Steam and Gas Power Systems
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Module No # 07
Lecture No # 35
Centrifugal Compressors

I welcome you all in this course on the steam and gas power systems, today we will discuss the centrifugal compressors. The compressed air in mechanical engineering applications is often required and centrifugal compressors are used in the gas turbines so it is imperative to discuss them here.

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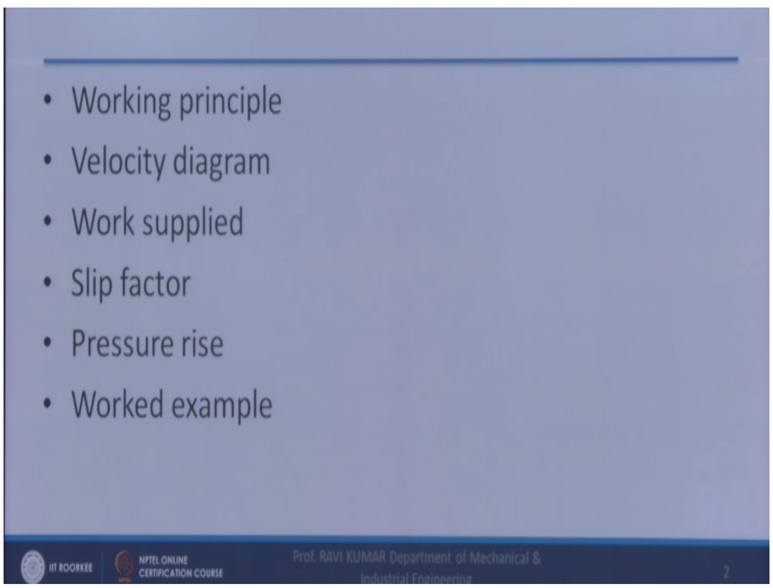

We will start with the working principle of centrifugal compressors then we will draw velocity diagram, how much work has to be supplied to the centrifugal compressor will the formula for that.

There is a phenomena slip factor we will discuss the slip factor pressure rise in a centrifugal compressor and we will do one word example as I said earlier the compressed air is required in variety of mechanical engineering applications.

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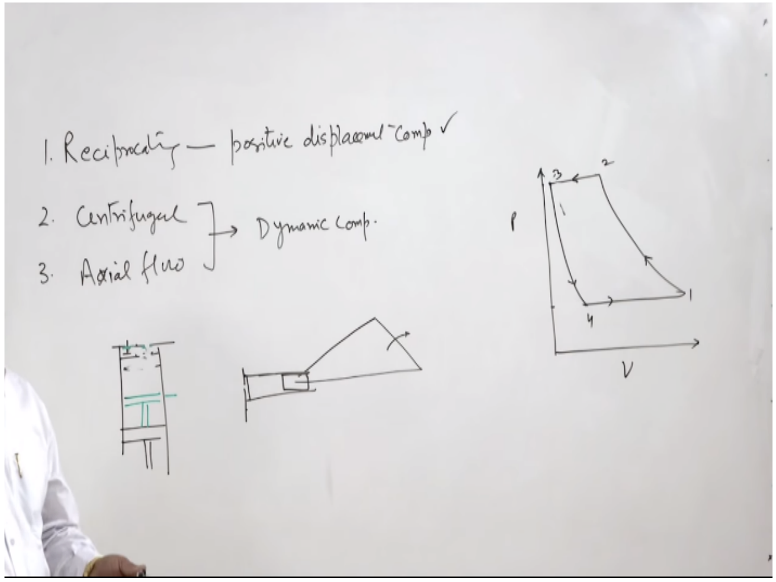

There are two types of compressors, one is reciprocating compressor, three types in fact reciprocating compressor they are known as positive displacement compressors. And another type is centrifugal compressors and third one is axial flow compressors and these are known as dynamic.

The positive displacement compressors are used where high pressure ratio is required, because but the mass flow rate is not very high in reciprocating compressors, because they work on slider crank mechanism, they work on, there is a slider crank mechanism as in the case of IC engines.

So, there is a crankshaft connecting rod and there is a piston which does to and froth motion in a cylinder and at the end or at the head there are walls. If I draw a vertical diagram of a vertical compressor, so head is having two walls, they intermittently open and discharge the gas or air to the supply pipe line. And if I draw the pressure and the velocity, sorry pressure and volume, PV diagram for a reciprocating compressor.

It is going to be like this, from state 1 to state 2 then the state 3. Now here the volume at state three is shown as zero but practically it is not possible. I mean there has to be some clearance between the top dead center within the top dead center and the cylinder head, otherwise breakage may take place or some hearing may take place. So instead of having volume at three, zero, some volume is left three, that is known as clearance volume right and since clearance volume is there.

This is at the end of the stroke right, so the process starts like this, the piston starts moving in upward direction, both the walls are closed, so it a closed system. So, process one to two takes place in a closed system, the process two to three when piston has travelled certain distance now initially both the walls are closed one of the wall, exhaust wall will open and pressure will be relieved sorry the gas will be released from the piston.

