Fluid Dynamics And Turbo Machines.
Professor Dr Dhiman Chatterjee.
Department Of Mechanical Engineering.
Indian Institute Of Technology Madras.
Part D.
Module-2.
Lecture-12.
Steam and Gas Turbines.

Good morning, I welcome you all for the last topic of the course on fluid dynamics and Turbo machines, that is steam and gas turbines. In the last discussion lecture we talked about compressible flows. So now we will see what happens in steam and gas turbines, what are the different types of steam turbine configurations that we have and the thermodynamic plots, the HS plots or the TS plots that are applicable for the steam and gas turbines respectively. So we will start this today's discussion with an outline of a steam turbine plant.

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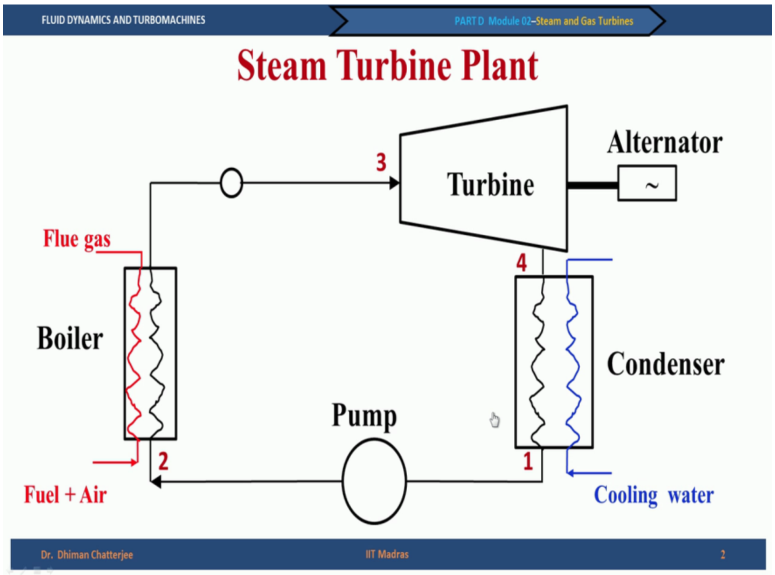

This is a typical layout of a steam turbine plant which you studied perhaps in the first level course on thermodynamic. Let us look at these numbers, we have the components pump, boiler feed pump is there which feeds the water to the boiler where the water goes into the constant pressure heat addition and then it goes to the turbine and in the turbine we have the expansion and the work done. This turbine is connected to the alternator which produces the electricity and then the out, the outlet of the turbine is connected to the condenser and the cycle is repeated.

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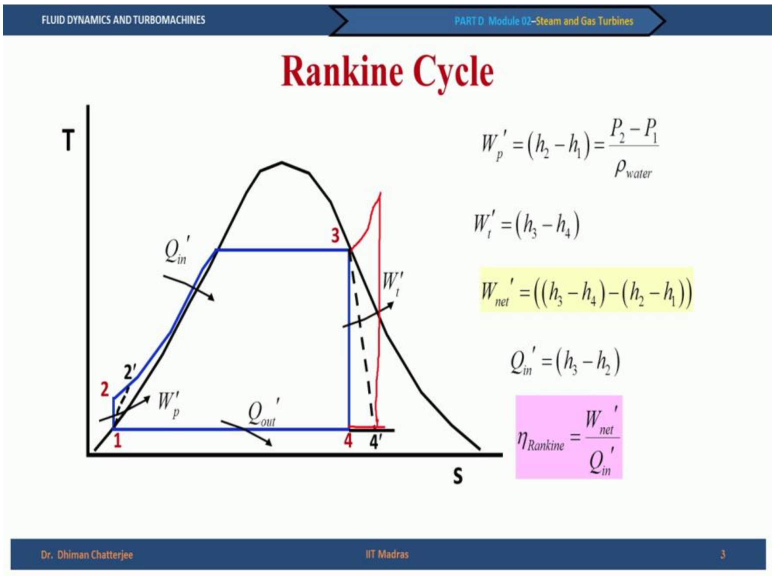

So this is the layout and the corresponding, the cycle is called the Rankin cycle which you are familiar with. In this Rankin cycle you can see that this is an ideal Rankin cycle, so we are talking about isentropic expansion and compression, so 1 to 2 is across the pump, so this is a pump work that is required to be supplied, then 2 to 3 is the isobaric heat addition that we are talking about in the boiler. 3 to 4 is isentropic expansion in the turbine and 4 to1 is the heat rejection in the condenser.

