Applied Thermodynamics for Marine Systems

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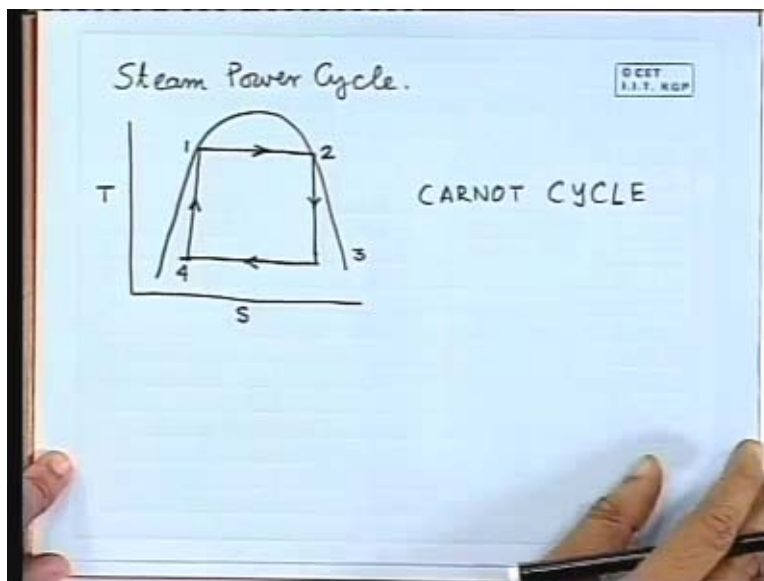
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Lecture – 9
Vapour Power Cycle

Good evening. We were discussing the steam power cycle. A steam power cycle is basically a heat engine cycle where steam is used as the working substance.

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The working fluid medium is steam. In part of the cycle it will be in the form of steam and in part of the cycle it will be in the form of water. As is in a heat engine cycle, always, it is the motto or it is the attempt of the engineers to have the maximum output from the cycle. In the steam power cycle also we will try to have the maximum output from the cycle and if the heat source and heat sink are given as I have discussed in the class of previous day, we can construct a reversible cycle between the given heat source and heat sink to have the maximum output and one can think of a Carnot cycle. I will try to construct a Carnot cycle. This is the TS plane and we are trying to construct a Carnot cycle. This is the process of heat input and it is inside the two phase dome. Basically, it is evaporation or boiling process. In this process, the temperature remains constant. This is nothing but isothermal heat addition. From 2 to 3, this is reversible

1

adiabatic expansion process. Then from 3 to 4 it is reversible isothermal heat rejection process. This is nothing but a condensation process and from 4 to 1 we can go back by a reversible compression process. This compression process will also be adiabatic. It is reversible and adiabatic. So, basically we have two reversible isothermal processes that is 1-2 and 3-4 and two reversible adiabatic processes that is 2-3 and 4-1. It is a Carnot cycle using steam as the working fluid.

Let us see whether we can realize this cycle in practice or we will have some problem in realizing it. The main problem comes for point 4. Here, what we can see is that this is a condensation process and we have to stop exactly at point 4 so that by a reversible compression process we can go back to point 1. That means, the condensation process we have to stop somewhere in between, in the two phase dome, so that we can go back to the initial point of the cycle, the starting point of the cycle and this is very difficult to achieve. To control the condensation process in this way is extremely difficult. This is one reason which makes the realization of Carnot cycle using steam a difficult proposition.

The second thing what we can find is that from 4 we are compressing the working medium so that we can go back to point 1. That is the initial point of the cycle. At point 4, we are having a mixture of gas and liquid or vapour and liquid. We know that if we have liquid only, we have devices for increasing the pressure that is a pump. If we have vapour or gas only, then, we have devices for increasing its pressure that is a compressor. But, it is very difficult to handle both liquid and gas together with the help of a mechanical device. Not only that, if we do it, we will consume lot of energy. It is difficult to design such a device. If such a device is designed, that will consume lot of energy also. These two are two main drawbacks for realizing a Carnot cycle using steam as the working fluid. What we can do is we can modify the Carnot cycle to some extent. This is the Carnot cycle.