It is a constant pressure process, for open system right. So, in fact the volume is reducing and in fact the mass flow rate is taking place across the system that is why the volume is reducing. So, up to this is the entire stroke one, two, three, so part of the stroke the system remains the closed system and the part of the stroke the system becomes the open system at the top dead center, the outlet wall is closed and inlet wall is open.

But the pressure is high this gas available at state three is expended to state 4. And from state 4 the suction starts then inlet valve will be open, fresh air will come in, both the valve will close then compression outlet valve will open the high pressure gas will leave the cylinder and then outlet valve will be close, inlet valve will be open. Then there is the expansion of gas takes place in return stroke.

Here the inlet valve will open and the air will be breathe into the cylinder. Now here in this case, because it is a reciprocating machine working on the slender peg mechanics, we cannot go for very high RPM, because this is not totally balanced. There are certain unbalanced forces in this mechanism and if we go for very high RPM, unbalanced force will be very high. So, these types of compressors are used where pressure ratio is very high, and mass flow rate is low mass flow rate, high pressure ratio.

Our theme of these compressors is approximately 1000 RPM or 800 RPM or 1200 RPM. Now if you take the centrifugal compressor, this is a rotor dynamic machine. It is a rotary compressor.

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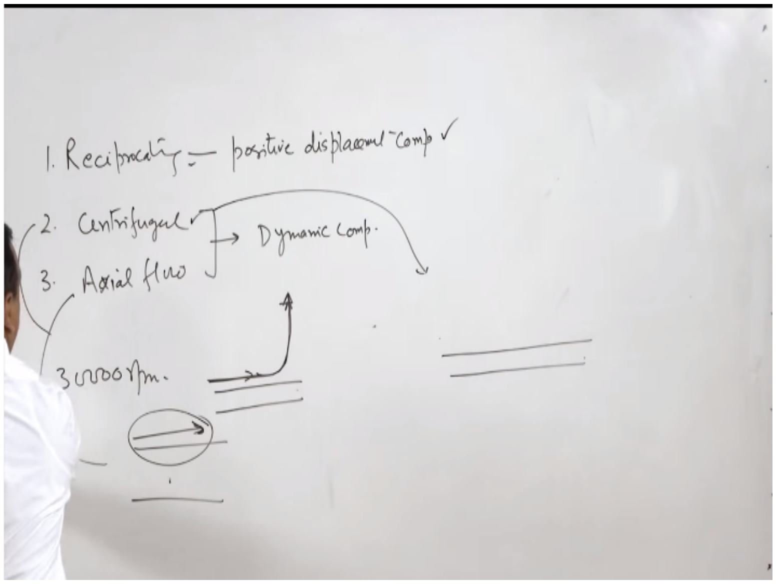

In a rotary compressor there is a shaft and impeller is fixed and there is housing. So there is no unbalanced force so these type of compressors, they can go up to say 30,000 RPM, right. In centrifugal compressors because I will explain you the mechanism later on there is an axial entry of air and radial release. So along the shaft there is an axial, the air breathes into the compressor in the axial direction and it leaves the compressed air leaves the compressor in radial direction.

So there is a change in direction. In axial flow compressor the flow is in only in axial direction, right. Because there is no deviation in the direction so efficiency of the axial compressors is the highest, followed by centrifugal compressors and the reciprocating compressors have low efficiencies. So a normally reciprocating compressors they have efficiency for the order of 75 to 80%.

It varies between 70 to 80%, 85 or it may go up to 85 %. But, these compressors have efficiencies more than 90% or more than 90%. Now in centrifugal compressors, now we will discuss in details about the centrifugal compressors. Now the elements of a centrifugal compressor is first of all there is an inlet pipe which is connect, suppose there is shaft, right. First of all I will draw the end view of centrifugal compressors.

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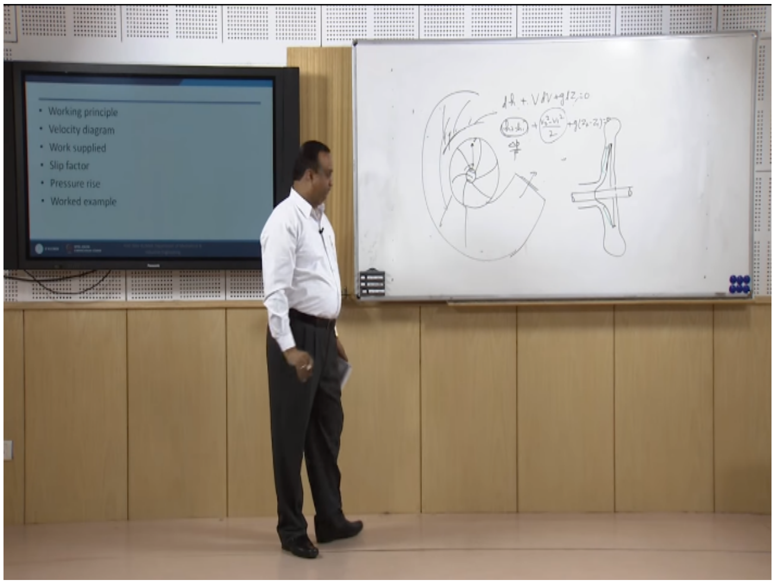

It necessarily has one impeller that is very important part of a centrifugal compressor, it is a disc, impeller is nothing but a disc. And it is disc is mounted on a shaft. Right. And it has veins. The number of veins may differ it is 15 to 20 veins and veins are diverging passages, right. And veins are surrounded by the diffusers, because when the air enters, in axial direction. The compressor is rotating in certain RPM with the help of a motor.

