Basic Thermodynamics

Prof. S. K. Som

Department of Mechanical Engineering

Indian Institute of Technology, Kharagpur

Lecture - 22

Vapors Power Cycle – III

Good morning. We are discussing the reheat cycle, the concept of the reheat in a steam power plant or in Rankin cycle last class. The concept originated from the fact that an increase in the mean temperature of heat addition in any heat engine cycle increases the thermal efficiency of the cycle and also the thermal efficiency of the plant where the cycle is the theoretical cycle.

In this regard we first thought that if we increase the maximum temperature of the cycle. In a Rankine that is the temperature at the end of the heating process in the boiler or at the entry to the turbine then obviously the mean temperature with addition will increase. But, there is a limit to this maximum temperature of the cycle which comes from the consideration of the turbine blade materials. That means the turbine inlet temperature cannot exceed certain values so that we have to restrict to a maximum temperature to the cycle that is the turbine inlet temperature. So, keeping that temperature fixed still we can increase the mean temperature with addition.

If we increase the temperature of that part of the heat addition which is the sensible heat to the liquid and also the heat which is given to the liquid for change of phase and then superheat to that fixed maximum temperature by increasing the boiler pressure. That means if we increase the boiler pressure and if we heat the water at that high pressure to vaporize to be steam and superheat to the same maximum temperature then also the average temperature of heat addition increased that was discussed earlier.

But what happen to that? This was also discussed that if we do so we see that the expansion process comes up or ends up to a point where the dryness fraction decreases or during the entire expansion process the dryness fraction is on an average much lower than that corresponding to the case where the boiler pressure is lower. If we increase the boiler pressure keeping the maximum temperature fixed. We increase the average temperature of heat addition but at the same time the dryness fraction in the expansion process in the turbine at any pressure is reduced.

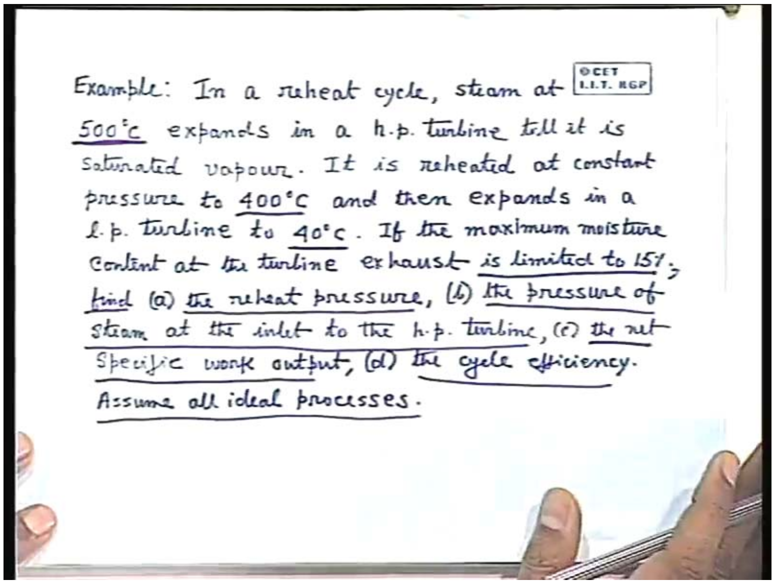
Finally we will end up to the end of some expansion process the dryness fraction which may be lower than which is required that restriction comes also from the turbine blade material. The turbine blade materials cannot have a dryness fraction lower than some value which is usually 0.85 to 0.85 below with the corrosion and erosion problem of the blade come into picture.

To overcome this we consider that we can use the high pressure. That means we can increase the boiler pressure but we go to the concept of reheat that means we consider the expansion in the turbine in two stages. In one stage the expansion takes place from the initial pressure that is the boiler pressure to an intermediate pressure not to the condenser pressure that stage is known as high pressure turbine.

Then the steam which is at the exit of the high pressure turbine at an intermediate pressure is again heated at that constant pressure that intermediate pressure to a temperature. Usually to the initial temperature of this steam and then again it is expanded in another stage of turbine or low pressure turbine stage where it is expended to be condenser pressure.

We have seen in the Rankine cycle diagram in TS plot or HS plot that this ensures a high dryness fraction within the available limit at the end of the expansion process. This thing we discussed thoroughly in the last class so as a continuation of that today we will first solve the problem and then I will go to another aspect regeneration.

(Refer Slide Time: 04:40)



CET I.I.T. KGP

Example: In a reheat cycle, steam at 500°c expands in a h.p. turbine till it is saturated vapour. It is reheated at constant pressure to 400°c and then expands in a l.p. turbine to 40°c. If the maximum moisture content at the turbine exhaust is limited to 15%, find (a) the reheat pressure, (b) the pressure of steam at the inlet to the h.p. turbine, (c) the net specific work output, (d) the cycle efficiency. Assume all ideal processes.

This example we will clear that thing. In a reheat cycle steam at 500 degree celsius expands in an h. p. turbine so it is only given that steam temperature not the pressure till it is saturated vapour that means it is expanded in an h.p turbine till it is saturated vapour.

It is reheated at constant pressure to 400 degree Celsius means it is reheated at the constant pressure to 400 degree Celsius and then expands in an l.p. turbine to 40 degree Celsius. This is the temperature of the condenser that means the condenser pressure is the saturation pressure corresponding to this.

Boiler pressure we do not know there may be a superheated steam so boiler pressure we do not know and then expands in l.p turbine to 40 degree celsius. If the maximum moisture content at the turbine exhaust is limited to 15% that means the corresponding dryness fraction is 85% (0.85). What are the things to be found out the reheat pressure that the pressure at which reheats was done.