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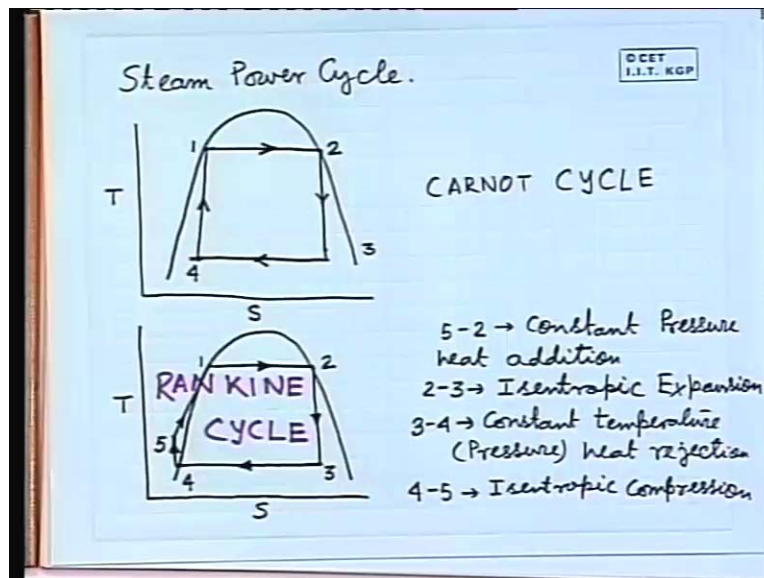
If we modify, let us keep it side by side; we will have TS. If we modify, we will have 1-2; this is again isothermal heat addition process, 2 to 3 is reversible adiabatic expansion process and from 3 to 4 we are having isothermal heat rejection by condensation process. But here, what we have done is, we have not stopped the condensation process in between. We have continued the condensation process till we get a saturated liquid. The entire vapour is condensed to saturated liquid. We have carried out the condensation process up to that point. At this point, at 4, we are getting a saturated liquid. What we can do? We can see that the cycle is being operated at two different pressure levels. One is this one that is 1 to 2 that is at one pressure level that is the boiler pressure and 3 to 4 that is at another pressure level which is the condenser pressure. We are getting a saturated liquid at condenser pressure. From there, we have to raise the pressure to the boiler pressure level. This can be done by some adiabatic compression process in a pump and then we can have heating along this constant pressure line. Basically, what we are having now is another point. Let us put point 5 here. Basically, we are now having our cycle as 1-2-3-4-5.

We can identify the processes. 5 to 2, we call it constant pressure heat addition; 5 to 2 is the constant pressure pre-heat addition. In the Carnot cycle, we had a constant temperature heat addition. Here we modify the process slightly and we have a constant pressure heat addition. But, inside the two phase zone, the constant pressure heat addition becomes a constant temperature heat addition also. Then, 2 to 3 is isentropic expansion; then 3 to 4 is constant temperature, this is

also constant pressure heat rejection. This is similar to your Carnot cycle. 4 to 5 is the isentropic compression. We can see that basically we have modified one process that is the heat addition process. Instead of the constant temperature heat addition we have constant pressure heat addition. But, the process is such that a large part of the heat addition is also at constant temperature. This cycle is known as a Rankine cycle. This is the basic Rankine cycle which we use for steam power plants where we generate or convert thermal energy into mechanical energy using a heat engine cycle and where the working fluid is steam; that particular cycle is a Rankine cycle and we have drawn the basic Rankine cycle here.

In the basic Rankine cycle what we can see is that we have got constant pressure heat addition. The process 5-1-2 is constant pressure heat addition. What we find in this constant pressure heat addition? 5 to 1, in this region or in this part of the process, the working fluid is in sub-cooled liquid or it is in liquid state. At 1 it is saturated liquid, at 5 it is sub cooled liquid. At this portion, the heat addition is by constant pressure. But, 1 to 2 this is within the two phase zone. This is basically the evaporation process and at this condition, the heat addition is both at constant pressure and constant temperature. At point 2, we are getting saturated vapour and then, this saturated vapour is being expanded or it expands through the turbine. Ideally it follows a reversible adiabatic path. If it follows a reversible adiabatic path, then during the expansion, not only its pressure decreases but we can also see that its quality falls. That means we have started with 100% quality. Now at point 3, we are having quality less than 100% or we are having wet steam.