Because in compression external energy is required. External work is required, so a motor is fixed so motor moves the compressor right, with a certain RPM right. And when the fluid enters this impeller, I will draw the end diagram also, it is something like this. There is a housing inside the housing there is impeller. And impeller is having the veins, veins I will draw with a different color, impellers are having the veins.

So when this disc is moving it can have entry for both the sides. The impeller can have entry flow of here from both the sides. It can have entry from one side or it can have entry from both the sides. Now this impeller, the air enters this impellers. So air has, it is already moving with very high rotational speed this energy is imparted to air also starts moving with the high velocity. Now if you look at the first law for open system.

First law for open system says DH + VDV + GDZ = 0 or H2 - H1 + V2 square - V1 square by 2 + GZ2 - Z1 = 0. Right now when high velocity, this H1 and H2 right, it is delta P by row, VDP.

So the kinetic energy is imparted to the gas, so physically if you look at a scientifically compressor, the air is and the coming in contact with the impeller and kinetic energy is important to the air right.

Now the energy, the kinetic energy from impeller is imparted to the air moves in outward direction. Right, then this energy, kinetic energy is converted into the pressure energy in a diffuser, so there are two types of diffuser one vein less diffuser and another is weight diffuser. So when air enters the vein diffuser it is also a diverging section. When the air enters the vein diffuser, the velocity is reduced and the pressure is increased.

And after the vein diffuser there is a volume casing of increasing the cross section, this is increasing and at the end of the volume casing there is exit. So, in a nut shell initially the air is sent into the compressor, kinetic energy is imparted by the impeller. Now this kinetic energy is converted into the pressure energy in vaneless diffuser vain diffuser and volume casing and it goes out of the system. Now if we draw the enthalpy entropy diagram for centrifugal compressor.

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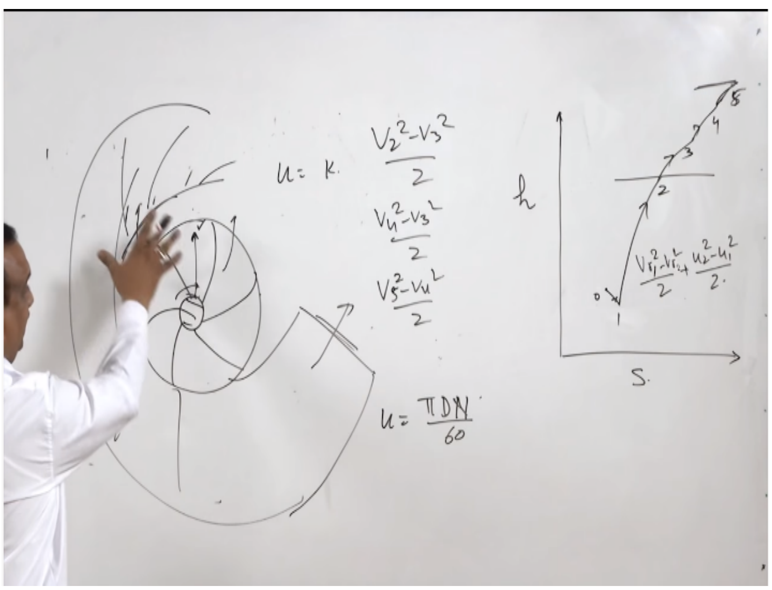

Instead of temperature entropy if you draw it is more the same thing if you draw enthalpy entropy or temperature entropy, enthalpy and entropy diagram for a centrifugal compressor. So initially the air is sucked in, so air is available at state 1, it is sunk into the compressor, so the pressure and the suction of the compressor is below the atmospheric pressure. Only then air can be sucked in and it is not an isentropic process.

So, we can say the process is 1 to 2 or 0 to 1. This is entry to the compressor at reduced pressure. Now in the impeller enthalpy is increased, right. Enthalpy is increased and the air enters with certain relative velocity right. Now here in compressors machine is already moving with very high velocity. So, relative velocity at inlet is higher than the relative velocity at the outlet in turbine it is reversed.

So in turbines normally a relative velocity at outlet is greater than rate of velocity at inlet. But here because work is being done on the fluid in turbines, the work is done by the fluid but here is work is done on the fluid, so relative velocity is inlet is higher than the relative velocity at outlet and that is where these passages are be diverging. So the relative velocity is reduced at the outlet of impeller right.

And if you notice in turbines in axial flow turbines, we have considered us constant PI DN by DN and is it is U = PI DN, if it is enough RPM then it is sixty by DN by 60. But, here you can see it is moving in a radial direction in turbines, it was moving in axial direction in parsons turbine or d level turbine, it was moving in axial direction now the fluid is moving radial direction.