The net work that you can get from this cycle is WT prime, that is the turbine work minus the work added to the pump WP prime. Of course there other variants possible and what we have shown, the point 3, the state 3 is saturated vapour, it need not always be the case. That you have studied in thermodynamics and I will not going to these details. So to get the basics right, we can say that the pump work is given by, I am talking about specific work, if you want to get total pump work, you have to multiply by the mass flow rate.

So is equal to H2 minus H1 which can be written because the density of water is about constant, so we can write it as P2 minus P1 by rho water. The turbine work is given by H3 minus H4 which you already know from the discussions we had thermodynamics and also of course from the thermodynamics lessons that you have taken earlier. So the net work that we get is WT prime minus WP prime which is nothing but H3 minus H4 minus H2 minus H1. And the heat addition is in the form of we have written Q prime in which is given by H3 minus H2.

And we can say that the cycle, Rankin cycle efficiency is given by W net prime whole divided by this Q in prime. Of course we can substitute H3, H4, H2, H1, etc. and get a value for Rankin cycle. The difference between the Rankin cycle which is for the steam plant or the vapour power plants and the gas turbine cycles, which is the joule or the Brayton cycle that we will discuss is a fact that in case of the expansion of steam, the end-stage, that is the 4 in this one is in the wet region.

Even if you start from the superheated points, let us say somebody in the constant pressure line, we can say that even if I draw it here, I can say that I will still end up getting in the wet region. So this feature does not exist in case of gas turbines. And hence what is possible in gas turbine is one level of simplification because they can also assume that the specific heat is constant. So let us look at 1st the different gas turbine cycles that are possible and then the thermodynamic or TS representation of the same.

This 3 to 4 prime I have shown is actually the process that will take place which is not isentropic and similarly you can have the pump work going from 1 to 2 prime which is also an actual work and you know already how to find out from the thermodynamic relationship the efficiency of the pump and turbine. We will also take up this aspect when we discuss the steam turbine in greater details.

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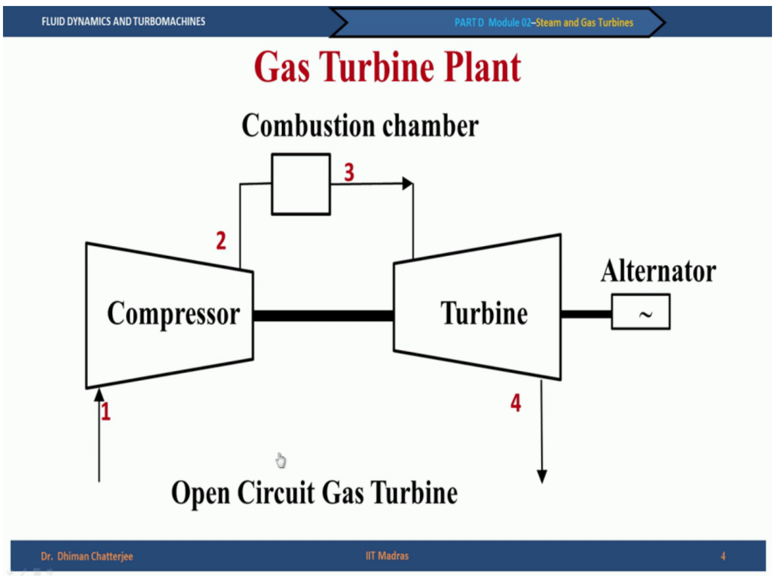

So this is the simple open circuit gasturbine, if you see the air is taken in in the compressor, this is the combustion chamber where this high-pressure, slightly high-temperature air goes in and this combustion product goes to the turbine where it is expanded and it leaves. The turbine is coupled to the compressor and is connected to the alternator. Strictly speaking, this is not a cycle because the 1, State 1 and 4 are not connected and it need not be the same.