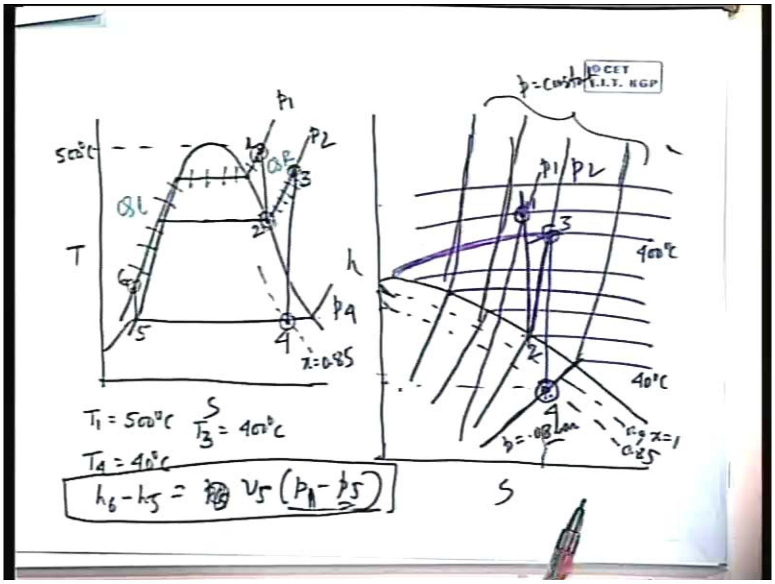
The pressure of steam at inlet to the h.p. turbine what was the pressure of this steam? That is definitely not saturation corresponding to this temperature why? because steam is not well saturated steam is superheated. That means the saturation pressure will be the pressure at the boiler will be the saturation pressure corresponding to the temperature at which the steam was vaporized. The net specific work output, the cycle efficiency assume all ideal processes means assume a Rankine cycle.

We have taken this data so how to solve this problem?

First of all these are the pertinent points. You take the steam entry an inlet temperature is 500 degree Celsius that means T1 the point 1 in the Rankine cycle then the reheated at constant pressure. Now this reheat is not up to the initial temperature 400 degree Celsius and then expands in a l.p turbine to 40 degree Celsius.

These are the three important data maximum moisture content is 15% that is also important then we have to find out the reheat pressure. The pressure of steam at the inlet to the HP turbine the net specific work output the cycle efficiency. To do this what we require is that, we better draw the TS diagram first you understand the TS diagram first. Let us draw the TS diagram.

(Refer Slide Time: 07:18)



$T_1 = 500°C$

$T_3 = 400°C$

$T_4 = 40°C$

$$\boxed{h_6 - h_5 = v_f (p_1 - p_5)}$$

What is this TS diagram?

This is the inlet point1 then it is reheated. This is the intermediate reheat pressure that means this is the P_1 so this is P_2 and this point 2.Then it is reheated to a temperature which is not same as that this is 500 degree Celsius so this is 400 degree Celsius. Then it is expanded down to the condenser pressure. This is the condenser pressure simple problem condenser pressure so this part remains the same this is the pressure line boiler pressure P_1 line so this is 4 and this 4 is such that it passes through the x=0.85 that means this point is fixed.

Let this is 4, then this is 5, then this is 6. So 6 to 1 is the boiler pressure constant pressure heating represents the boiler heating so here it is heated. Now heat is added which is the boiler from the boiler that is Qb. Now 1 to 2 takes place in the first stage of high pressure turbine this is the reheat pressure then it is reheated so here also heat is added we denote it as QR that is the heat for the reheat.

This is a heat addition process at constant pressure which occurs in the re-heater is the coil placed in the boiler which takes the heat from the flue gases burn products of combustion, fuel and it is heated up to a temperature T_2 is less than T_3 so T_3 will be 400 this is given. It is expended to point 4 which ends up to 0.85 dryness fraction this is the condenser pressure so P_4 is the condenser pressure.

What are the data given? Data given T_1 is 500 degree Celsius, T3 is 400 degree Celsius, T4 is 40 degree Celsius and x is point 0.85. First of all we have to find out the reheat pressure how to find out the reheat pressure?

If you see this steam table then you know the point where is the entropy of this point because you know the dryness fraction at this 40 degree Celsius temperature you see the saturated steam table then you can find out these two points entropy and accordingly weighted average of these 2 with x we give you the entropy here.

That means S_4 is equals to S_3 so therefore you will have to look in the table of superheated steam or superheated steam table that at 400 degree Celsius each pressure equates this value of gives these values of the entropy to understand.

Geometrically if the pressure lines are there in TS plot if you have a TS diagram then you can find out this pressure. You know the point 3 how to know the point pressure? You can now heat to at constant pressure to the point 2 in the re-heater in the reheated pressure to the saturated condition. Therefore what you know is the entropy at this pressure. That means when you know this pressure fixed so at this pressure at upon the saturated steam table you know S_2 if you have got any difficulty you tell me then you set S_2 is S_1.

Obviously then you find from this steam table at which pressure for the superheated steam at 500 degree Celsius give this entropy. Geometrically things that very clear but to find out from this steam table you may have to do little trial and error to find out this thing so it will be difficult therefore always this type of problem is preferred to be solving the use of Mollier diagram or HS which I discussed in the last class.

Let us consider the HS diagram. HS diagram looks like this again I repeat this is the $x=1$ line and we have got $x=0.9$. We have got let $x=0.85$ which I want now like that different x lines are there. This is actually originating from this critical point.

These are the constant pressure lines, these are the diverging lines and this is P constant these lines are P is equal to constant. These are the important lines in HS diagram which you require and these are the constant temperature lines. Which always meets this curve a part of the curve I am showing at this point and so that the constant pressure line matches with the constant temperature line in the vapour dome.

