic relation. So I get P1.

When I get P1 and T1, I can find out rho 1 as P1 by R T1. That means by guessing a rho based on the stagnation condition I find out is V. When V is found out, I find out the dynamic equivalent temperature and with that temperature I can find out the static temperature in the static pressure by isentropic relation. When these 2 things are known, static pressure and temperature, then rho one is P1 by R T1. That means rho is getting connected. With this rho I find out again the corrected velocity.

So this way both rho and V, rho 1 and V1 1, V1 1 and rho 1 1, rho one is getting connected so that we get a converged value. When we have a converged value, then we get V1, when we get the V1, which is constant, the actual velocity of low throughout the impeller passage is same. That means it is same as the, at the root and tip. Then what we will do, when we will use the peripheral speed at the root, then we will get the angle of the vane at the root and at the tape, then I will get the angle at the tip.

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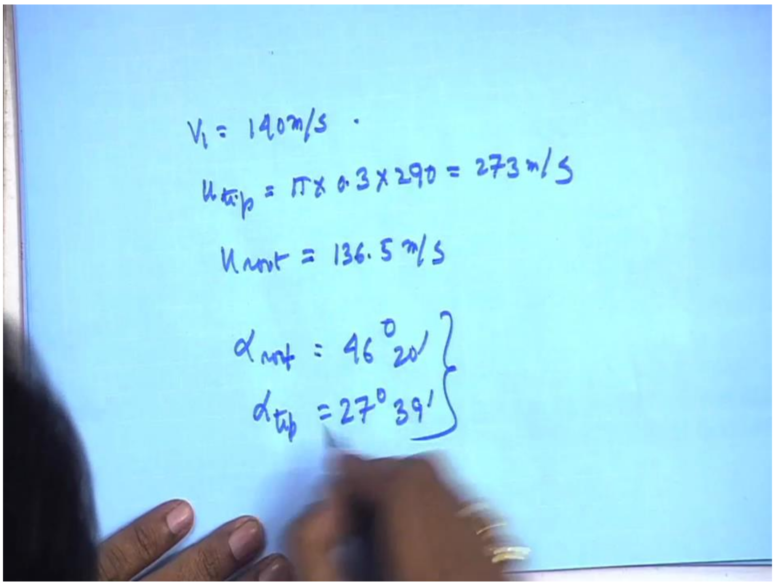

And if to do so, then you will get, I am giving you this value, the V1 converged value of V1 comes out to be 140 metre per second and U tip, you find out pie into as the value is given, you check the rotational speed into tip diameter, 273 metre per second and U root is equal to just half, the diameter is half metre per seconds and Alpha root, that by 10 Alpha, that formula, V1 by U, perpendicular by base, V1 by U, it becomes 46 degree and Alpha tip becomes 27 degree. This is 20 minute in more from where I have taken, this is the value. So there is an iterative process by which you have to do. Okay. Thank you.