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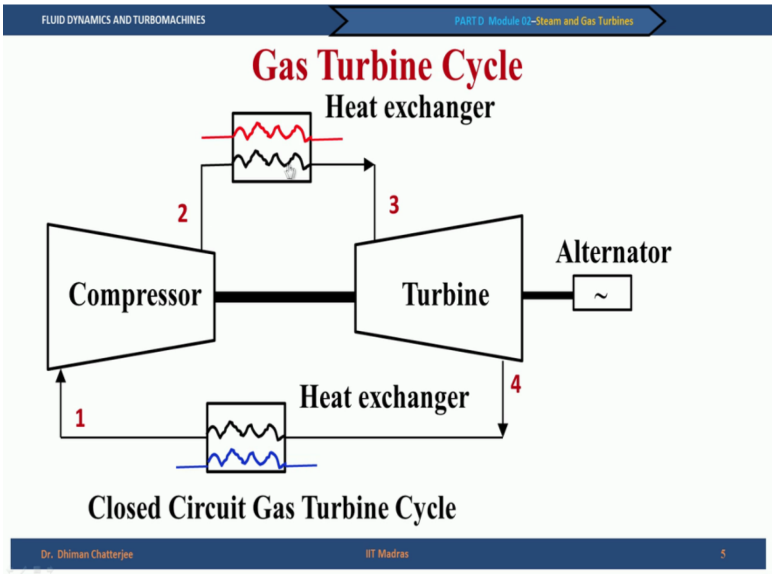

So an Air standard cycles can be thought about and this is a closed circuit gasturbine cycle in which this combustion chamber is replaced by a heat exchanger, the purpose is served by the transfer of heat to the gas, to the air and then it goes to the turbine, it expands and it gives out the heat and it is fed to the compressor.

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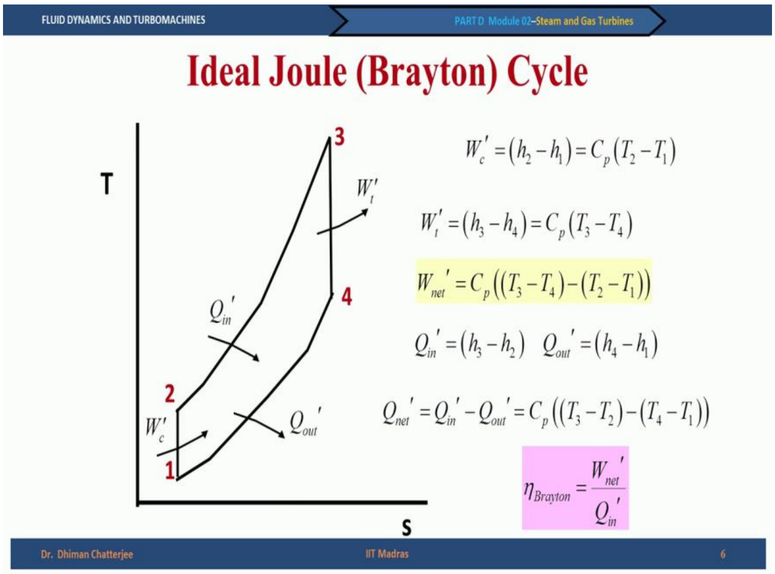

So this is what we will see in the next slide which is that thermodynamic representation of the closed-circuit gasturbine cycle which is called the Joule or the Brayton cycle. The joule or the

Brayton cycle, before we go into that let us see the numbers again. 1 to 2 is across compressor, 2 to 3 is heat exchanger, the constant pressure process, heat addition, 3 to 4 is expansion in the turbine and 4 to1 is again constant pressure but heat rejection this time. So if I look at 1 to 2, 2 to 3 is heat addition, 3 to 4 is work done by the turbine and 4 to1 is heat rejection.

So now let us look at the compressor work WC prime, again I am talking about specific work and not the total work, so you have to the power out requirement and in that case you have to multiply by the mass flow rate M dot. So if I look at it, it is H2 minus H1 and look at the sign carefully, this H2 minus H1 is greater than 0 but this compressor work as we have indicated here by the arrow is the work done on the compressor and so when we calculate the net work, we need to keep this sign convention in mind.

And since we are assuming that this is a perfect gas, so we can say CP is constant and we can write H2 minus H1 as CP times T2 minus T1. The turbine work can similarly be written in terms of temperature or enthalpy as H3 minus H4 or CP times T3 minus T4. And we get the net work CP times T3 minus T4 minus T2 minus T1. Of course as you know from thermodynamic that we could have established the same thing by saying Q in prime which is H3 minus H2 and Q out prime which is H4 minus H1 and talking about the net heat addiction which is CP T3 minus T2 minus T4 minus T1 which is the same as W Net as it should be.

And as we can define the efficiency of this Brayton cycle as W net prime by Q in prime. So this gives us the thermodynamic background of the gas and the steam turbines which we are going to discuss now. And also let me make one point clear that when we discuss the steam turbine, actually I will talk about with reference to steam turbines, but I am not really considering wet steam. So my approximation for this work is that I am considering the steam also to be a like a gas which is possible approximately when we are talking about in the superheated zone. In the superheated zone the steam can be also considered as a gas with the equivalent properties.