This is very simple 40 degree Celsius and this dryness fraction 0.85 so how do you find out this? You will take the forty 40 degree Celsius. For example, I just tell that this is the degree Celsius isotherm this cuts here this point. This pressure and temperature, they are constant pressure temperature line. If you see constant pressure line which runs like this. This pressure may be equal to 0.8 bar approximately or 0.1 bar which is the saturation pressure corresponding to this temperature that means this is the condenser pressure.

This pressure cuts here therefore I have the point 4 here for which entropy is directly found from the abscissa you do not have to calculate it so enthalpy is directly found in the ordinate so this is the point. I have to go vertical that means HS diagram constant entropy process means the vertical line upwards and here I know the temperature that means if I go up let this is the 400 degree Celsius temperature line therefore this is my point.

That means I am generating the cycle in hs diagram that is the only thing but it is not a plane paper the way I do HS diagram and show only the processes that I require but they are constant pressure line, constant temperature line all these things are done that means in a graph paper you plot the process very classical method and very simple method.

Therefore how do I know the reheat pressure? This temperature 3 cuts somewhere here. Actually there is something this diagram should be like this otherwise this looks odd I just change this diagram so this is the constant temperature line. Whatever is there we have to think because the diagram is not very proportionally there is geometry. However doesn't matter therefore this is the reheat pressure that pressure is P_2.

Now I cool it at constant that means I can read the point where it cuts a isobar line that means this point cuts this 400 degree Celsius because the this point is here through this point there is an isobar passing so this isobar is P_2.

To generate Point 2 I will move along this isobar to come to this Point 2. That means 3 to 2 so these are the process my geometrical drawing shows very stiff actually this is not this much stiff. However understanding is more important. From 2 again I go up and cut the 500 this is 400. Let this is 500 so this is my P_1 so the isobar which runs from this point, let this is the isobar which runs at this point so this is my pressure P_1.

I know the pressure P_1; I know the pressure P_2 enthalpy and entropies are found so the rest part is very simple. When you find the all these that means you can draw this right or this portion of this curve in the HS diagram or Mollier diagram. Then you know everything you can find out the net specific work output. Net specific work output will be h_1-h_2 that is the work output in the high pressure turbine plus h_3-h_4 and which are directly read from this ordinate enthalpy.

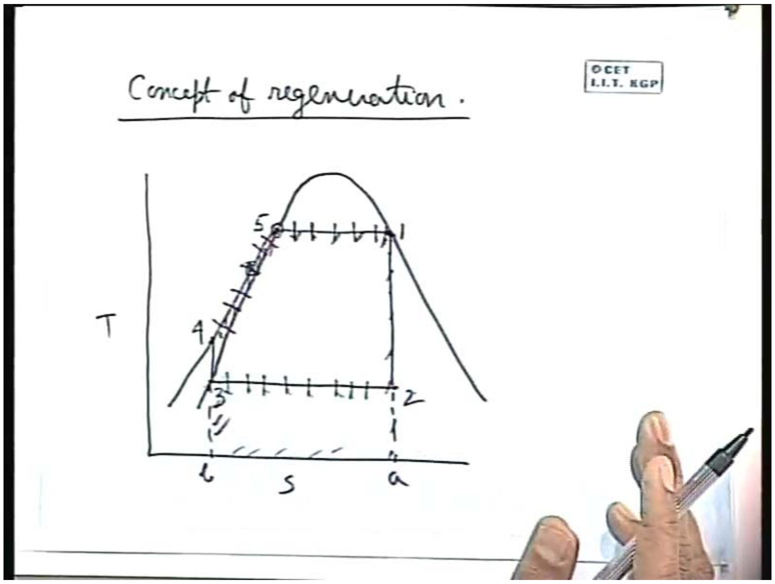
Net specific work output the cycle efficiency this is the network output and the heat added, heat added is $h_1-h_6+h_3-h_2$. h_3-h_2, h_1-h_6 which is not there in this diagram. This is very simple you can find out h_6 considering this pump well I have already told that how to find out h_6? Because $h_6-h_5 = V_5 (P_6-P_5)$

P_5 is the condenser pressure that is this pressure saturated pressure corresponding to this and P_6 is P_1 that means P_1so that means this has been found out by the application of steady flow energy equations and considering the isentropic and the water is incompressible so that specific volume between 6 and 5 remains almost the same.

This has been discussed earlier so you get everything. That means this part of the cycle diagram is generated here so it is always preferable to work out this type of problem in HS diagram though you are conceptually all right but sometimes to find out from this steam table to the pressure P_1 P_2 will be little difficult because you will have to do some trial and error method this gives the clear concept of reheat.

We will come to the concept of regeneration what is regeneration? Concept of regeneration let us write this thing which is very important.

(Refer Slide Time: 17:56)



Before coming to the concept of regeneration I must first discus the basic Rankine cycle again in diagram. This is the TS diagram of the Rankine cycle. Let us consider the dry saturated steam for the time being. It may be superheated steam but for simplicity we draw the dry saturated steam at the entry and I draw the basic Rankine cycle 1, 2, 3, 4.

What is concept of regeneration? The concept of regeneration comes in consideration of the increase of thermal efficiency by increasing the average temperature of heat addition. Now we see the average temperature of heat addition, now heat addition is some temperature from 1 to 4 and the total heat added is represented by this area. You always represented by the area of 1 4 under x axis. This is a, this is b, that means the area 1, a, b, 4 is the amount of heat added and these area is the heat added area and heat is added during the process 4 to 1 again repeat. The heat rejection is the area 2 a b 3 because heat is rejected during the process 2 to 3.