So peripheral velocity is also changing the referral velocity when off C is changing these kinetic energy is also changing right. So it has two component in impeller then, there is a change in relative velocity, relative kinetic energy corresponding to relative velocity and there is a change in kinetic energy corresponding to peripheral velocity these two components are here when the air leaves this impeller it has very high kinetic energy.

Absolute velocity is very high. At inlet absolute velocity is not high, but at the exit with those kinetic energy has been imparted to the air the kinetic energy is very high. So this kinetic energy is converted into pressure energy in well left diffuser, so this is one, this is state 2 in Vilnius diffuser state 3 and this will be V3, V2 square - V3 square by 2, then vein diffuser, similarly vein diffuser that is 4 then V4 square - V3 square by 2, then in volume KC.

Five so then it is V5 square by 2 and finally the gas emerges from here. This is the enthalpy entropy diagram for the movement of fluid in a centrifugal compressor. Now work, how much work, or power will be consumed in running the compressor, so in order to find the energy consumed in running the compressor we will have to draw the velocity diagram, right.

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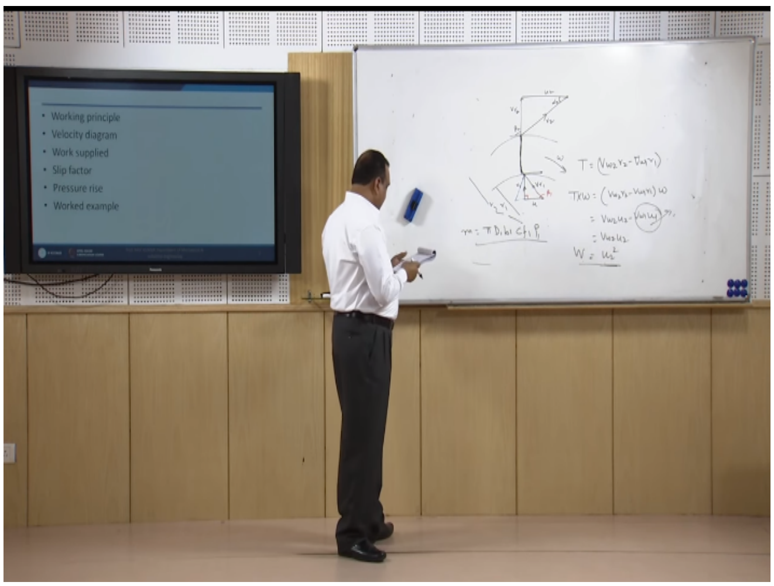

Now in this velocity diagram the veins are radial, this is the easiest one when the veins are radiant, this is impeller, and veins are radiant, they are like this. They are moving with certain peripheral speed of omega or rotational speed the certain rotational speed it is moving and omega R1 this is R1 and this is R2, so omega R1 will give U1 and omega R2 will give U2. So in this velocity diagram the U will also change.

Now there is an axial entry that is like this and blades have peripheral velocity in this direction. U, this is U. so relative velocity will be like this that is why this blade is curved at the bottom. So that there is no shock entry, the fluid will slide over the surface. This is V, R1, V1and this is also velocity of flow and this is U1 and this is blade inlet angle and this is mosses inlet angle but that is in 90 degree.

As we call in turbines right, now if the discharge normally gas turbine the radial blade type of because RPM is very high. So, that is why the radial vein type of central compressor is used. Now at the outlet this is going to be the relative velocity, right. Because it is radial this is peripheral velocity U2. And this is going to be the absolute velocity V2. Right, and this is alpha 2 and this is beta 2.

Now in this compressor at the entry there is no wind component because power is calculated with the will component only. So at the inlet there is no wind component at the outlet this is the will component. So output is will, first of all we will drive the generalized equation and then we will go for the specific case. Suppose inlet also there is a will component the log inlet velocity instead of it is like this that is known as prevail.

We will discuss prevail later on then tort is VW2 R2 – 1R1 and when we multiply torque with omega that is VW2R2 - VW1 R1 multiplied by omega that will give the output, right. And this is VW2 U2 - VW1 U1. Here when the when there is a radial entry this is 0, it is VW2 U2, now VW2 this is V2 cos alpha by 2 is also U2, so output is U2 square. If you know the peripheral velocity at the outlet will get the power consumed or work and the mass flow rate because the impeller has certain width, right.

And the mass flow rate will always be calculated as PI B1 B1CF1 and row one, because the density will also change when the gas is compressed density will be also changed, this is the expression for mass flow rate in a centrifugal compressor. Now if you take this generalized equation and we consider these velocity diagrams.