Strictly speaking please note that we need to consider the steam as wet and more so if we are interested in the low-pressure stage of the turbine. But that is a separate discussion, the effect of the wet steam which I will not do in these introductory lectures on steam and gasturbine. So 1st we will start with different types of steam turbines.

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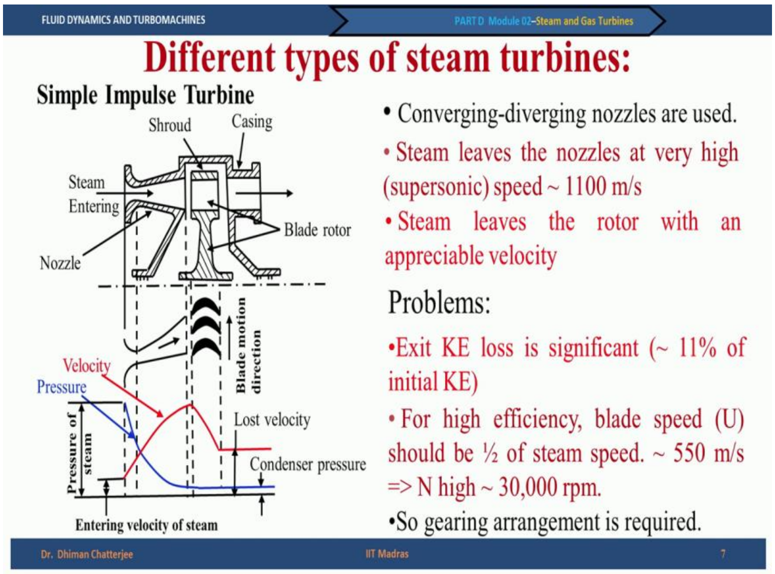

This is an axial flow simple impulse turbine, so let us look at the components. The 1st component you can see a is a CD nozzle which we have discussed the last lecture. What was the role of the CD nozzle, the CD nozzle actually accelerates the steam from the subsonic condition to a sonic throat and then goes to the supersonic. So we get a very high rise in the velocity shown by the Red Line here. And there is a corresponding drop in pressure. Since it is an impulse turbine and by the definition of impulse turbine, we talk about no pressure change should take place in the blade, rotor blades.

So we see here that in the rotor blade region, the pressure does not change and it is a condenser pressure which is attended. So the steam and from here, gets expanded in the rotor blade, you can see the rotor blade is connected to the shaft here and it moves out. So this is very simple construction, you can see these blade profiles. The blade profiles also deserve special mention. You see these blade profiles appear like as if it is a plate which is bent in the form of C.

Now you know that in an impulse turbine, the angle of deflection or the path that the outflow will take from the blade with respect to the incoming direction, there will be a larger deviation. So this angle of deflection is large which is a characteristic of impulse turbine. But what about the shape? If you look at the shape, the shape is not simple plate of uniform thickness, the plate has more thickness at the Centre and less thickness at the sides this, at the edges. This is because we do not want the flow to separate here and then this contouring is very essential.

Now this simple impulse turbine is easy to construct but then we do not really opt for it. Why, let us look at the features. The 1st is the converging diverging nozzles are used, as we have discussed, the steam leaves the nozzles at very high supersonic speeds typically around let us say 1100 metres per second. These are just numbers to give you a feel for how high the speeds can be, you do not have to consider that this number is very sacrosanct.

So the next is the steam leaves the rotor also with an appreciable velocity you can see. Now what is the objective of any turbine, the objective of any turbine is it possible we should extract all the energy including the kinetic energy from the fluid. So you can think about it like you are trying to extract the maximum energy and then you see that such a large velocity magnitude is going out as unutilised. Then what happens, if this is not utilised, then the total tower that can be produced for the turbine is not properly utilised.

So exit kinetic energy has to be minimised. Like in the hydraulic turbines for example, we have used the draft tube. So similarly here also this exit kinetic energy from the turbine should be recovered. And the other problem that will come in is that for high-efficiency we know that the blade speed should be half of the steam speed. This was already discussed in case of impulse turbine, the other impulse turbine we studied, the Pelton turbine. In that case we showed you if you remember that the highest, the highest efficiency will come when the blade speed is half of the jet speed.

In this case of simple impulse steam turbine, we can say that the blade speed should be half of the steam speed, that is the absolute velocity which is coming out of the CD nozzle. So now if we take the example of number, we are talking about the steam leaving at 1100 metres per second which means the blade, the rotor blade speed, the peripheral blade speed, whatever you call it should reach 550 metres per second and then typically we will get a very high rotational rpm. This is not desirable because in that case we may have to use some gearing arrangement.

