Power Plant Engineering
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Lecture – 02
Steam Power Plant Cycle

Hello. I welcome all, I welcome you all in this course Power Plant Engineering and today we will discuss about Steam Power Cycles.

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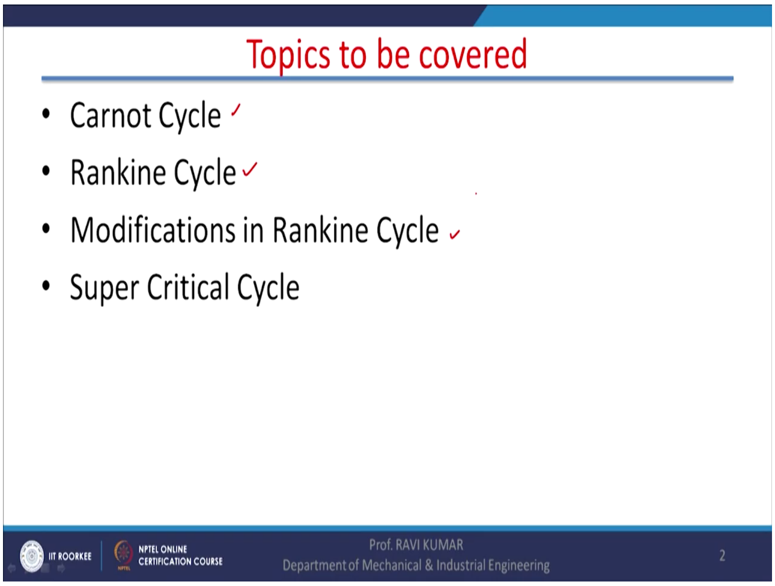

Topics covered to be covered in this lecture are first the Carnot cycle, Rankine cycle, modifications in Rankine cycle. The modifications in Rankine cycle are done to improve the efficiency of the cycle or the increase the output of the cycle. And then we will talk about super critical cycle.

To begin we will start or we will start with the Carnot cycle which was proposed by Nicolas Leonard Sadi Carnot. Carnot was Lieutenant in French Army and he was an engineer. He was the first person who gave the backup theory of a steam power generation. Steam power generation or a steam engines were in existence for the last for more than 150 years and there was no back up theory for this steam engine. So, Carnot was the first person who gave the backup theory and talked about the efficiency of a steam engine.

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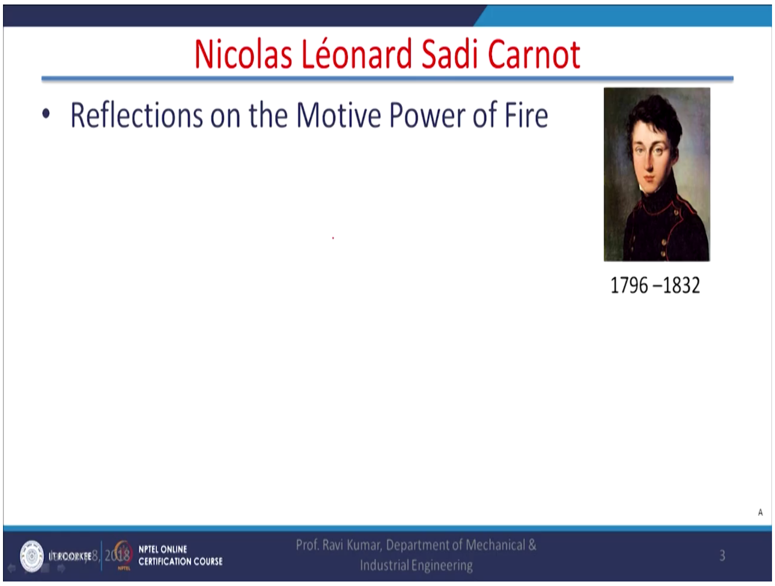

And this efficiency of the steam engine, this is sole publications reflection on the motive power of fire which he discuss about the efficiency of a steam engine, and this publications was taken into very much consideration by a lord Kelvin and Clausius while explaining the second law of thermodynamics.

It was Thomas Newcomen who proposed the steam engine in fact, who gave the steam engine which gives the output by reciprocating action. And he had taken ideas from the engine of Thomas Savery and papins Papins pressure cooker. I mean pressure cooker in fact, the idea of pressure cooker was given by Papins and he suggested that on in a pressurized speed the cooking is faster.

So, I out of these two he gave the Thomas Newcomen was the Newcomen was the person who gave this power generation by steam through reciprocating piston. Thomas Newcomen was a person who gave the steam engine which was producing output by a reciprocating action.

Now, let us go back to the Carnot cycle because Carnot cycle is important because it is the standard cycle for comparing performance of different cycles.

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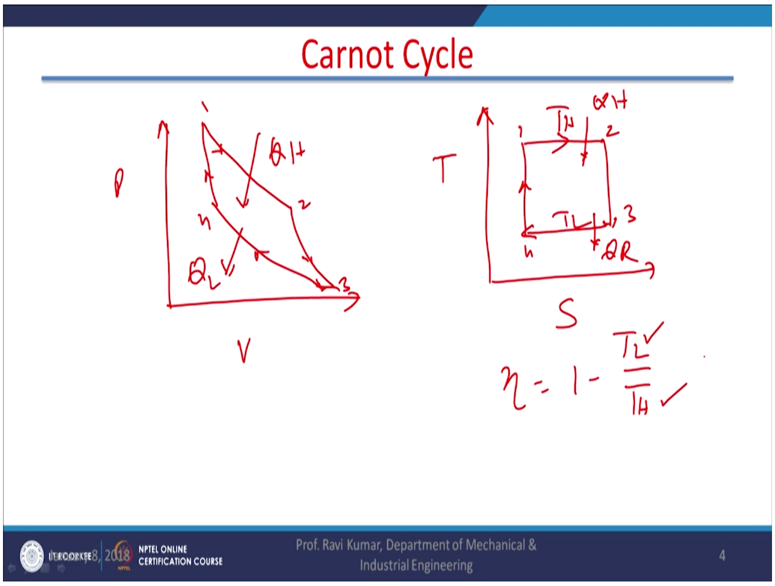

In Carnot cycle if we draw Carnot cycle on P V diagram, pressure and volume diagram then it has two adiabatic processes and two isothermal processes.