We have started with dry saturated steam after the expansion we are having wet steam. From a thermodynamic point of view, there is no problem. But from a mechanical operation point of view this is not desirable. What will happen at the later stage? Actually in a steam turbine, there will be different stages of turbine. As we go towards the later stages or down stream of the turbine, you will see that the amount of water will increase in this steam and this water is in the form of water droplets. They will impinge the turbine blades. The density of steam and water droplets is different. The inertia of the water droplets is higher. They will impinge the turbine blade and that will create some problem in the operation. This will not only damage the blade, but will also reduce the generation of power. The output also will get reduced due to the impingement problem of the water droplets. That is why the wet steam has to be avoided or at

least it has to be reduced at the later stage of the turbine. That is why, if we start from the dry saturated condition of steam we will get much wet steam or low quality steam. We can improve the condition if we start with superheated steam. The next improvement on the Rankine cycle what can be done is that we will go to the superheated region inside the boiler itself and then we will allow the superheated steam to expand through the blade passages of the turbine.
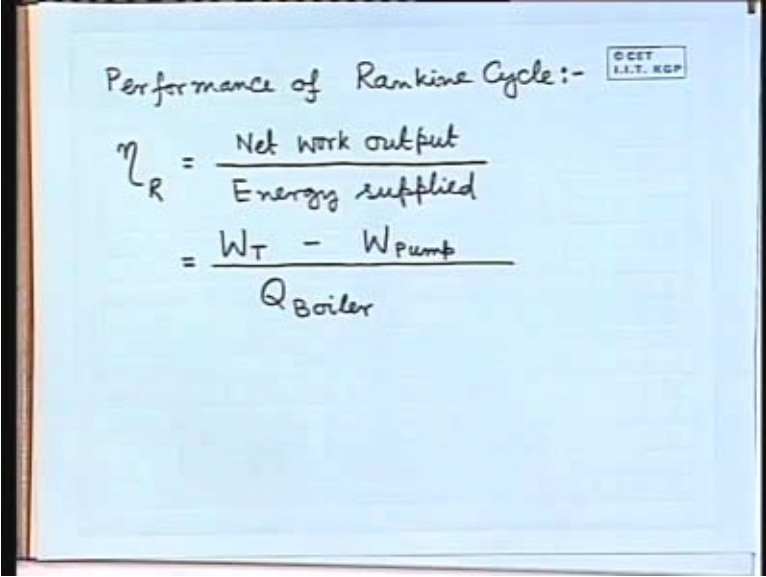
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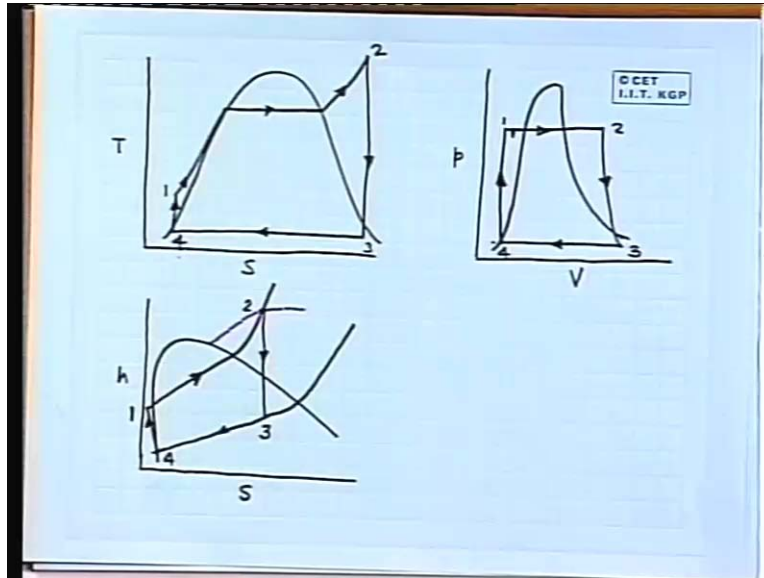
Let us have 1 to 2 which is the heating process, 2 to 3 is the expansion inside the turbine and 3 to 4 is the condensation of steam and 4 to 1 compression or pressure rise in the pump. This is what we will get if we use superheated steam in the steam turbine. Here we can see that this heating process is a constant pressure heat addition process. One can represent the process or cycle both in pV and h-S diagram also. 1 to 2 is a constant pressure heat addition. This is constant pressure heat addition, 1 to 2. Then, 2 to 3 is a reversible adiabatic expansion process, then this is 3 and this is 4. 3 to 4 is condensation process, heat rejection process and again this is adiabatic compression process. This is how the cycle can be represented in a pV plane.