So because of these 2 reasons, that is exit kinetic energy loss and for high, very high rpm, we need to resort to an alternate arrangement for steam turbines. And that is called the compounding of impulse turbine. Compounding loosely speaking as I will explain you more in the next slide onwards, compounding loosely speaking means basically staging or arranging the turbines. Okay, I will come to that in the next slide itself.

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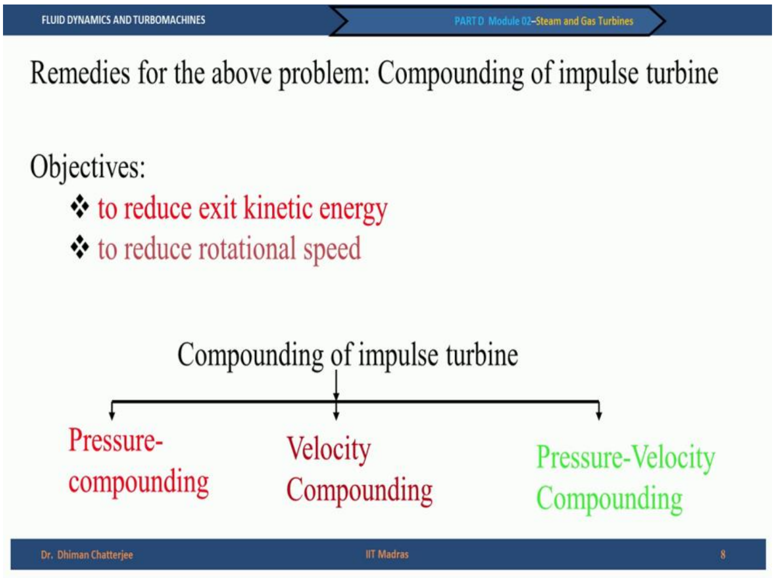

So we say that the compounding of impulse turbine serves 2 purposes, one to reduce the exit kinetic energy loss and to reduce the rotational speed. And this compounding of impulse turbine can be done in 3 ways, the 1st one I call it as pressure compounding or it is called pressure compounding. The 2nd one is called the velocity compounding and the 3rd one is called pressure-velocity compounding. Now we will take up each one of these to know the features of pressure compounding, velocity compounding and pressure-velocity compounding.

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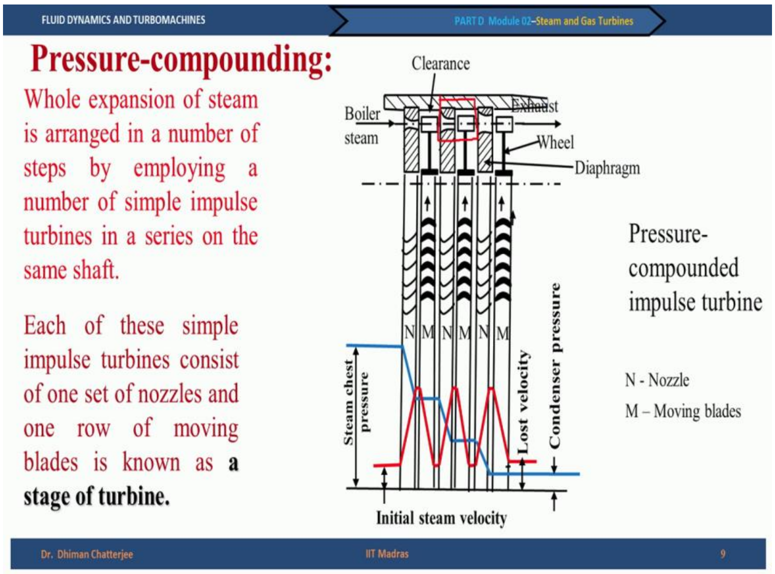

So this is the schematic of the pressure compounding. Let us look at, let us look at the structure of the flow here. The steam that comes out from the boiler enters through a CD nozzle, then it goes through the moving blade, you can see M written here, M stands for moving blade, N stands for nozzle. And then it goes through the 2nd nozzle, set of nozzles and then the moving blade, again the nozzle and the moving blade. So what does this combination of 1 nozzle and 1 moving blade tell you?