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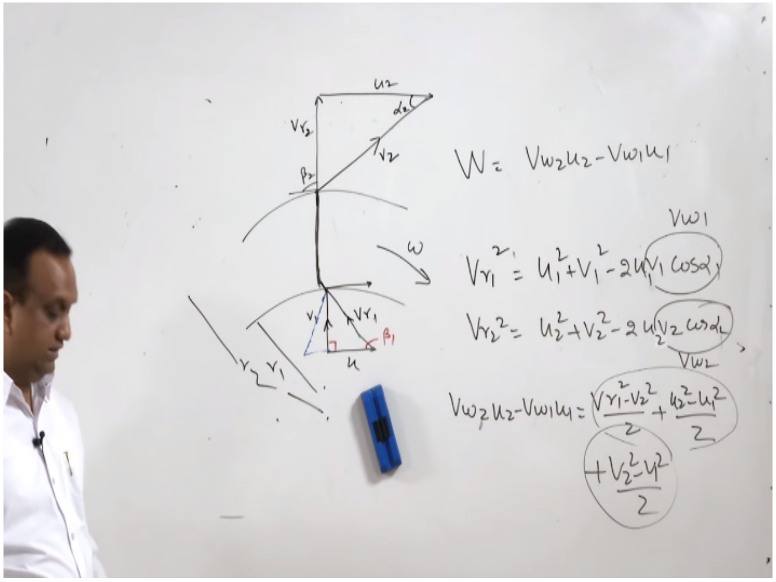

Now, work is VW2 U2 - VW1 U1, now VR1 square VR1 square = U1 square + V1 square - 2 UV1 cos alpha 1. That we have already done, now VR2 square = U2 square + V2 square - 2U V2 cos alpha 2, right. Now V1 cos alpha 1 is VW1 and V2 cos alpha 2 is VW2. Now if we rearrange these then we will get VW1 sorry VW2 U2 - VW1 U1 = VR1 square - VR2 square by 2 + U2 square - U1 square by 2 + V2 square - V1 square by 2.

Right, now this energy, this energy if you remember this h pi diagram this transmission takes place inside the impeller, and this transmission of energy takes place inside the diffusers. Now there is a term slip factor which is commonly used in case of centrifugal compressors.

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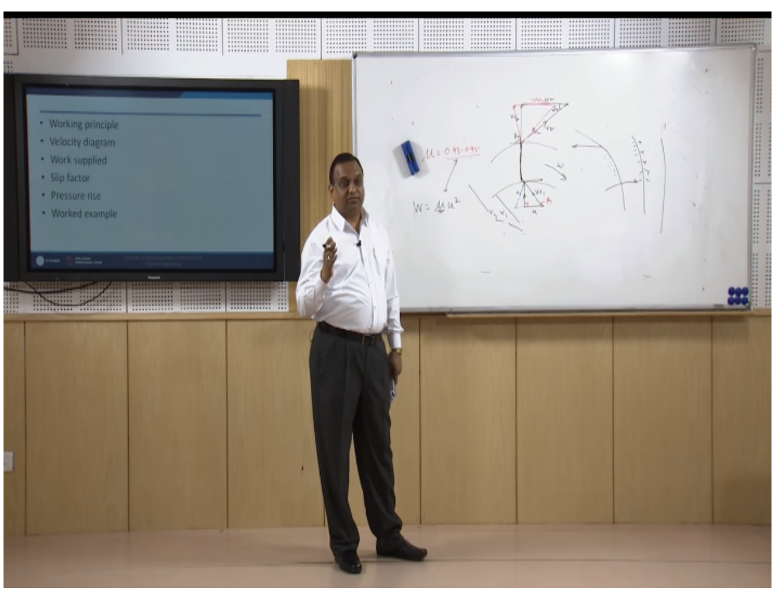

The silly factor is when the vein suppose there is a curved vein moving in this direction in leading direction the pressure is high, but in trailing direction the pressure is low and the break is created, right. And because the number of veins they are number of veins they are numbers so this side there is the negative pressure, this side there is a positive pressure. So instead of leaving in this direction the fluid tense to leave in this direction with a certain angle.

So here instead of having a radial case, instead of having, leaving in vertical direction it leaves in this direction. When fluid is leaving in this direction definitely because peripheral velocity is constant our V2 component will change. And this will change the will component also or the output will be reduced. So slip factor is denoted by mu and the values of slip factor is, it varies between 0.93 or 0.95.

So the output is W = Mu U square then mu is this one and there is another phenomena that is known as primal. Now, when the air is moving in the centrifugal compressor it is moving with a very high velocity and it is likely in some of the cases it may exceed the sonic velocity or chocked flow may take place in order to the moment it causes the sonic velocity then and they exit, right. The shock will take place. The shock flow will take so in order to avoid that because in that case that might damage the compressor also, it is not there will thing to happen, so primal is provided.

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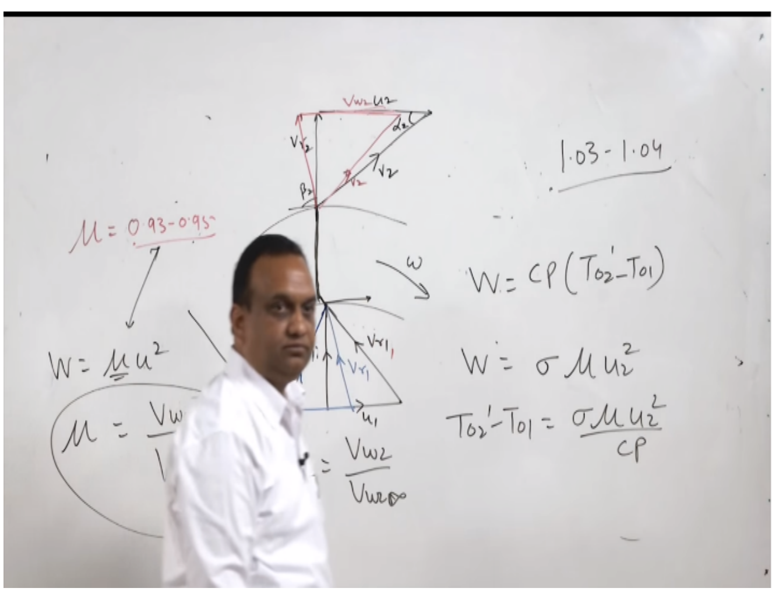