If we go for h-S plane, these are two pressure levels; one is boiler pressure and another is condenser pressure. We have started with superheated steam. At point 2 it expands. It goes here then there is constant pressure heat rejection, it becomes saturated liquid. This is 2-3, this is 3-4 and then it is compressed up to point 1 which is at a high pressure. We will have the coordinates

5

like this, h-S. 1 to 2 is the constant pressure heat addition, 2 to 3 is the reversible adiabatic expansion, 3 to 4 constant pressure heat rejection and 4 to 1 again reversible adiabatic compression. This is the temperature at which it is being superheated. By this modification, where we are using superheated steam at the inlet of the turbine, we are also gaining in work output. That means we are using the same working substance; same amount of mass flow rate is there but during the same amount of mass flow rate or same flow rate of the working medium we are gaining in output. That is another advantage of using superheated steam.

Next, let us see how we can find out the performance of the cycle.

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Let us say that we try to find out the efficiency of the Rankine cycle. If we want to find out the efficiency of Rankine cycle, η_R that is equal to from our definition of efficiency for heat engine cycle, one can write net work output divided by energy supplied. In terms of the physical quantities, we can write W_T, which is the turbine work that the cycle is doing, minus W_{pump}, which is the pump work which has to be supplied from outside to the cycle, this divided by Q_{Boiler}, the thermal energy supplied to the boiler. It is basically the net work that we will get from subtracting the pump work from the turbine work. By subtracting the pump work from the turbine work, we will get the net work done by the cycle and energy supplied is nothing but what is the energy supplied to the working fluid in the boiler.

6

What is W turbine? W turbine, again I will ask you to recall what we have done in first law of thermodynamics for steady state steady flow process. We are considering that a steam power plant is working in a steady state. So, the process through a turbine is a steady flow process and in this case we are also neglecting the changes in kinetic energy and potential energy. We are also neglecting the heat transfer from the turbine. It is assumed that the turbine is well insulated, so, no heat is transferred from the turbine to the surrounding media. If we take all these assumptions, then the work done in the turbine will be the change in enthalpy between the inlet and outlet. That means it is the change in enthalpy of the incoming steam and the outgoing steam. If we do the analysis based on a unit mass flow rate of the fluid, we can write; if we take this diagram then the work done in the turbine will be h_2 minus h_3. h_2 minus h_3 is the work done by the turbine minus the pump work. The pump work is slightly .... How we can estimate the pump work? We will come back to this later on. First we will try to estimate what the pump work is.