It tells you that this is one stage. So we can say that in a pressure compounding steam turbine, whole expansion of steam is arranged in a number of steps by employing a number of simple impulse turbines in series on the same shaft. For example the 1st one might can be called as the 1st stage, because we know that a simple impulse turbine has a nozzle and the rotor or the moving blade. And then this is 2nd stage, 3rd stage and so on and so forth. So we can say that a typical stage is comprising of this unit a nozzle and a rotor.

So this is called a stage and hence pressure compounding is essentially nothing but a simple impulse turbine in stages. Also, one more point we have to note is that in the nozzle, the velocity increases, in the moving blade it reduces, increases again, reduces and it goes. But what happens to pressure? If you see the pressure reduces in the nozzles and does not change in a moving blade as it should not change and then again reduces and so what we see… To remember loosely that what is pressure compounding, let us say after a few years of doing this course if someone asks you what is pressure compounding, you should be able to think that pressure compounding means as if the total pressure drop is divided into smaller steps.

So how or where does the pressure drop take place, in the nozzle. So in this case pressure compounding means one nozzle and of course it should be followed by a rotor. So that perhaps will help you to remember what is a pressure compounded impulse turbine. And as I said this is called a stage of a turbine. So if somebody asks you what does a pressure pressure compounded impulse turbine one stage comprised of, you should be able to say it comprises of a nozzle and a rotor or a moving blade.

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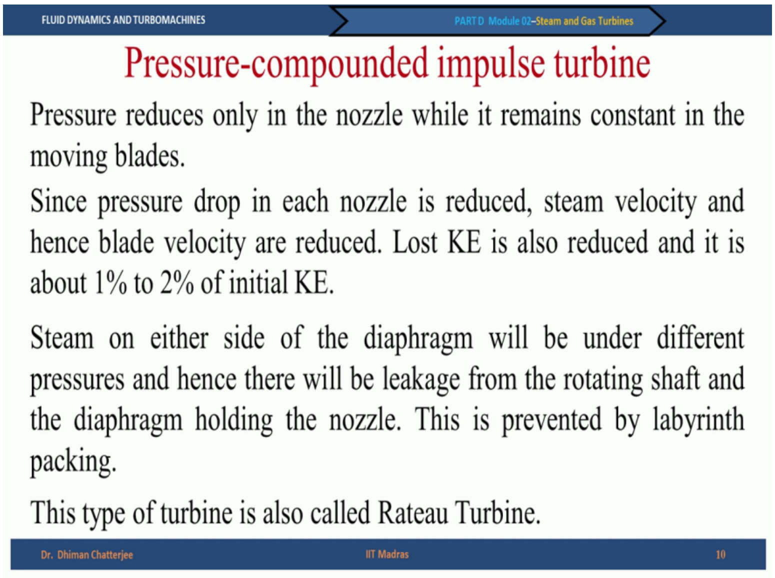

Let us continue the discussion. Pressure reduces only in the nozzle while it remains constant in the moving blade. Since pressure drop in each nozzle is reduced, steam velocity and hence blade velocity are reduced and lost kinetic energy is reduced and it is about 1 to 2 percent of the initial kinetic energy available. You consider that in the simple impulse turbine, it is about 11 percent, now we are talking about 1 to 2 percent. Steam on either side of the diaphragm will be under different pressures and hence there will be leakage from the rotating shaft and the diaphragm holding the nozzle.

Let us look at the pressure compounded impulse turbine once again. So what we are saying is that there is a pressure difference on across the diaphragm and hence there will be a leakage, so the leak prevention has to be considered as a major task. And this is achieved by Labyrinth packing. This type of turbine is also called Rateau turbine.

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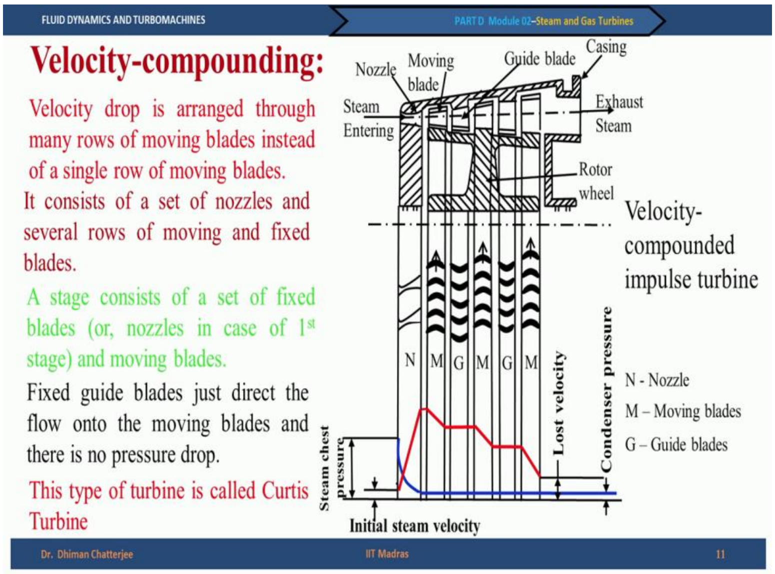