So, 1 2 is an isothermal processes, 2 to 3 is reversible adiabatic process and then, 3 to 4 is again isothermal process and 4 to 1 again reversible adiabatic process. Now, in 1 to 2 process the heat addition and heat rejection was taking place in isothermal processes and in process 2 to 3 and 4 to 1 because their adiabatic process there is no heat interaction, right.

And if you draw these processes on temperature entropy diagram, it is simpler to understand on temperature entropy diagram and isothermal process 1 to 2 entropy temperature remains constant. Now, process 2 to 3 is reversible adiabatic process. So, reversible adiabatic process means the entropy remains constant, so 2 to 3 entropy remains constant.

Now, 3 to 4 again it is isothermal process temperature remains constant and this is entropy remains constant 3 to 4 and 4 to 1 this is T H and this is T L. As you must have studied in the thermodynamics, the efficiency of the Carnot cycle is 1 by n s T L by T H right temperature at which the heat is rejected and temperature at which Q H, this is Q H and this is Q R.

Now, we can increase the efficiency of Carnot cycle either by lowering the sync temperature or by increasing the temperature of the source.

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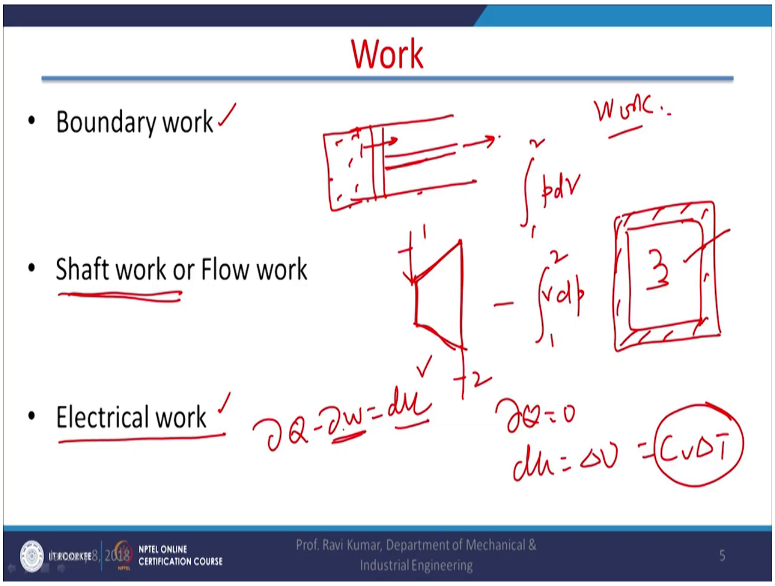

In the cycle, there is a term which comes into the picture is work. Now, there are two types of works in thermodynamics that is boundary work and shaft work or the flow work. Now, the boundary work means in a in a closed system if there is a movement of the boundary of the system. For example, there is a piston cylinder arrangement, if there is a piston right and there is a cylinder and piston arraignment it is filled with the high pressure gas the gases will exert force on this piston and piston will move in this direction.

Now, the volume will increase, volume will increase and we will get work output on this side, right. So, this is the work we are getting by movement of the system boundary. When the work is obtained by the movement or through the movement of system boundary it is known as boundary work.

Now, the shaft work I will give you shaft work for example, turbine. In a turbine, steam is entering from one side and leaving from another side. There is no movement in the system boundary system boundary is fixed. When the system boundary is fixed it is known as the shaft work. Boundary work is expressed in terms pdv from state 1 to state 2. Shaft work output is again expressed 1 to 2 sorry vdp, vdp.

There is another work which is known as electrical work. Suppose for example, in a room we put a room heater and when we are doing thermodynamic analysis of that room, right, suppose in this room we are putting a room heater and when we are doing thermodynamic analysis of the room though the heater is operative we will consider the heat transmission to the room is 0 provided the walls are insulated.

So, if there is an insulated room, right, the walls are insulated and the room is fixed with the heater right and heating from is taking place. So, when the heating of room is taking place internal energy room of room internal energy of the room is changing, it is raising in fact, walls are insulated. So, there is no heat transfer across the wall. Now, in thermodynamics sense we say when heat transfer to the system means heat transfer across the boundary of the system.

So, now, in this case room walls and roof and floor all are insulated there is no heat transfer across the boundary of the system, right. So, heat transfer is 0. So, del Q is 0 right and du is the change in the internal energy it is always C v DT C v delta T and this is the amount of electrical work which is being done on the system because we have to satisfy this equation del Q minus del w is equal to du.

When internal energy is raising, it is rising at the expense of electrical work which is being done on the system. So, when the work is being on the system, so negative will become positive and this positive energy will be stored in the system as the internal energy.

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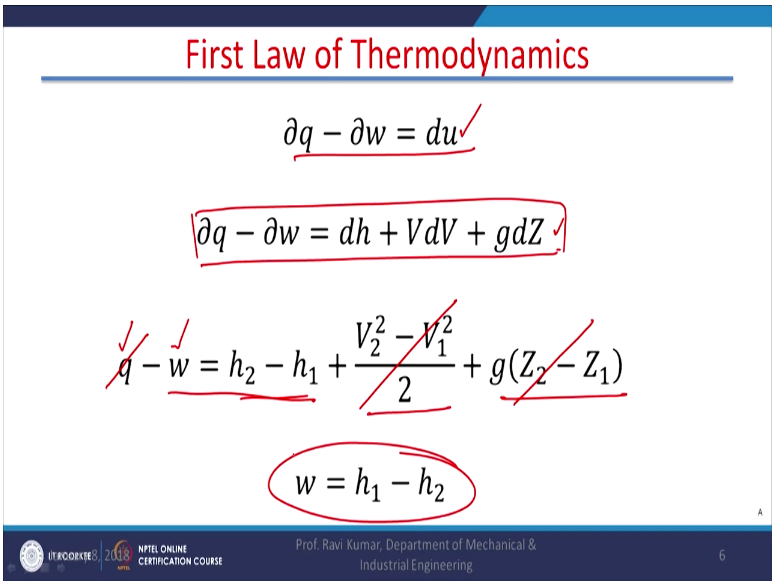

Now, first law of thermodynamics where we are very much converse with our first laws of thermodynamics which says that del q minus, it is a derivative of the first law of thermodynamics. Now, there is a first law of thermodynamics for open system also. Suppose there is a control volume. Control volume means for example, a wire mass box in the air is an example of control volume. So, in control volume heat interaction and mass interaction both takes place, right. So, suppose there is any control volume and in that control volume, this is an it is a open system. So, an open system this is going to be the governing equation.