So if let us draw this ideal diagram this is VR1 V1 and this is U1, right. So primal is primal is sorry this is V1, so instead of radial entry this angle is change. When we change this angle then relative velocity at the inlet is also change. Or relative velocity at the inlet is reduced. And that avoids the chock flow inside the compressor which is not desirable. Now regarding the slip factor this is Mu it is the work done on the compressor that is VW2 U2 right divided by work done on the compressor when there are infinite number of ways.

It is an imaginary situation when there are invalid number of ways there is no slip. So when there is no slip VW2 infinite U2 and this will give or this will be cancelled also slip ratio is VW2 by VW2 infinite. Now after this we will we will also calculate then pressurize in a centrifugal compressor W. we know that the W is, TO2 slash TO1 we are taking stagnation properties in the dynamic compressors.

Stagnation properties are taken because kinetic energy of the gas is never neglected. So it is always taken into the account that is why it stagnation properties are taken and the work is also Mu U square by Mu U square, right. And there is a factor sigma which is known as power input factor to take into account the losses and power input factor varies from 1.03 to 1.04.

So sigma mule U square this is so this both are equal so TO2 dash - TO1 = Mu sigma Mu U2 square by CP right and once these values are given we can find that PO2 by PO1 = 1 + sigma U, U2 is 6 sorry sigma Mu U2 square divided by CP PO1 raised to power gamma over gamma - 1 by manipulation we can find this 1. Because PO2 by PO1 = TO2 by TO1 raised to power gamma or gamma - 1.

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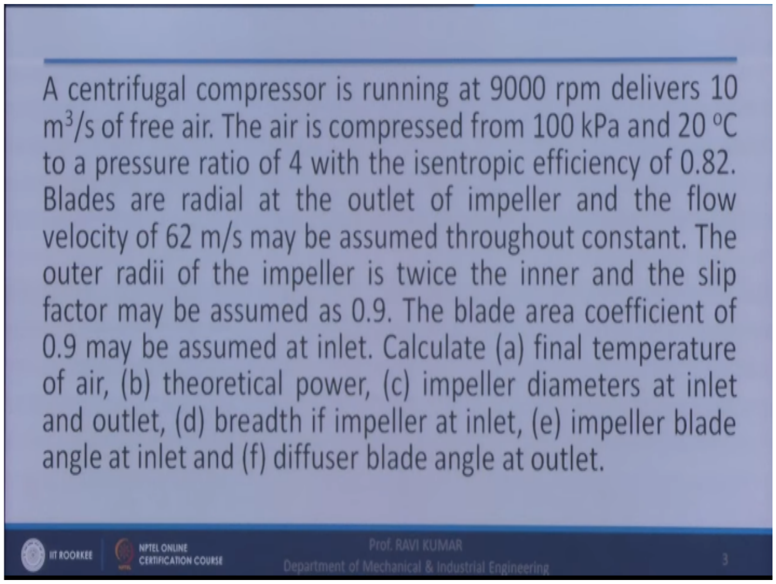

Now we will solve a numerical on this a centrifugal compressor, so quickly we will solve this numerical centrifugal compressor is running at 900 RPM sorry 9000 RPM delivers 10 meter cube of free air. Free air means air available at atmospheric pressure and temperature, the air is compressed from 100 kilopascal and 20 degree centigrade.

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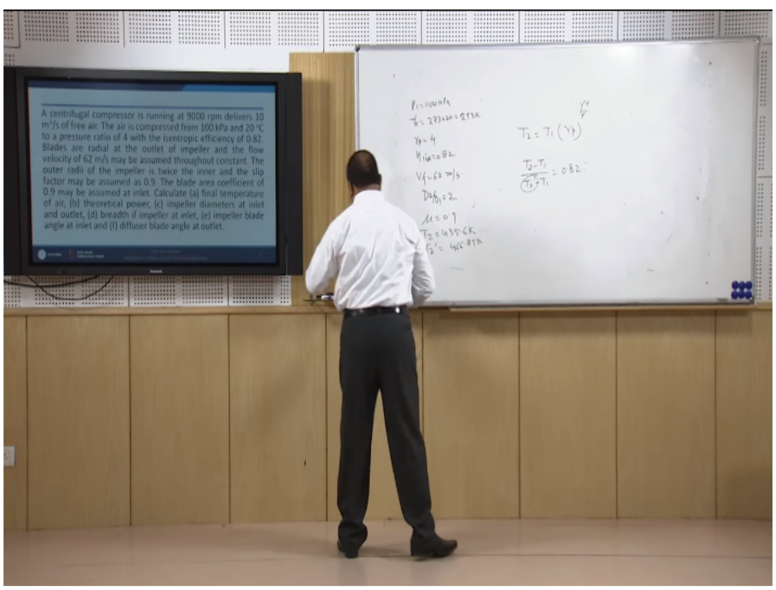