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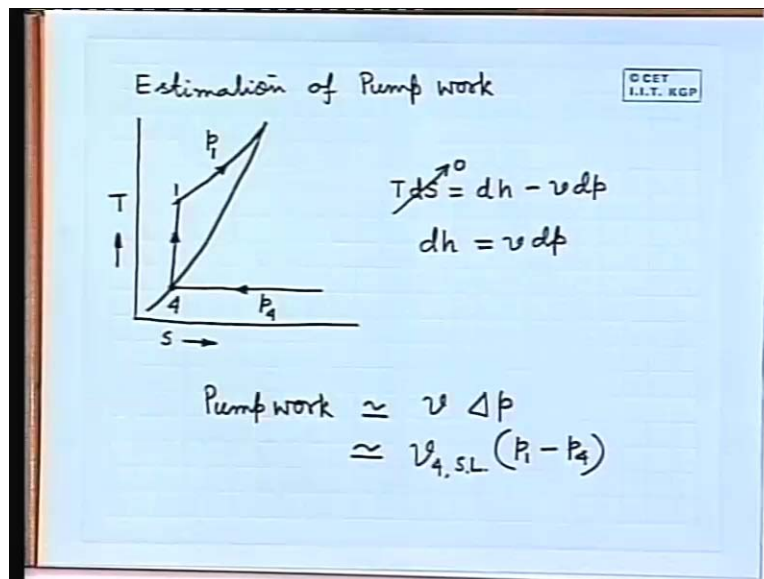
Let us draw an exaggerated view for the calculation of pump work. Let us say this is the condensation process and this is the heat addition process. As we have written this is 4, this is 1 and let us say we denote this pressure as p_1 and that is the pressure of the boiler and this pressure we denote as p_4 and that is the pressure in the condenser. As usual you have the TS diagram. This is the TS diagram. How can we calculate the pump work? One may say that just like turbine

work, can we not follow the same procedure for determining the pump work? There is one point. Here we know the enthalpy; at point 4 the liquid is in saturated condition, we know the condenser pressure, here we know the property of the fluid. So, here we can determine the enthalpy. But at point 1 we do not know the enthalpy of the fluid from our steam table.

In this steam table as I have mentioned that, only the property of the saturated fluid is given. 1 is at sub cooled condition. What is the energy addition due to the pressurization process? We are at difficulty to find it out. But, one can use some sort of an approximate analysis. From thermodynamic relationship, one can write Tds is equal to dh minus vdp. By combining the first law and second law and then assuming the isothermal process, one can write this equation. As it is an isentropic process, Tds is equal to 0; this also, we can put. So, dh can be written as vdp. We are interested in finding out the change of enthalpy between 4 and 1. By this method, we can find out the change in enthalpy between point 4 and 1 and this change in enthalpy is nothing but the work done during this process, just as we have found out the work done in the turbine, here also we can find out the work done by computing vdp. We can write the pump work as approximately equal to v into delta p. That is one can write v_4 saturated liquid; I am writing SL that is saturated liquid. At condition 4, the specific volume of saturated liquid can be found out from the steam table and $delta_p$ we can write down. It is nothing but p_1 minus p_4. This will give you the work done by the pump.

With this, we can go back to our previous analysis and then we can write v_4 saturated liquid and p_1 minus p_4.

This is the work done by the pump. What is the heat addition in the boiler? Again, if we go back to our earlier diagram h_2, enthalpy at condition 2 that is the enthalpy of the steam which is coming out of the boiler and h_1 is the enthalpy of water which is entering the boiler. We can write h_2 minus h_1. We can write that simply and from there we can get the efficiency of the Rankine cycle.

You see in some cases, a simplification can be made if the boiler pressure is not very high. This is basically p_1 minus p_4 and p_1 and the boiler pressure p_4 is the pressure of the condenser, it is close to atmospheric pressure. If the boiler pressure is not very high, then this total quantity, work done by the pump is not high and is quite small compared to the work done by the turbine. In that case the total quantity can be neglected and one can write eta_R is approximately equal to h_2 minus h_3 divided by h_2 minus h_1. This is an approximate expression for the efficiency of Rankine cycle. Either we can use the previous expression or if the boiler pressure is not very high then we can use the moderate level of boiler pressure expression for determining the efficiency of the Rankine cycle.

If we see the justification for this simplified expression for efficiency, this is the TS plane and we are having the two phase domes like this and the constant pressure lines are like this.