Now, if we write in for open system heat transfer to the open system minus work done by the open system is change in enthalpy, change in kinetic energy and change in potential energy, right. When there is in significant change in the kinetic energy and potential energy then and there is no heat transfer then we say work is equal to h 1 by h 2. This happens in case of turbines.

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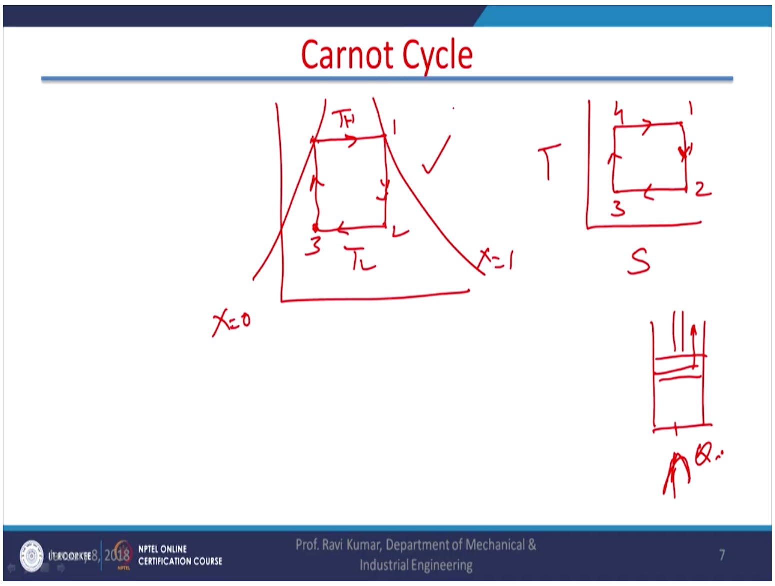

Now, we will again go back to the Carnot cycle because earlier when we have drawn the Carnot cycle on temperature entropy diagram, it was rectangle showing different processes 1, 2, 3 and 4. And there are certain drawbacks of this Carnot cycle because isothermal process has to be very slow right, so that constant temperature is maintained whatever heat is added to the system is used is converted into the work, right. Heat transfer is equal to work transfer, right. So, there has to be no change in internal energy. So, whatever heat is added it will not raise the temperature, but it will not raise a increase the temperature it will raise the weight.

For example: there is a piston cylinder arrangement and heated, heat is added from the bottom. So, in isothermal process whatever amount of heat is added shall be used for raising the weight. It will not use it will not be used for increasing the internal energy of the gas. So, process has to be very slow.

Now, 1 to 2, it is reversible adiabatic process. Reversible adiabatic process heat transfer is 0, right. So, process has to be very fast. So, there is no time for heat transfer. So, this process has to be fast. Again, this is isothermal process this process has to be slow this process has to be fast, this process has to be slow, I mean we will have alternate slow process and fast process. So, such type of mechanical system is or is difficult to develop, it is not it is not possible I cannot say, but it is not practical.

So, this is main drawback of Carnot cycle. An constant especially constant temperature heat addition constant temperature heat reduction, but if you remember that during boiling and condensation of liquids there is a constant temperature heat addition and constant temperature heat reduction. So, instead of using for the gas if we use Carnot cycle for a steam so, there are their chances of high to attain such type of a system where we can have a boiling, right or so this at a constant temperature then expansion as a turbine is not a problem, so 1 to 2, right and then 2 to 3, heat rejection, right, in a condenser at lower temperature and then again compression. Now, this is the Carnot cycle for two phase, two for a case were boiling and condensation is taking place this is x equal to 1.

Now, here also there are certain drawbacks. For example, in a condenser the steam is entering with a certain quality. Now, you have to extract steam at this particular quality only that is difficult. I mean judging first of all fighting out the quality of the steam and getting taking steam out of the condenser exactly at this quality, right and this is the major drawback. Second thing is when you are compressing the two phase flow we have compressors to compress gases or pump to compress liquids, but we do not have devices which can increase the pressure of a two phase flow at constant entropy. So, such devices are not there. The moment you start compressing the fluid it will start condensing right. So, in order to avoid that because, now we are going we want to have some practical cycle. So, this cycle is also not a practical cycle.

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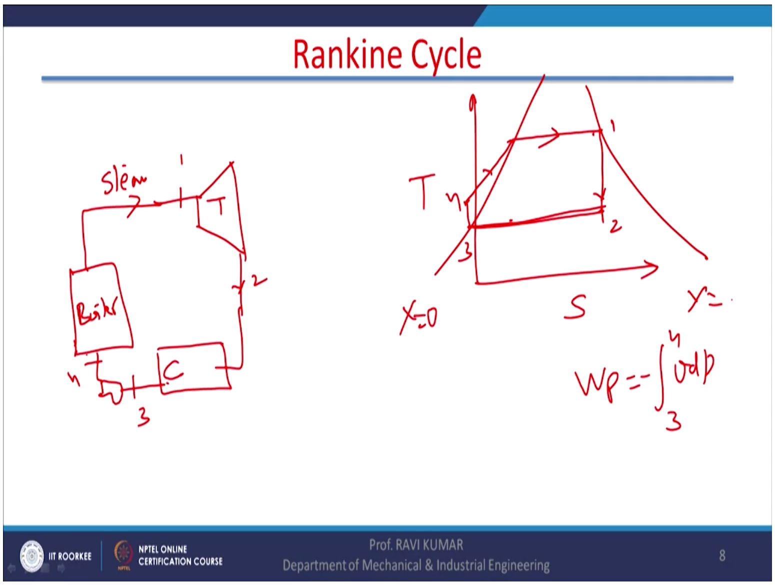

So, in order to have practical cycle this practical this Carnot cycle was modified further modified and we get temperature entropy diagram. This is X is equal to 0, X is equal to 1, cos and temperature heat addition is not a problem. I mean it is something like boiling of fluid, boiling of liquid, then expansion is also, expansion can takes place inside the turbine.