So let us take P1 = 100 kilopascal T1 is 273 + 20, 293 Kelvin, to the pressure ratio of 4. So R pressure ratio is 4, with the isentropic efficiency 0.82. Blades are radian at the outlet of impeller and the flow velocity is 62. So we have faced 62 meters per second. Maybe assume throughout constant the outer a radii of the impeller is twice the inner and the slip factor may be assumed as 0.9.

So, D2 or R2 by R1 or D2 by D1 = Mu = 0.9. The blades are having coefficient the blades area coefficient of 0.9 maybe assumed inlet calculate final temperature of air. So final temperature of air is, so first of all T2 as we did earlier T2 = T1 pressure ratio, raised to power gamma - 1 over gamma and T2 - T1 divided by T2 dash - T1 = efficiency 0.82 that will give the T2 dash from because the T2 we have calculated here is 435.6 kelvin.

And T2 dash is 466.84 kelvin many times we have done this exercise so I will cut short it like this right. Then mass flow rate, free yield anyone free yield reward we get the mass flow rate.

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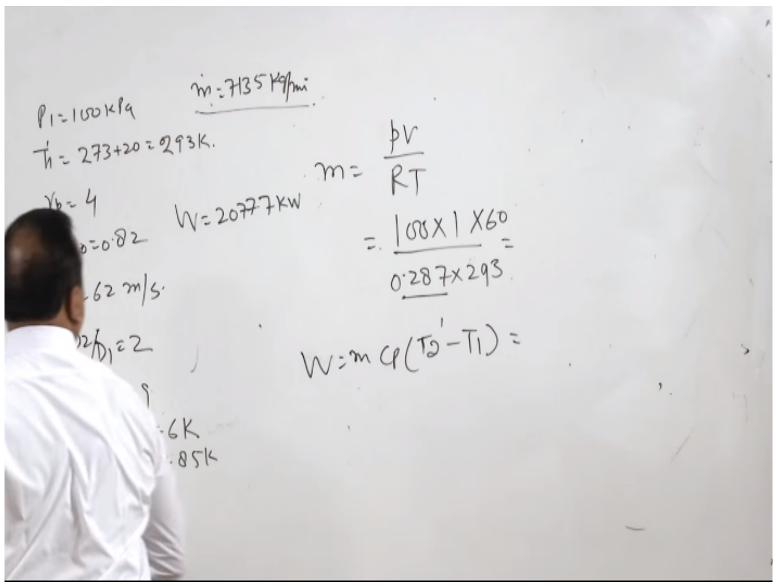

M = PV over RT, pressure is atmospheric 600 kilopascal volume is 1, R is 0.287 and T is 293 and this gives the let us take in per minute multiplied by 6, so mass flow rate is 713.5 kg per minute, right. So this gives the mass flow rate is 713.5 kg per minute. So work is MCP T2 dash - T1, now we have the value of T2 dash, we have the value of T1 we have the mass flow rate.

We have the value of CP so, work is calculated, work is 207.7 kilowatt. This is the amount of energy which will be required to run this compressor right.

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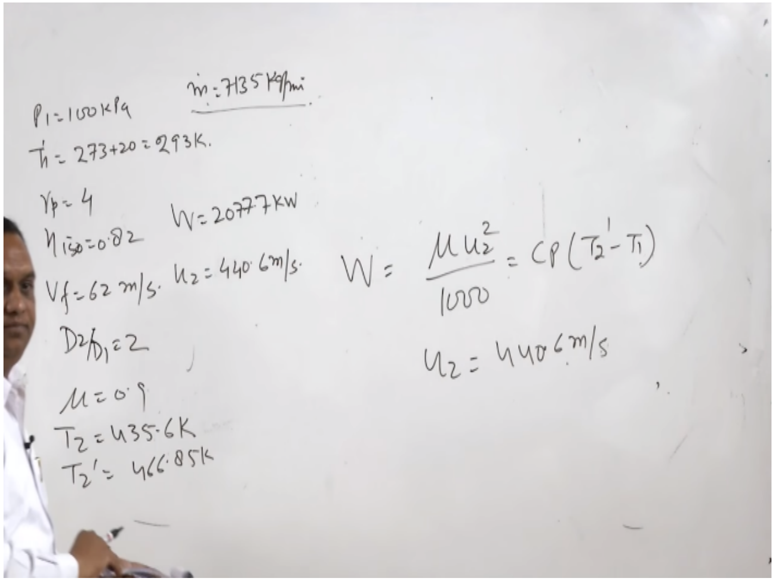

And when the blades are radian W is Mu, U2 square divided by 1000 that = CP T2 dash - T1. That is for per kg of air and that gives the value of U2S 440.6 meters per second. So U2 is 440.6 meters per second. Now, we have calculated the Mu sorry U2 and now we can because we have the ratio.