This is the heat added and this is heat without reheat. Now this area 2, a, b, 3 is the heat rejected. You see while we discuss first the increase in the mean temperature of heat addition what would be? We increase the inlet temperature that means the maximum temperature of the cycle which was increased like that the superheated domain but there was a maximum temperature fixed or what we did. We go with a different higher boiler pressure try to understand I am not drawing it that means 4 point we go somewhere here there is an another pressure line so that we can increase the mean temperature of heat addition because the range of temperature for the heat addition is increased.

Another way we can increase the mean temperature of addition what is that? If you observe this heat addition process you see the basic difference from this cycle with the Carnot cycle is that a very less portion of heat is added at the maximum temperature.

Heat is added distributed from temperature 4 to1, if you somehow can heat the water at its lower temperature. For example, in the lower temperature range from 4 to somewhere here for example. Let us consider this saturated temperature and consider this temperature at 4 to 5. 5 is this saturated state at that pressure. This is the sub pool state that means the sensible heating part of the liquid.

It can be taken from the heat generated internally that means the heat of the cycle, if you can take the heat from the hot steam while flowing through this expansion process and can somehow make an arrangement to transfer that heat internally from the cycle to heat this liquid.

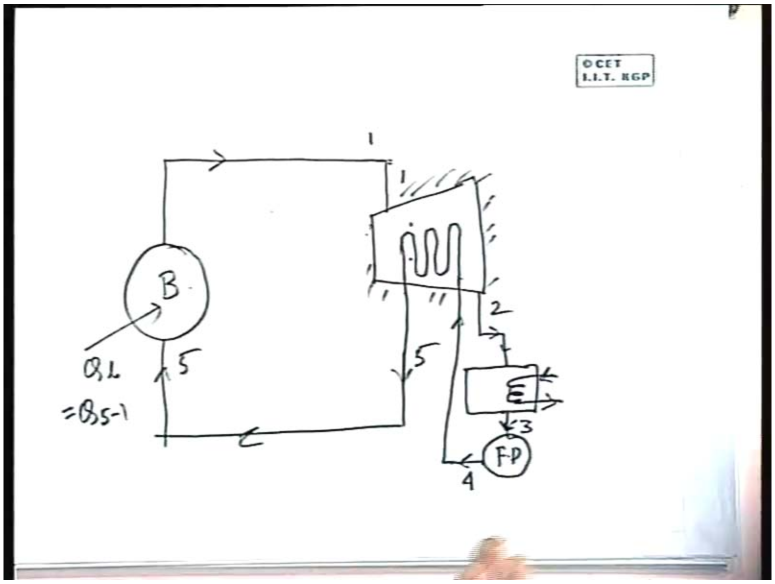
For example, from 4 to 5 only I have to add heat in the process 5 to 1 which is at constant temperature and in that case it becomes equal to a Carnot cycle because heat is added at the maximum temperature of the cycle so the average temperature of heat addition is T_1 and the temperature of heat rejection is T_2 so this is $1-T_2/T_1$. Basic philosophy is that even if we cannot go up to 5 we can up to this that also is all right.

If you can heat up the water in its lower range of temperature by utilizing the heat up the system in some other part where the system is hot that is the internal if we can use the heat by doing so what happens if we can make the range of temperature higher that means if we heat up to this then the mean temperature will be something between T1 to this point which is definitely higher than T1 to T4 and if we can go up to this point then verifying the mean temperature of heat addition is T1 only that is the maximum temperature.

If you do so then the average temperature of heat addition is increased and in a limiting or ideal case, if we can do up to 5 then the process the cycle becomes almost or identically a Carnot cycle. This concept is known as regeneration that means we heat it internally this part of the heat addition is done internally by utilizing the heat of the system in the cycle itself this is the concept of regeneration.

How it is done? First of all to understand regeneration we have to go through this. Now what is done in regeneration? Before that I just draw diagram first otherwise it will be difficult for you to understand. Let us consider the diagram like this

(Refer Slide Time: 23:45)



This is the boiler this goes to the turbine, let one stage of turbine this goes to a turbine where it comes and goes to the condenser. This is the circulating water goes to the condenser. Then what happens is that the feed pump is here. If I place theoretically I consider which is not possible.

First of all we have to understand the thing theoretically a heat exchanger that means this heat water is being heated and then we give it to the boiler that means what I do? Try to understand 1 is the turbine inlet steam which is being expanded to the point 2 then it is being condensed to the point 3 that is in the condenser heat is taken away by the circulating water then the feed pump heats this to 4.

I do not heat this water that means if I fed this water 4 to the boiler what will happen that means I will have to heat up from the point 4 to 5 but instead of that if I place this water through a coil placed in the turbine when the steam expended and let the heat transfer to take place between this steam and the water.

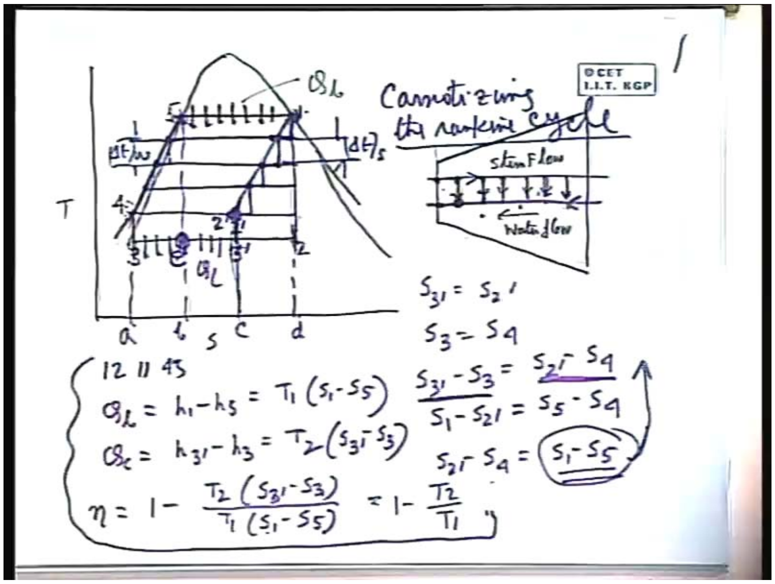
That water takes the heat from the steam the entire turbine is insulated there is no heat transfer with any third body outside. Then water is heated and I consider the water to be heated at the point 4, 5 that means which I wanted. The water be heated up to the saturation temperature corresponding to the boiler pressure.