Now, here at two instead of condensing up to a certain quality, the fluid is entirely condensed totally condensed, all two phase mixture is converted into the liquid, inside the condenser itself, right. So, volume is reduced and we have single phased fluid. Now, this simple phased fluid pressure can be increased with the help of a pump. A pump will consume power vdp, vdp from state let us say 3 to 4 minus 3 to 4.

Now, pressure is increased. After increasing pressure the liquid is sent to the boiler or for the heat addition. Here this is the sensible heat addition, this is latent heat addition and now this is workable cycle or all steam power plants they are working on the Rankine cycle, right. Steam power plants have major components, one is boiler, boiler, right. Boiler where heat is added; pressurized water is converted into the steam, right this steam goes to the turbine where expansion of a steam takes place.

After expansion in the turbine it goes to the condenser right, where condenser this is turbine in condenser the heat is extracted from the mixture of water and steam, right. And the mixture the two phase mixture of water in a steam is entirely condensed in the condenser then it goes to the boiler, where 3 and then 4. With the help of a pump it goes to the boiler this is basic arrangement of any steam power plant.

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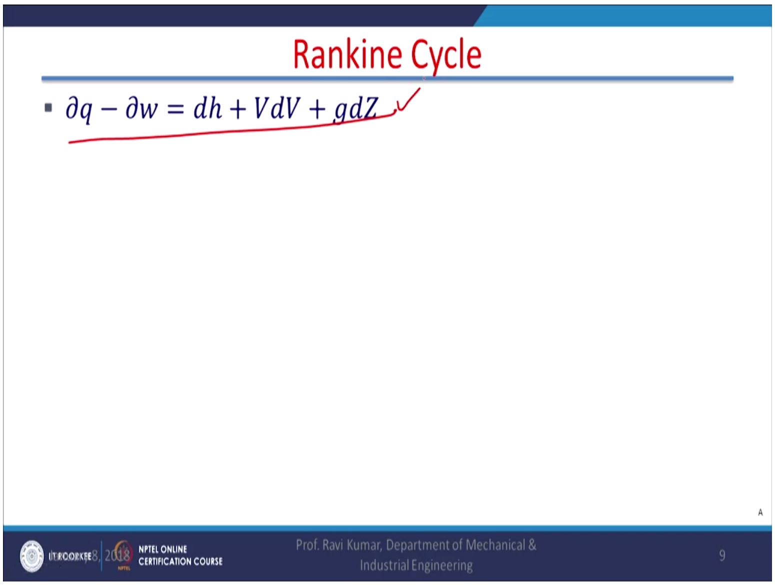

Now, as we know this is the governing equation of for the open system.

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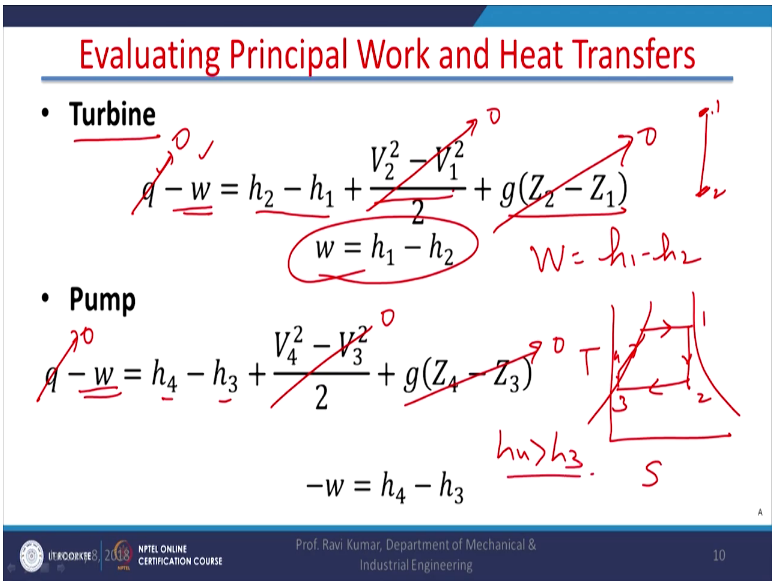

We will evaluate different parts of an a steam power plants. We will start with the turbine because the work and heat interaction the relation relationship between these two has to be established in a in a thermal power plant. So, we will start with the first law for open system q minus w is equal to change in enthalpy, change in kinetic energy and change in potential energy.

Now, inside the turbine when the shaft is horizontal there is no change in potential energy. Inside outside velocity of a steam there is not much change, so kinetic energy is also 0. Now, h 2 minus h 1 is equal to minus w. So, w is equal to in that case w is equal to output on a work we are getting from the system. So, work we are getting from the system is going to be h 1 minus h 2. So, during expansion process if we know the enthalpy at the inlet of the turbine and we know enthalpy at the outlet of the turbine we can get the output from the turbine. If we know the mass flow rate if that is going to be specific output, if we know the mass flow rate mass flow rate multiplied by this change in enthalpy will give output of the turbine.

Now, regarding pumps, now pump also we can apply because pump is also an open system, turbine is an open system with rigid boundary wall, right. Pump is also an open system. Now, if we do first law analysis of the pump then there is no heat transfer, q 0 here also there is no heat transfer, turbine, ok. Pump there is no heat transfer. This change in potential energy 0. Change in velocity is this kinetic energy is also 0, because if we draw this temperature entropy this Rankine cycle it is going to be like this, so 1, 2, 3, 4. So, process 3 to 4 is taking place inside the pump.