The next type of turbine we are talking about is the velocity compounded impulse turbine. Look at the 1st one, 1st one it has a nozzle, the same CD nozzle, then it has moving blades, then onwards there is a difference. So you have a guide blade or the stator, then you have rotor or the moving blade, guide blade and moving blade and in this way it goes. So what happens here is if you see that the pressure reduces only in the nozzle and then it remains constant to the condenser pressure. The velocity in this case 1st increases in the nozzle and then reduces in the moving blade, remains constant roughly in the guide blade, reduces again in the moving blade and so on and so forth.

Now in case of pressure compounded impulse turbine I said that you can try to visualize and remember that a pressure compounded impulse turbine is nothing but an impulse turbine in which pressure is reduced in stages. So if I use this way of explaining, then what will velocity compounded impulse turbine will do? It will try to reduce velocity in stages. And that is exactly what we see in this diagram. So in this case you have to understand that the 1st stage comprises of nozzle and the moving blade but a typical intermediate stage or a typical stage to say simply well comprise of the guide vanes and the moving blade, so stator and the rotor.

This is the velocity compounding, so velocity drop is arranged through many rows of moving plates instead of a single row of moving blade and it consists of a set of nozzles and several rows of moving and fixed blades that we just now saw. A stage consists of a set of fixed blades or nozzles in case of 1st stage and moving blade. So this is important, that only in the 1st stage, I repeat there is nozzle, otherwise it is having the guide blades or fixed blades or stationary blades or simply stator. So fixed guide blades just direct the flow onto the moving blades and there is no pressure drop. This type of turbine is called the Curtis turbine.

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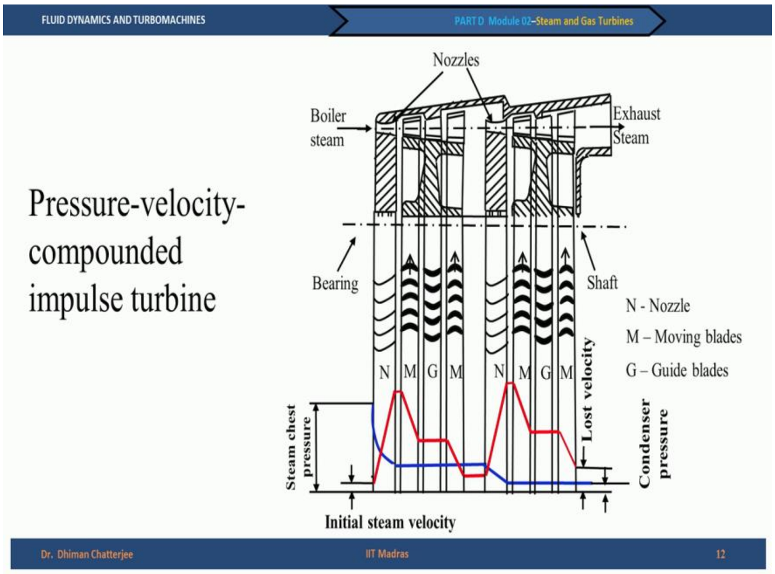

So we have learned 2 types of compounding, now what happens is if you try to have the pressure-velocity-compounded impulse turbine. So what we have, 1st we have the CD nozzle, then we have the moving blade, then the guide blade, then the moving blade. So far so good, then what happens is we start the again, this process again, so we have a nozzle, 2nd set of nozzles and then we have the moving blade, the guide blade and the again the moving blade. So you see here the pressure reduces in the 1st set of nozzles, then remains constant and then again reduces in the 2nd set of nozzles and then remains constant and goes to the condenser pressure.

So here you see the pressure gets reduced twice in the structure we have shown and both times in the nozzles so pressure compounding comes and velocity also reduces in the moving blade, increases again in the nozzle and goes back to the lost velocity or exit kinetic energy in the 2nd set. So this is called the pressure-velocity compounded impulse turbine. But steam turbine need not be always impulse turbine and we can have what is known as the reaction turbine.