It enters the boiler at the step 5 instead of 4. Difference is that they are at the same pressure but 4 is at sub pool state and this is at the temperature equals to the saturated steam that means the sensible heating is done here and then it give the heat that means this heat addition to the boiler is the is equals to $Q_{5\text{-}1}$ that means 5 to 1 and it gives only the latent heat that means at constant temperature heat addition.

This is the block diagram of the component that we envisage this way but question immediately comes are how can you put a whether if ah coil of this type as an heat exchanger can be put into a turbine that comes afterwards definitely no but to understand concept that the philosophy of this regeneration we think as if the water is allowed to pass through the tubes or through the condenser where it can exchange the heat directly to the expanding steam to be heated to a temperature 5 and then come to the boiler so this is at ideal regeneration process.

This is shown in an expanded view like this. Let me draw the diagram first.

(Refer Slide Time: 26:49)



$S_{3'} = S_{2'}$

$S_3 = S_4$

12 11 45

$Q_h = h_1 - h_5 = T_1(s_1 - s_5)$

$Q_c = h_{3'} - h_3 = T_2(s_{3'} - s_3)$

$\eta = 1 - \frac{T_2(s_{3'} - s_3)}{T_1(s_1 - s_5)} = 1 - \frac{T_2}{T_1}$

$S_{3'} - S_3 = S_{2'} - S_4$

$S_1 - S_{2'} = S_5 - S_4$

$S_{2'} - S_4 = \boxed{S_1 - S_5}$

This is the TS diagram y, this is the vapour dome in TS diagram let the point is like this. Let me first draw the basic Rankine cycle that means this is my point 1, this is my point 2, this is my point 3, and this is my point 4.

Let me draw the basic Rankine cycle like this. Beside this I conceive this way that if this be the turbine we consider a reversible heat transfer between this. That means when I consider is these two of course you do not confuse with these two otherwise these two will represent actually 1 to 2.

This two is all right 2, 3 is all right, 2 is all right, 3 is all right, 3 to 4 is all right, 4 to 5 all right everything is all right. If we consider this process of heat transfer between this steam and feed water to be reversible. How we can consider? This is very important this is not given in any book.

Let us consider this is the steam path and this is the water they are flowing in the counter flow direction. At each and every point there is a heat transfer that is heat is transferred from this steam as it expands in these directions steam flow. How to consider it? This direction steam flow and this direction let us consider water flow just for our understanding. As this steam flows in this direction the pressure of the steam is changing is decreased but water flows at a constant pressure but across this there is a temperature difference which is infinite small at any pressure that means at any section.

So that a reversible heat transfer takes place that means when water flows in this direction its gets heated that means there is increase in temperature while steam flow in this direction there is a decrease in temperature do you understand and each and ever point there is an infinite small temperature difference so that the water is getting heated or steam is losing heat reversibly.

For example, let us see here the steam from the inlet as expended to this pressure and then it exchanges heat these divisions are infinite numbers that means we have to consider in terms of infinite number divisions of pressure so for an infinite small such process the heat is transferred and because of which the water changes or increases its temperature from this point to this point. This is explained here now.

What is done? If we divide this into different pressures just I show infinite number of pressures infinite small divisions these are the pressures. We assume like this the steam part expands up to some pressure and then if it heats the water for example water is here so this steam heat to the water so that it reaches its temperature from this point to 5. Try to understand this is very infinite small difference that pressure.

For example, I am showing in such for clarity the big different if the steam has to give the heat to this water to be heated then steam will be condensed at some position that means steam is condensed like this. Therefore a steam at here will be condensed to some extent at that temperature where water at that temperature will take the heat and will rise this temperature.

During the heat transfer water temperature will rise so you can ask me that the temperature difference will be there but this temperature difference is so small that if you consider into infinite small division so there will be always a delta t temperature difference for the heat flow.

Similarly the steam will expand from this portion and come to this pressure and where it will condense here to heat the water which is coming at this point to get this temperature.

Similar way the steam will expand to this pressure and it has to condensed that pressure to this point so that the water here will be taken the heat and go to this temperature again what will happens steam is expanded to this pressure and then again condensed up to this point so that water which reaches here which I consider the inlet temperature of the water it is flowing in the counter flow direction which will be heated up to this.

Therefore we see the steam flows in a zigzag way. If we connect this terminal point we get a line like this that means if I denote this line as 1 2 dash what does it indicate this is the actual expansion process of the steam which is not isentropic why because it transfers heat.

Steam as a working fluid I can tell this suffers a diabetic process which is a reversible heat transfer process that means it is a reversible process but heat transfer process not an adiabatic process. Therefore it is a reversible diabetic process that mean which is 1 to 2 dash that means the exact expansion of steam from 1 to 2 is replaced by 1 to 2 dash.

From 2 dash this becomes the isentropic therefore this point is 2 dash so this point as 3 dash. Therefore the entire expansion in the turbine can be consist of 1 to 2 dash a reversible heat transfer why the heat is given to the feed water then 2 dash to 3 dash is the isentropic process.

This side whereas if you see the water side the cycle is very simple 3 to 4 is feed pump then from 4 to 5 the water is being heated by this steam 4 to 5 and therefore we see the entire heat taken in this process of 4 to 5 is coming from this stream between 1 to 2 dash process.