Now, we are getting minus w is equal to h 4 minus h 3, minus w h 4 minus h 3 h 4 is greater than h 3. It means the work is done on the system. So, pump is consuming work which is h 4 minus h 3 and that is why it is depicted by minus w, it is energy consumed by the or the work consumed by the pump.

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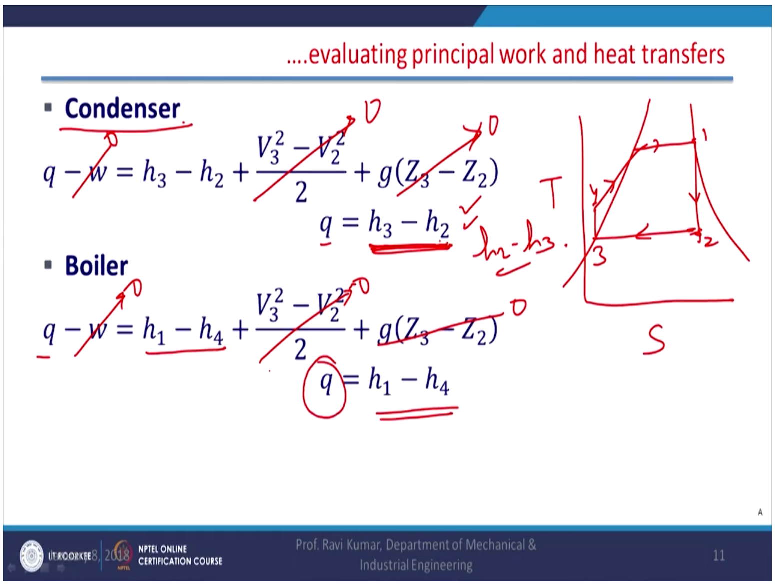

Now, another important part of the steam power plant is condenser. Now, if consider condenser as an as a control volume then there is no movement in the boundary of the condenser neither it is producing any output. So, this work is going to be 0, the change in kinetic energy 0, change in potential energy 0, then Q is equal to h 3 minus h 2 it is obvious right.

So, in a in a Rankine cycle 1, 2, 3, 4so, h 3 minus h 2 h 3 minus h 2 is going to be the heat, heat interaction or now here q is equal to h 3 minus h 2, h 3 is less than h 2. So, q we are going to get negative value. Negative value is there because we are extracting heat from the system when we are giving heat to the system it is positive, when we are extracting heat from the system it is negative. So, heat extracted from the system is h 2 minus h 3.

The last and the most important one is the boiler. So, if we do the first law analysis of a boiler, the boiler also boiler does not produce any output neither shaft work or nor any work through movement of the boundary that is 0. This potential energy 0, this change in kinetic energy 0 then heat transfer is h 1 minus h 4, h 1 minus h 4. So, at the exit of the pump when the water enters the boiler and at the entry of the turbine, right; this enthalpy difference is the heat transfer in the boiler.

Boilers will be discussing in details when we will discuss about the steam power plants because nowadays there are high pressure there are variety there is a variety of boilers and the boiler efficiency is also high. I mean if you look at the thermal efficiency of the boiler, it is and it has to be always more than 90 percent. If you look at the efficiency of the steam turbine it is approximately 60 to 70 percent, right.

If you look at the efficiency of internal combustion in your IC engine it is approximately 35 percent. 35 percent is very good I mean and 40 percent is excellent which is. So, this is how the efficiencies are appreciated at different levels. Now, there are certain performance parameters also for steam power system.

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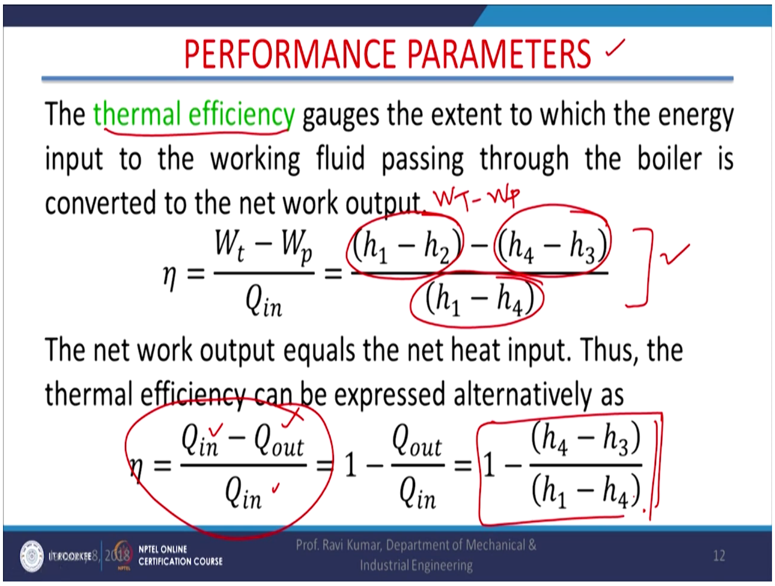

Now, in these performance parameters main thing is thermal efficiency. Thermal efficiency means how much heat has been converted into the useful work, that is thermal efficiency right. So, if you look at the turbine this is h 1 minus h 2 is the output of the turbine, if you look at the previous slide. And h 4 minus h 3 is the work consumed by the pump. So, net output is output of the turbine minus output of the work consumed by the pump or work interaction in total cyclic process right because it is consumed by the pump that is why it is minus w p.

And heat supplied that heat is supplied in the boiler that is h 1 minus h 4 and this ratio gives the output of gives the thermal efficiency of the cycle. It is stated here Q in minus Q out divided by Q in, right. It can be alternatively expressed by this also, ok.