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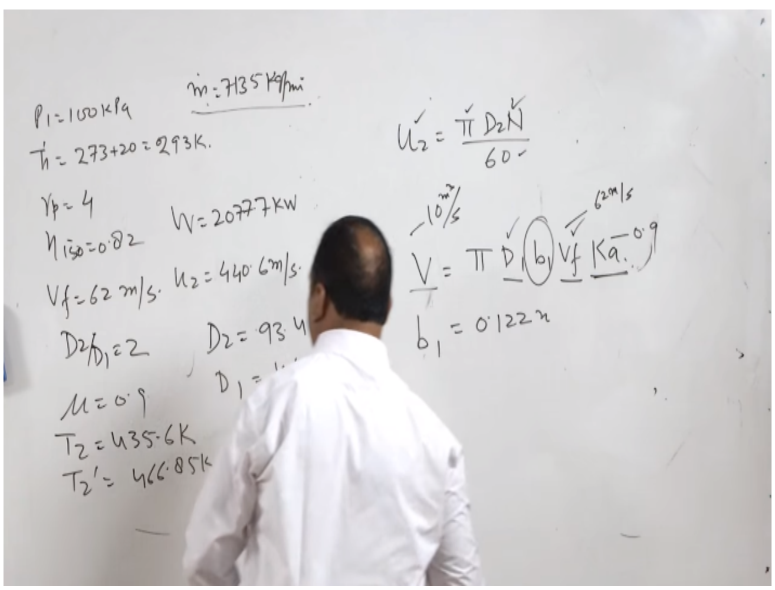

So once U2 is with us, U2 is = PI D2 N by 60 and is given 9000 RPM, D2 is not told to us PI is 360 we know and we know the value of U2, that will give D2s 93.49 centimeters. And definitely D1 is going to be 46.75 centimeters, this is half of the D2.

Now, V = velocity of flow PI D1, sorry valuating the charge, volumetric inlet, volume of air sucked into the compressor PI P1 B1 velocity of flow, N, K, this is blade area coefficient. Now, D1 we have already calculated we have the value of VF is 62 meters per second. This is 62 meters per second, right. V is 10 kgs per second, 10 meter cube per second, it is given here.

So volume metric suction, 10 meter cube per second D1 we have calculated, VF is with us, K is also with us, that is .9. And this will give us the value of P1. So B1 is 0.122 meter or 12.2 centimeters, now blatant angle tan beta 1.

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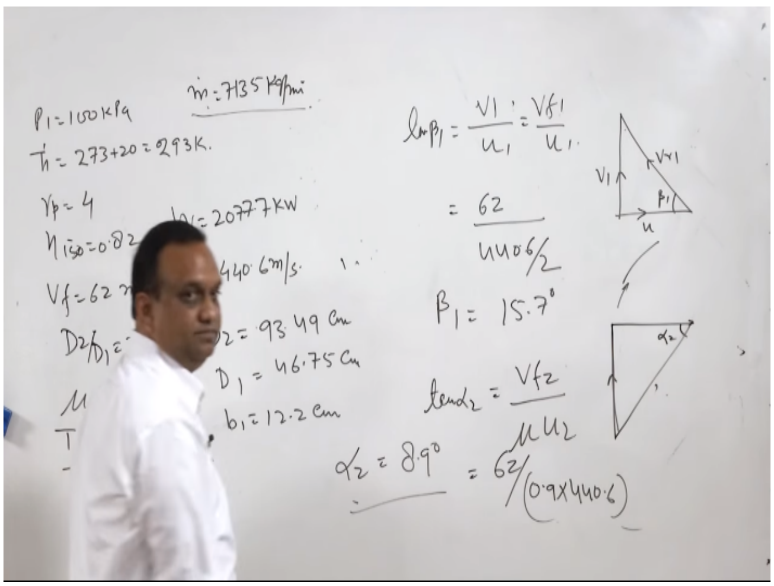

If you remember the velocity diagram at inlet, this is V1, VR1, U, this is beta 1. So tan beta 1 = V1 by U or VF1 by U. because vV1 = VF1 and that is 62 and this is U1. So 62 U, what is the value of U, this is 440.6 divided by 2, because we have the value of U2, so U1 is this divided by 2 and this gives the beta 1 as 0.28 sorry 15.7 degree.

Now regarding beta 2, sorry so the second angle is impeller blade angle at inlet and diffuser blade angle outlet. So diffuser blade angle means it is alpha three, diffuser inlet angle. So, will take the blade angle as the outlet, so this is the blades are radiant so this angle alpha 2 and this is going to be = tan alpha 2 and this is going to be the blade inlet angle for the diffuser that is alpha three right.

So ten alpha 2 = VF2 divided by Mu and U2 here slip factor will also come into the picture right. And this will give 62 divided by 0.9 multiplied by 44.6 and from here we will the value of alpha 2 as 8.9 B. in the coming class we will be solving more numerical on scientifically compressors that is all for today. Thank you very much.