It can be shown, therefore the external heat addition now what external heat addition is? Therefore the external heat addition I can use a different pen that external heat addition is this is so this equals to Qb. You see that it can be shows that these two lines are parallel this line 1 and 2 dash and 5 and 4 are parallel to each other.

How we can show it? The delta d is very small so at each and any state let us consider these two states. The rise in delta t steam side becomes equal to this delta t in the water side. Obviously because this delta t is same that means the temperature rise for the water will be equal to the temperature rise for the steam.

During this infinite small process that the steam flows along this direction water flows along this direction the entropy changes also same that means this distance becomes equal to if I make a projection. That this part of the curve is parallel to this and this will we can say that this is valid for all the part so that the line 1 2 is parallel to the line 4 5 all. Now make a projection like this let this is a, this is b, this is c and this is d. Now the heat added to the water….

Now the heat given to the water during the 4 5 process 4 5 is represented by this area in TS plane 4, 5, b, a and the heat rejected by this steam during the process 1 2 dash this point is given by the area 1, d, c, 2 dash and these two area are equal obviously these lines are parallel.

Let us find out the efficiency. Heat added Qb which I have written here this h_1- h_5 which is nothing T_1 (S_1 – S_5) this is at constant temperature this is very simple. What is the heat rejection? This heat rejection is this cycle changes from 1 2 3 4 5 to 1to2 dash, 3 dash, 3, 4, 5 now this is my cycle. It is a rhombus type 1 2 dash this is the 2 dash, 3 dash this is the vertical line 3 dash 3 4 5.

The heat rejection is now this because this heat is taken so heat rejection that means this is the heat rejected in the condenser so heat rejection is h_3 dash minus h_3 which is T_3, T_3 means T_2 because T_3 and T_2 are same in the earlier cycle T_2. So T_2 (S_3 dash-S_3) I am taking the positive value already I am telling this as the heat rejection so therefore what is eta? Eta is 1-T_2 (S_3dash–S_3)/T_1(S_1-S_5)

When it can be show that these two are equal how? S_1-S_5 and S_5 and S_3 dash minus S_3. Now S_3 dash is S_2 and S_3=S_4. Now S_3 dash minus S_3 is equal to S_2 dash mines S_4.Now S_2 dash minus S_4 is S_1-S_5 why because these two comes are parallel the same heat transfer has taken place that means for these two curve S_1-S_2 dash that means the decrease in entropy is the increase in entropy because the entropy change of has to be 0 in a reversible process. Therefore this equal to S_5-S_4 which tells that S_2 dash-S_4=S_1-S_5 again S_2-S_4 is S_3dash- S_3 because S_3 dash is S_2 dash, S_3 is S_4.

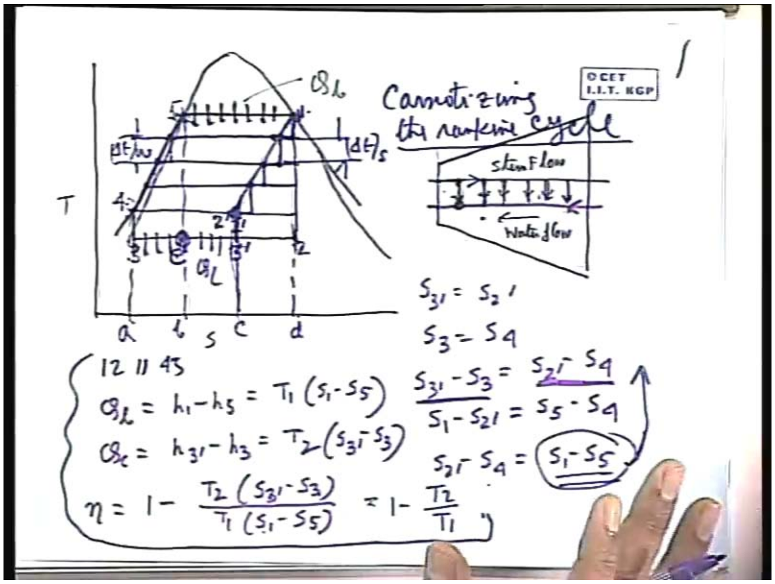
S_3 dash minus S_3 is S_2 dash minus S_4 is equal to S_2 dash minus S_4 is equal to S_1 minus S_5 that means if I make this S_2dash-S_4 is S_1-S_5 that mean this become equal to S_3 dash minus that means this becomes is equal to S_1- S_5 so that 1-T_2/T_1. It is very simple from the geometry therefore this becomes a Carnot cycle.

Geometrically also one intelligent student will be able to say that if you compare the Carnot cycle, what is the Carnot cycle 1 2. Let us give a point here b, c, d let give this point e. 1 2 e 5 that means this rectangle is a Carnot cycle and Rankine cycle is1 2 3 4 5 so from this rectangle geometrically I am deducting this part that means 1 2,3dash 2dash this part I am deducting.

Whereas I am adding this part 5 e 3 4 and these two parts are identical in areas. That means the rectangle is the Carnot cycle is deducted by this area 1 2 3 dash 2dash and on the other side on this half of this rectangle I am adding this 5 e 3 4 that means this area 3 4 5 1 2 dash 3 dash is synonyms to or is identical to 1 2 e 5 understand that is equivalent to that.

This rhombus type cycle diagram is equivalent to the rectangular cycle diagram corresponding to the Carnot cycle.