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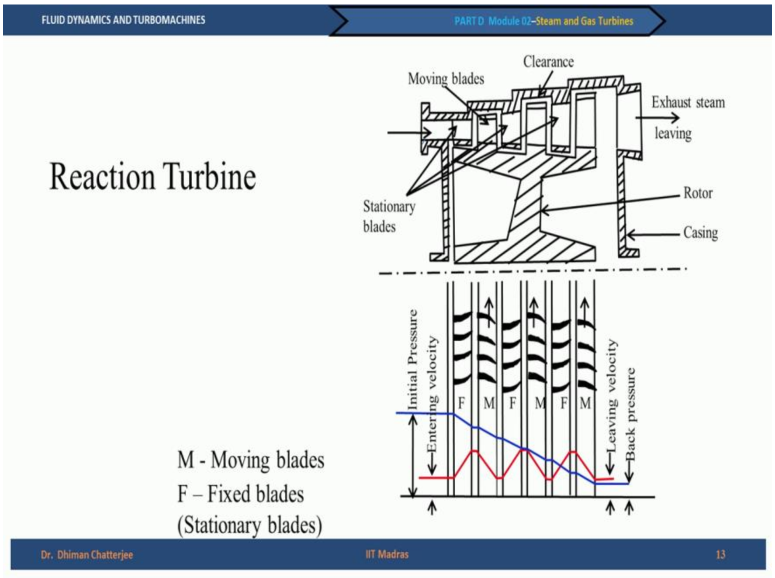

So in this case of reaction turbine, what we have is, the general case like what we have is a state or stationary blade or fixed blades or the guide blades and the moving blade. So we have the usual way of fixed blades, moving blades, fixed blades, moving blade and so on and so forth. So you see in this case the pressure reduces in the fixed blade, in the moving blade, fixed blade, moving blade. Why because in reaction turbine there is no restriction that pressure should not reduce in the moving blade.

And you can also see the deflection angle is not as significant as in the case of the impulse turbine, the blades are not so highly curved. This is also we have discussed in connection with the degree of reaction and the blade curvature. Try to connect that discussion we had on the blade curvature and degree of reaction with today’s practical example we are talking about. So this, this brings us to the end of today’s discussion on the classification of turbines, the steam and gas turbines, particularly the steam turbines.

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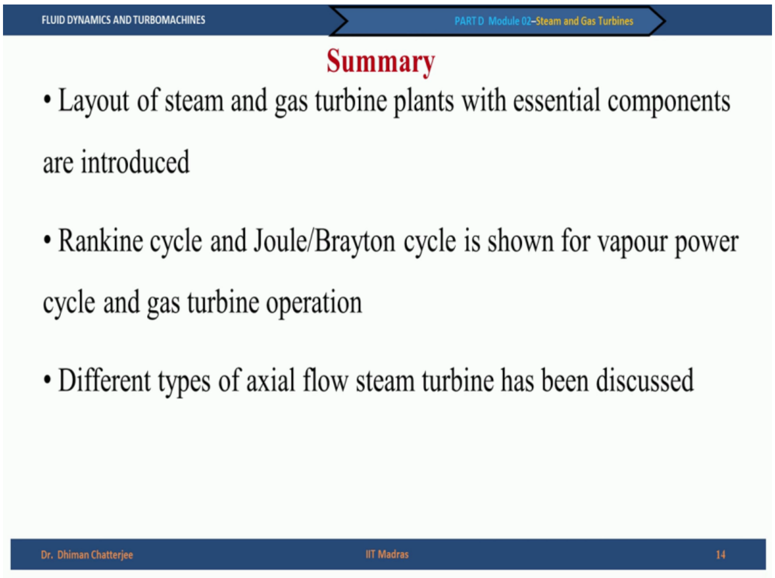

So we can say that in this today's discussion we have talked about the layout of steam and gas turbine plants and identified the essential components. We talked about the Rankin cycle and the Joule and the Brayton cycles that are used for vapour power and the gasturbine operations respectively. We talked about different types of axial flow steam turbines, we started with the description of a simple impulse turbine, we talked about the problems associated with the simple impulse turbine in the form of very high-speed and giving rise to lot of exit, large exit kinetic energy loss.

Then we talked about the compoundings, the pressure compounding, velocity compounding and pressure-velocity compounding and then we talked about the reaction turbine. So I will stop here for today's discussion and in the next class we will talk about how to represent the operations of these turbines in the thermodynamic HS plots and also talk about how to connect with the velocity triangles which you have learnt in the earlier part of this module. Thank you.