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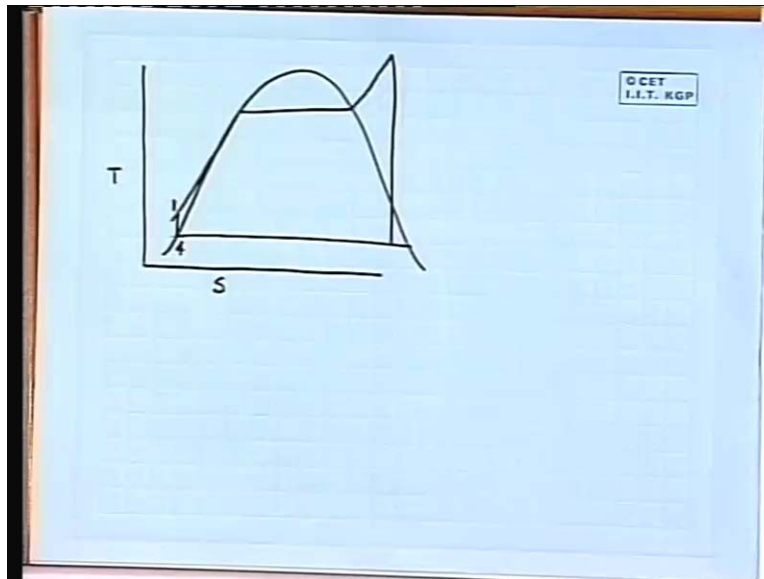
Basically, this is your point 4 and this is your point 1. When the pressure level is low in the boiler, one can see that 4 and 1 are quite close and their enthalpies are also comparable. The difference between h_4 and h_1 is small and that is why it is neglected. This can be made clear if we go to the h-S diagram. In the h-S diagram, where the enthalpy values are there, there also you will find that this will give a very small value compared to the enthalpy difference between point 2 and point 3.That is why this assumption is made sometimes. We will take up some problem and then it will be clear. Definitely we will practice some problem on steam cycle.

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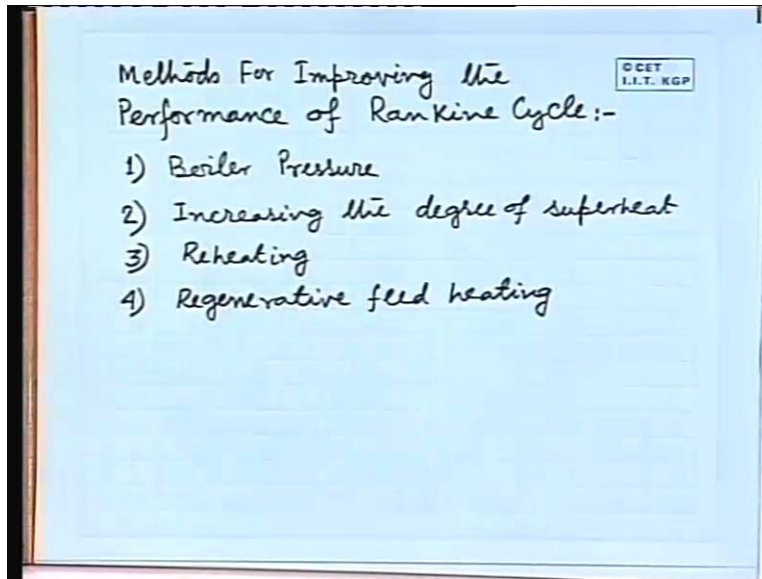
Let us see methods for improving the performance of the Rankine cycle. The way I have analyzed it, if we take some representative value of the boiler pressure and representative value of condenser pressure, take the values of enthalpy from the steam table and calculate the efficiency, we will see that we are not getting a very high efficiency. The efficiency is quite low and always we try to have high efficiency from a heat engine cycle which is used in practice. One can think of different ways by which the efficiency of a Rankine cycle is improved. There are different methods by which one can improve the efficiency of Rankine cycle. Firstly, what one can do is, one can increase the boiler pressure. Actually, what I am doing by increasing the boiler pressure is that I am increasing the pressure of the supplied steam or pressure of the steam which is going to the turbine.

Basically, I am increasing the energy content of the steam. At higher pressure it will have a larger enthalpy. But, you see that there are mechanical problems. As we increase the boiler pressure, the tubings, etc., are to be made thick at considerable cost, increase in volume. So, one cannot go on increasing the boiler pressure arbitrarily. There are some limitations from the practical point of view. Probably this exact value etc., we will discuss when we learn about the boiler but, it is sufficient to know at this point we cannot increase the pressure arbitrarily. There are some limitations up to which we can increase the boiler pressure.