(Refer Slide Time: 40:46)



Carnotizing the rankine cycle

$s_{3'} = s_{2'}$

$s_3 = s_4$

12 11 43

$Q_h = h_1 - h_5 = T_1(s_1 - s_5)$

$Q_L = h_{3'} - h_3 = T_2(s_{3'} - s_3)$

$\eta = 1 - \frac{T_2(s_{3'} - s_3)}{T_1(s_1 - s_5)} = 1 - \frac{T_2}{T_1}$

$s_{3'} - s_3 = s_{2'} - s_4$

$s_1 - s_{2'} = s_5 - s_4$

$s_{2'} - s_4 = \boxed{s_1 - s_5}$

Geometrically tell this, immediately from the intelligent but one can work out this and show that ultimately the cycle represented by 1 2 dash 3 dash 3 dash 3 4 5 for the regeneration cycle is same as the Carnot cycle. This process is known as Carnotizing the Rankine cycle. With the concept of ideal regenerative process a Rankine cycle can be carnotized but why it is ideal? Obviously it is apparent that a reversible heat transfer is not possible number one.

Number two that we cannot incorporate tube containing water into the steam turbine so that this reversible heat transfer will be there so these two things are not possible at all so we cannot have a reversible heat transfer by which the counter flow arrangement the water will be heated to the temperature exactly at the which the steam is entered it can never happen because the heat transfer will not be defined at this point.

It cannot at any temperature equal to the temperature of the hot fluid at this section the temperatures are equal. If you give an infinite long heat exchanger you will see if you make a counter flow it has a simple example a counter flow heat exchanger hot fluid is coming to the cold fluid is coming this direction. You can never expect the outlet temperature of the cold fluid will be equal to the inlet temperature of the cold fluid just common sense you think. If you have to do that you have to give an infinite long length of the heat exchanger you cannot exchange heat like that so then ultimately it will catch up to that temperature.

It will be infinitely long this type of concept cannot come in really the this is the actual concept of the reversible heat transfer which takes infinite as I mean large time and automatically the equipment will be infinitely long. This cannot happen in number 1. Number 2 is the practical difficultly that we cannot force or we cannot incorporate a heat exchanger tube which runs into the turbine.

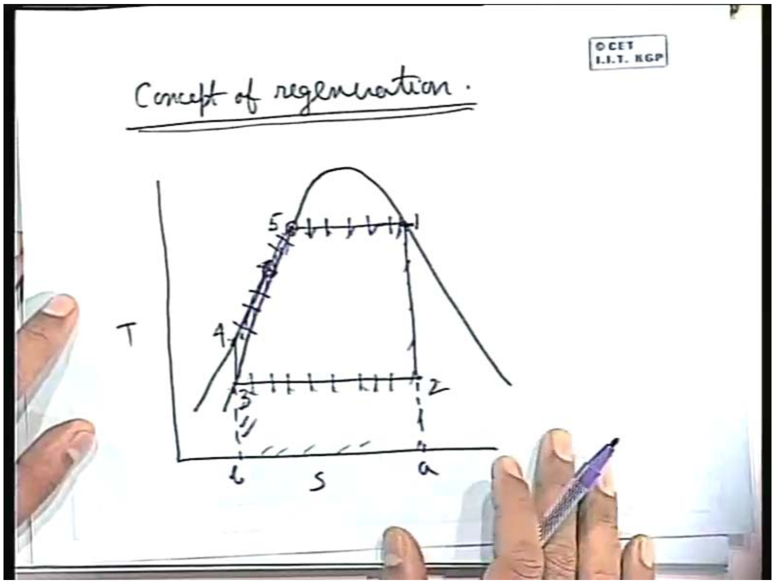
Turbine is not a device where there is a pipe or some bulbs are there through which the steam is flowing and it is getting expanded and giving the mechanical work this is not the system to get mechanical work from the expansion of a high temperature and high pressure steam the system is entirely different so in that system of turbo machine where is their no place where I can place? Or I can incorporate that heat exchanger which carries liquid water so this cannot be made.

This entire thing is ideal thing and this has been conceived to understand the basic philosophy of the process that is why it is known as ideal regenerative system or the ideal regenerative cycle. In case of this ideal regeneration that if we could have made a reversible heat transfer considering a infinite long turbine and incorporating into the turbine the coil or the tube carrying the water and considering there is an reversible heat transfer so that the outlet temperature of the water is the inlet temperature of the turbine and also the turbine inlet temperature is not superheated for a superheated Rankine cycle you cannot Carnotize it.

Superheated Rankine cycle can never be Carnotized so that de-saturated condition in those conditions if all these conditions are fulfilled and which part into the ideal regenerative system. Then Rankine cycle 1 2 3 4 5 is Carnotized to 1 2 dash3 dash 3 4 5 this is known as carnotizing the Rankine cycle and for this ideal regenerative cycle we get the efficiency exactly equal to the Carnot cycle through in fact Carnot cycle cannot be implemented in practice.

This also cannot be implemented in practice but why this has been studied this concept leads to a situation where we can implement by some other means these regenerative heating of the feed water so that we gain an efficiency that I told earlier that we may not be able heat up to 5 but by some arrangement a reversible heat transfer.