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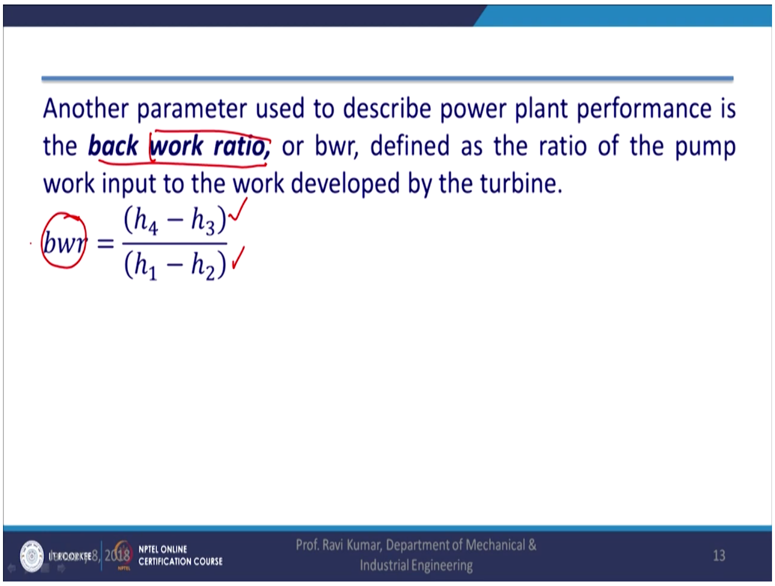

And after thermal efficiency there is a term back work ratio, work ratio. Work ratio is the h 4 minus h 3 divided by h 1 minus h 2, it is known as back work ratio. So, back work ratio also gives us an idea about how much energy is produced and how much energy is consumed by the system itself. So, back work ratio has to be 0 in ideal case, it has to be 0. So, it gives us idea about how much energy is produced and in fact, produced by this what is the output of the system and part of that output how much is consumed by the system itself.

Now, we want to do some parametric analysis.

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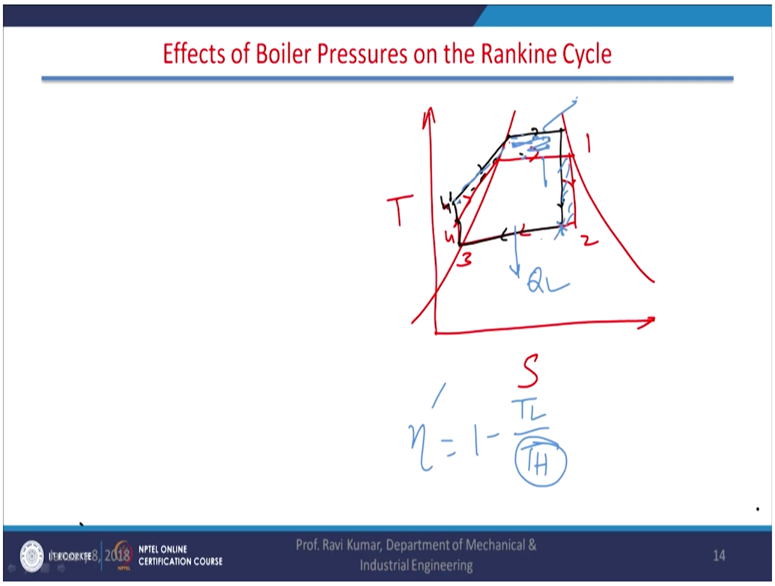

Parametric analysis means suppose there is a Rankine cycle it is a typical Rankine cycle. Now, if I increase the boiler pressure, suppose boiler pressure is 40 bar, I make boiler pressure 50 bar. So, the moment I increase the boiler pressure it means the pressure at the outlet of the pump will increase. So, it will be 4 will be shifted here 4 dash, it will be 4 dash, right.

Now, from here heat addition will take place and the cycle will be modified like this. So, the moment we increase the pressure, the pump work will increase, we will get more output in the form of this area. This area will provide us more work output. This part of the output we will be losing, right and at the same time the quality of vapor which is entering the condenser will also reduce. So, heat rejected will reduce, right and heat supplied will increase. The net effect is, the net effect if we look at the net effect net effect is efficiency of this cycle will increase because efficiency is if we look at the Carnot efficiency it is 1 minus T L by T H, right.

The moment you increase the pressure the saturation temperature will also increase. So, saturation temperature here will be less than the saturation temperature here. While the saturation temperature is increased the mean temperature of heat addition is more in this size, is more in this case. Mean temperature of heat addition is less in this case when the mean temperature of heat addition is more it means T H is high, right. So, efficiency of this if we increase the pressure in the boiler the efficiency will increase, but at the same time, but at the same time the quality of vapor which is leaving the turbine will reduce that may cause erosion in the turbine that is a practical problem, right and there are many ways to take care of that.

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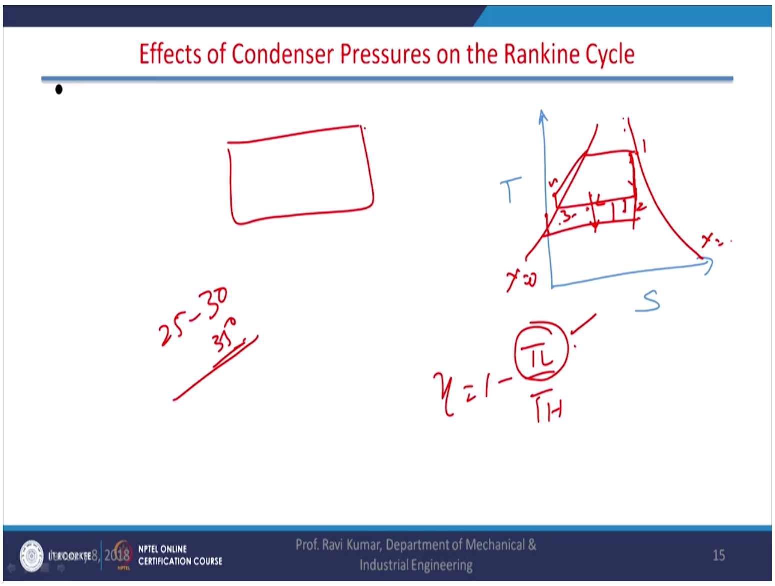

Now, after this we will discuss condenser pressure, effect of condenser pressure. So, if we draw again the turbine the cycle temperature entropy. So, again suppose we draw diagram 1, 2, 3, 4, that is it.