11

One can increase degree of superheat. This has got the same advantage. That means we are having the same working substance, we are having the same basic equipment. But, when we are using steam with a higher degree of superheat and supplying heat to the turbine, the energy content of the steam is higher. One can expect more work output and possibly a higher efficiency. But, again, there is a mechanical constraint. As it is a steady flow device, the part of the boiler will always be exposed to very high temperature. The high temperature steam is going to the turbine. The turbine blades will be always subjected to high temperature and material failure will take place if we go to extremely high temperature. From the material point of view, maximum temperature that can be associated with the flowing steam is limited and we cannot go beyond that. Though we try for increase of pressure and increase of temperature, basically, from the material point of view and mechanical point of view we have got limitation in these cases.

The third thing which is tried is the reheating of steam and fourth what can be tried is regenerative feed heating. I have just written the name but I have not explained it because they need certain elaborate discussions. Reheating and regenerative feed heating I will discuss in a bit detailed manner, because they are very important means for improving the performance of a steam power cycle or a Rankine cycle.

In reheating, what is done is that steam is initially superheated in the boiler and then it is sent to the turbine. In the turbine it expands, not up to the condenser pressure, but up to some intermediate pressure. Then this steam is taken to the boiler again, where it is again heated back to a high temperature and sent back to the lower stage of the turbine where it expands up to the condenser pressure. So, heating is done at two stages. Initially we heat the sub cooled water to get superheated steam and then we heat the low pressure steam to get again superheated steam and using the same working material we can extract more work. I like to draw both the mechanical arrangement and the cycle diagram for a reheating arrangement.
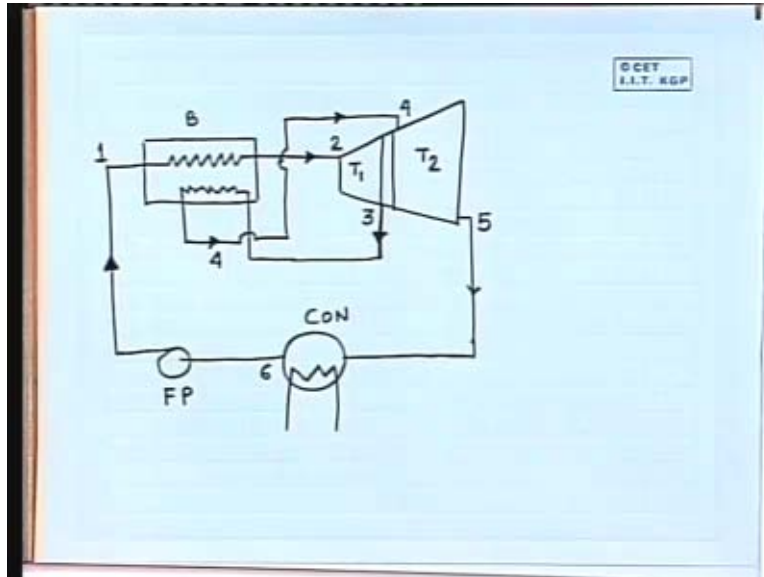
Let us say this is the boiler. We have got superheated steam. This goes to the turbine. We can use two turbines or let us say there are two turbines side by side and we are taking the steam out and sending it to the boiler again for reheating. Again it is going to the second stage of the turbine and then it goes to the condenser, it goes to the feed pump and then it goes to the boiler. I will put the numbers to show the sequence of flow. This is the first stage of the turbine, this is the low pressure stage of the turbine T_1 and T_2, then this is the condenser and this then this is feed pump. Let us give some name. Let us say that as it enters the boiler we denote it by 1. Then when it comes out from the boiler this stage is 2. When it comes out from the turbine it is 3 and then when it comes out from the re-heater it is 4. This stage is also 4. Then, when it finally comes out from the low pressure turbine, at the condenser pressure, its condition is denoted by 5. After the condenser, its condition is denoted by 6 and then it goes through the feed pump and after pressurized its condition is denoted by 1.