(Refer Slide Time: 44:42)

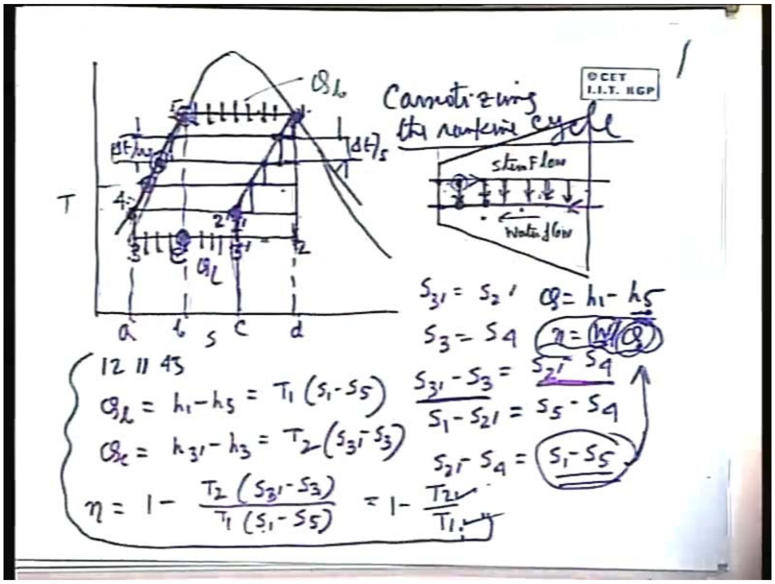


If we can heat some part of this sensible heating part by the internal heat then at least we can increase the mean temperature of heat addition because the range of temperature over which the external heat addition takes place is increased. So that mean temperature of heat addition will increase this is precisely concept of ideal regenerative cooling.

What exactly is the case for actual practice what is done?

Lecture: what I think the time need not permit. What is the time left? It is 5 or 10 minutes more therefore I will not do that thing that means the actual case what is done but I will ask you if there is any question you can ask me regarding this. I will entertain that, that will be better. First let him.

(Refer Slide Time: 46:12)



Efficiency is a function of two temperatures mean temperature of heat addition and mean temperature of heat rejection. Any heat the water with the steam we do not loose the efficiency because these internal it is used to heat up the water. Efficiency if you think in that way forget about the temperature conclusive way of telling whether it is increased or decreased is to think in terms of the temperature issues but if you define heat efficiency from more basic equations that efficiency is the work done by heat added.

When the steam is transferring this heat to this in this way the work done may be little reduced but at the same time you increase the heat, decrease the heat added that means you heat up increase the temperature of heating the heat added is h_1-h_5 not h_1-h_4. Which is independent, it is independent of the state 5 means if you go to state 5 then the it depend very much dependent on the state 5. Q =h_1-h_5.

How much heat added will be reduced depends upon the state h_5. Therefore it depends upon this thing very interesting question that even if you loose the water that will be explained afterwards. The actual case what happens steam is bled from the turbine so less amount of steam is going throughout the turbine. Initially the steam flow that if it is one then the steam is bled from the turbine to heat the water.

What is that mean the steam flow rate is reduced but in this case steam flow rate is not reduced but steam is exchanging its heat that means the thermal energy contained at this point is lower as compare to that what it was having earlier. Based on which you have that query work may be reduced but at the same time this is reduced. Therefore you can never be conclusive if you always look from the work to heat ratio that means the work done divided by heat added this is a very important massage to you.

Afterwards also even in the interviews different and different ah platform will ask this question how do you tell that if this is increase but if you start with that is not conclusive because work done is reduced but at the same time heat added is reduced and the reduction or heat added depends upon h_1 is fix that how close this 5.1.

State 5 is very important therefore we cannot conclusive ultimately you tell probably as I know in this case the efficiency increases that means decrease in this is less than the decrease in this. You have to conclude like that but not definitely, not conclusively, not emphatically but if you explain this from the mean temperature of heat addition then you are conclusive, you can tell no not probably it is definitely increasing and it is definite that the reduction in this is less than the reduction in this why because the mean temperature of heat addition is increased so always defined efficiency in terms of mean temperature.

This is decreased that means the work output of the turbine is decreased. Do not consider in terms of efficiency because turbine itself does not decide on the efficiency. Efficiency will be decided on the overall performance of the component that means you will have to search what is the heat added? What is the heat rejected? or what is the network output? What is the heat added?

Turbine may give less work output but at the same time the decrease in the heat is much more less. An engineer are not bothered about the output it is the efficiency always in our daily life we should bother with the efficiency not with the output that output is achieved at the cost of how much input. It is the efficiency which matters not the output.

Output can always be raised at the cost of input but this ratio is very important that means we will always target to increase the efficiency of a machine so that to achieve a particular targeted output we have to spend the least amount of input.

Another point in this case the dryness fraction is also reduced but these two things are so important or so much impracticable that this does not come into picture in book you will see as third point. Number 1 a reversible heating of water and a reversible cooling that a reversible heat transfer is not achieved. Number 2 it is impracticable to place a heat exchanger tube into the turbine.

Number 3 is that even you allow this process to takes place. The dryness fraction increases because this is a practical limit I do not bother with that but still this gives a limit. Yes, the dryness fraction is reduced that means the moisture content is increased that is one point because if you allow the steam to expand in this way that means in this process of heat transfer in ends up to a point where the dryness fraction is reduced. The concept of regeneration is clear.

Efficiency does not depend on the state 5 actual case. In this case we assume that it is heated up to 5. The efficiency is considered in actual if you cannot heat up to 5 efficiency depends upon state 5 but if you consider it is heated up to state 5 efficiency is T_2-T_1 but if you cannot heat up to 5 if the state 5 is definitely efficiency depends upon 5.

One thing is true if we heat at any point more than 4 efficiency is increased that you are appreciating. Not through this but to the average temperature of heat addition so average of any temperature between T_1 to anything more than T_4 is more than the average of T_1 to T_4.

Average of T_1 to T_4 is always less than the average of T_1 to any temperature it is more than T_4 so if any part of this sensible heating can be done by the internal heat and we can land up to any state 5 which is higher than 4 in respect of temperature then we gain into the mean temperature of heat addition it may be a marginal but there is always a gain.

The maximum gain will go to the Carnot cycle if we can heat up to the 5 point that means the entire sensible heating is done by the internal heat so that external heat addition is taking place only to change the phase that means at constant temperature it is equivalent to a Carnot cycle.

Thank you.