Now, if we reduce the pressure in the condenser if we reduce the pressure in the condenser again if we compare with this 1 minus T L by T H. According to this formula that we reduce the T L the efficiency will improve. When we reduce the pressure in the condenser the this the cycle will be shifting in downwards like this, right. And in that case, we will be getting more output we will be getting the more output, the diagram area will increase, but there is a limitation in reducing the condenser pressure.

We cannot reduce, we are not create vacuum, if we are able to create vacuum there we will be getting the I mean the efficiency will become 100 percent, all heat will be extracted from the steam, but it is not possible. We cannot reduce the pressure inside the condenser or we cannot reduce the temperature of the condenser below the cooling water because in a condenser the heat is taken away by the cooling water. Normally, in thermal power plants it is the lake water or the sea water or river water. So, river water will be available in the range of 30, 25 to 30 degree or 35 degree centigrade. So, the temperature in the condenser cannot be reduced below 40 degree centigrade or 45 or 40 degree depending upon the location in India. So, there is a limitation on the temperature of the condenser.

Similarly, there is a limitation on the pressure of the boiler also, because the moment you increase the pressure the design of the boiler has to be robust first of all. The temperature will also increase that will increase the cost of the plant. Temperature will also increase and we cannot go beyond a certain temperature also that we will discuss in subsequent slides.

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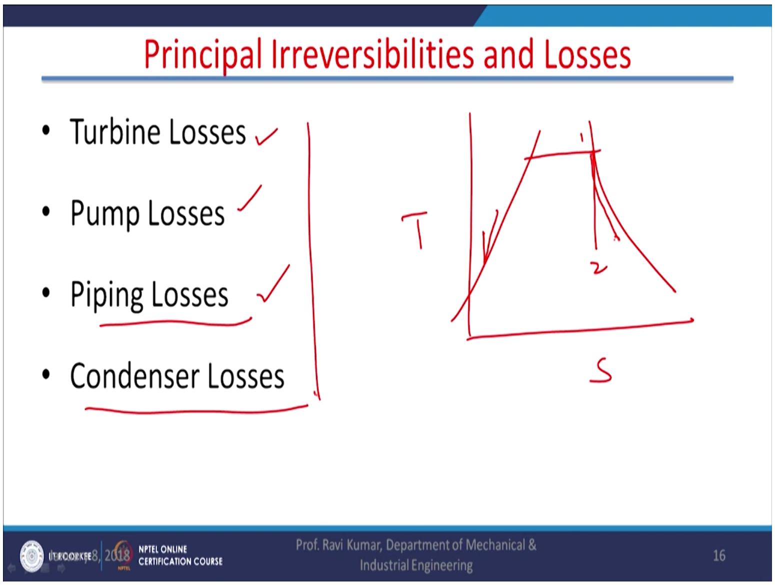

Principle irreversibilities and losses because what we have discussed so far is about the ideal cycle, but in actual cycle if you draw on temperature entropy diagram. We will talk about the major losses not the minor losses. First of all there is a turbine loss. We say it is state 1 to state 2 right. But in actual practice there is internal resistance the heat loss of or the entropy increased due to internal resistance. The process may be adiabatic may not be reversible.

So, if it is not reversible the entropy will increase and that will cause the loss. Second thing is pump losses. Pump is also, I mean it is not reversible adiabatic it may be some irreversibility will be there. So, entropy will increase here also. Piping losses when there is a flow in the pipe especially there is a flow of a steam in the pipe. Then the velocity is high and the losses are substantial.

So, these losses have to be taken into account while analyzing the steam power plant, and there are losses in the condensers also. So, these losses have to be taken into account while analyzing the a steam performance of a steam power plant.

Now regarding the improvement of performance of a steam power plant.

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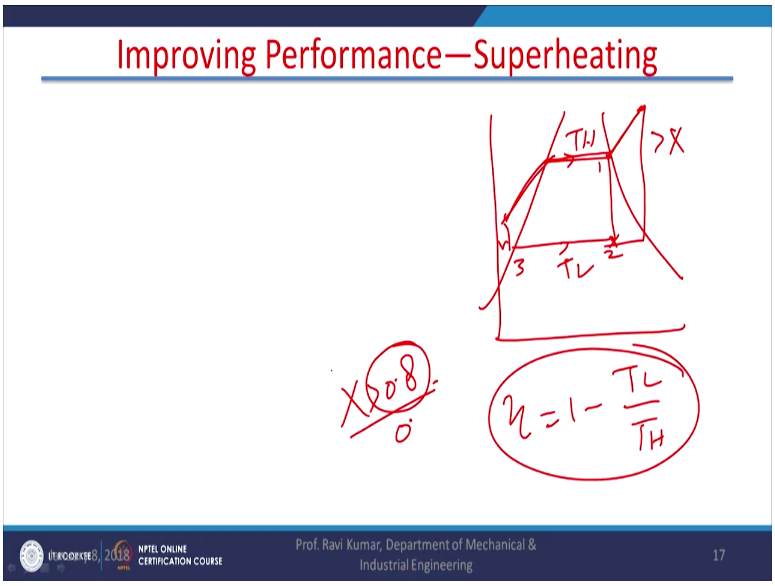

If we want to improve the performance of a steam power plant, then suppose there is a Rankine cycle: 1, 2, 3, 4. I want to improve the performance of this cycle. Instead of, beyond the saturation point if the steam is heated superheated and then it is expanded it will definitely improve the output of the turbine. And if you look at this formula one minus T L by T H: this is T L and this is T H net temperature of heat addition will also increase right or average temperature of heat addition will also increase.

So, the efficiency of the turbine will increase by a super heating. And at the same time by super heating by erosion of the blade we can also prevent. We can operate plant on a higher pressure, because the quality of the vapor should not be less should be greater than sorry X has to be greater than 0.8. In fact, it is kept 0 more than 0.8 it is between 0.8 or two 0.9. X has to be more than 0.8 in case of; if we want to prevent the erosion of the blades.