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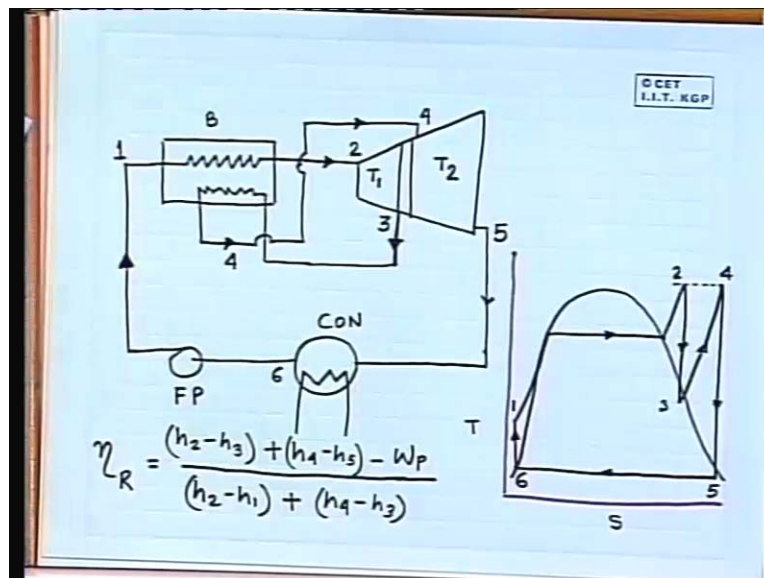
Let us try to have it on a TS diagram. If we have these two diagrams side by side it will give a good comparison. This is S and this is T. This is the two phase dome. Let us say this is 1, this is 2, this is 3, this is 4, this is 5 and this is 6. Let me tell you once again. 1 to 2 we can compare both the diagrams which are side by side. Let me put the arrow marks. 1 to 2 is the heating inside the boiler. Here, constant pressure heating. So, here basically the sub-cooled liquid is being heated to the saturated liquid condition. The saturated liquid evaporates and then the dry saturated steam is brought to superheated condition at point 2. Then, it expands in turbine T_1. This expansion process is 2 to 3. This expansion process is such that either at the end of the expansion, the steam is dry saturated or it is marginally wet.

Actually, it is very difficult to control the expansion process so that we will get dry saturated steam but the condition is such that it is marginally wet and then again we are going for reheating process. The reheating process takes place in the same boiler; 3 to 4 is the reheating process. At 4, we will get the superheated steam but the temperature of 2 and 4 generally are same. It is not mandatory to have the same temperature, but generally they are the same because the highest temperature is dictated by the material property of the boiler and the turbine. We maintain the same highest temperature for both the initial superheated steam and the reheated steam. From 4 to 5 it expands in turbine T_2. At 5 we will get possibly at wet region this exhaust steam from the turbine and then that steam condenses in the condenser and we get saturated liquid at point 6.

14

Then, we have the feed pump and we pump the liquid from point 6 to point 1 that is to the boiler pressure. We have gained something and at the same time we have paid something for that gain. What have we gained? What we have gained is with the same amount of mass flow rate, we will be able to extract more amount of work and what we have to pay is we have to pay for the extra fuel; the complexity of the plant has increased, piping, etc that will increase. These are the extra payments we have to make or extra provisions we have to make for the modification of the cycle.

If we analyze the performance of the cycle, we will see that we will get more work output per unit mass flow rate. But, in terms of efficiency we may lose or we may gain. One cannot be very much assertive that always we will have higher efficiency. The work to volume ratio will increase, but depending on the working condition or the state of the steam at different points of the cycle, we may have a higher efficiency, we may have a lower efficiency. The calculation of efficiency for this reheat cycle is not very difficult. From this diagram itself we can determine it. We will have two turbine works and that means the efficiency reheat will have two turbine works. We can write h_2 minus h_3 that is one work plus h_4 minus h_5 and that is the second work minus W_p pump work. We know how to calculate it. Then, we will have energy input and that is h_2 minus h_1 plus energy input for reheating that is h_4 minus h_3. This will be the expression for efficiency of the reheat cycle. I think we will stop here and other things, we will do in our next class.