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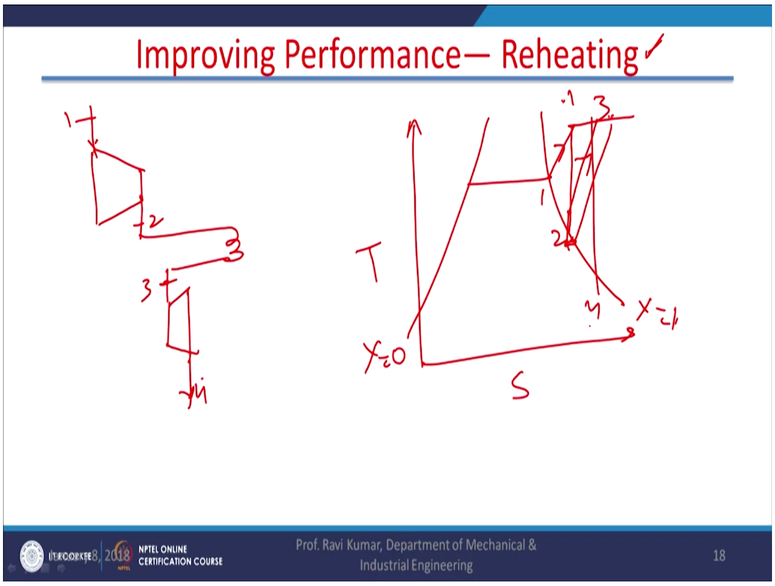

After super heating reheating can also be done, if we want to improve the cycle for reheating: suppose steam is superheated. Now expansion of a steam is taking place, we can either at saturation line or before or after the saturation line. We can super heat the steam; could be expanded up to here and then it is up to here, and super heat sorry reheat the steam.

So, there are two turbine there are number of turbines. Suppose this is a high pressure turbine, expansion of a steam is taking place from state 1 to state 2, after that it is reheated. And after reheating again it is sent to steam is sent to the turbine for expansion. So, 1; so sorry 1, 2, 3 and then again it is sent for expansion. So, reheating also improves the output of the turbine. It may increase and it may not increase the efficiency of the turbine, but it definitely improves the output of the turbine.

Now, there is another process which can improve the efficiency of the turbine that is regeneration.

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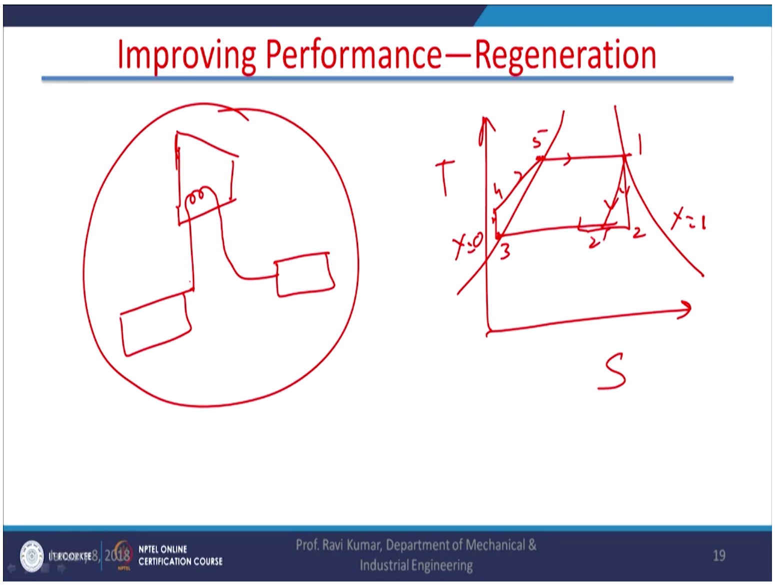

In regeneration, if you look at the again temperature entropy diagram in case of regeneration this is. So, if (Refer Time: 32:35) or after condenser, after condenser the steam. So, the water is sent to the steam turbine shell or steam turbine casing. And from there if the heat is taken and the boiling or the heating of the feed water from state 3 to state 5 takes place here then when this water is entering the boiler it will entering at state 5.

So in fact, the heat addition will start from state 5 in the boiler this process is known as regeneration. I mean we can have a number of I have given you very very simple example and very simple arrangement. So, we can have variety of arrangement for this. And in this case because heat is extracted during expansion the process 1 to 2 will become like this. And this also improves this process will also improve the efficiency of the cycle.

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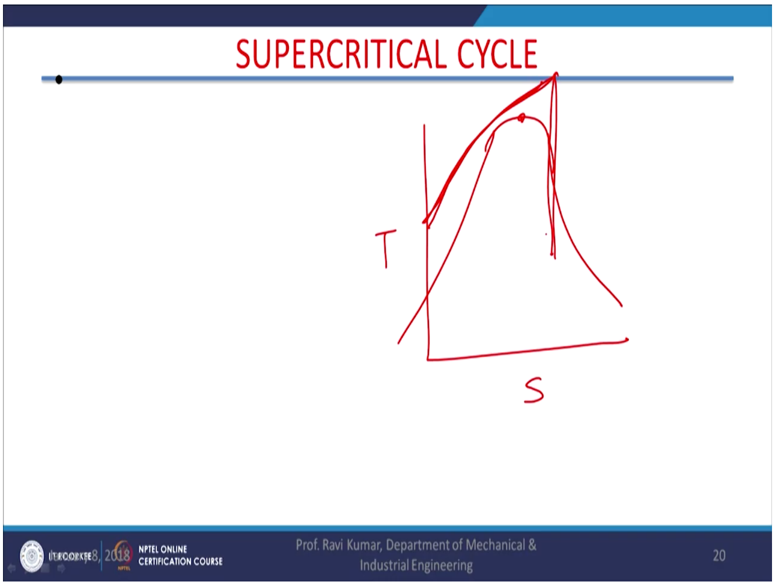

Now, the last one is super critical cycle. Nowadays, we have super critical thermal plants where the operation of the thermal power plants take place in the super critical and beyond the critical temperature. So, the entire heat addition takes place beyond the critical point of water. And these super critical power plants they operate on high pressure and high temperature and they give high output, and then expansion takes place in a the rest of the processes are same. Only heat addition, in the in the water takes place in super critical zone beyond the critical point.

So, these are this is known as super critical cycle. This is and for today.

Thank you very much.