Applied Thermodynamics

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Steam Power System
Lecture - 08
Improvement in Rankine Cycle Efficiency: Superheating and Reheating

I welcome you all to the session of Applied Thermodynamics and the topic of our today's discussion is to look into the ways by which we can increase the efficiency of the Rankine cycle. Now, before going to discuss that part, as we could not complete a few aspects of ideal Rankine cycle in the last class.

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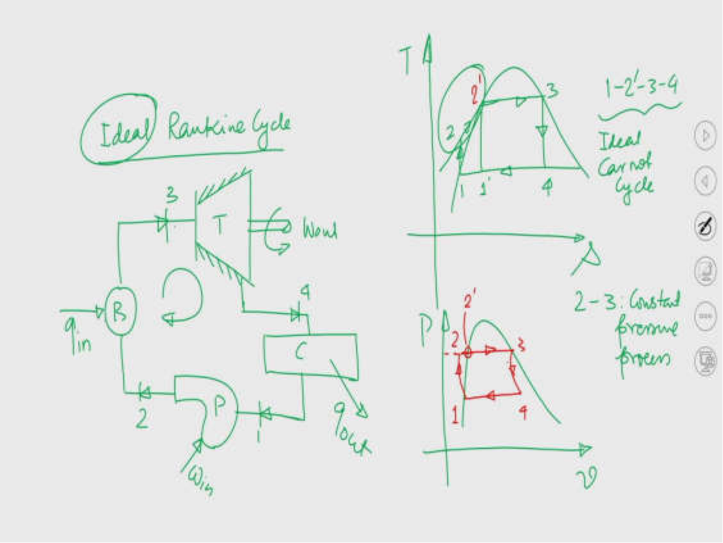

See if we try to draw the schematic, this is boiler and this is turbine, this is pump and we have condenser here. So, this is work output W_{out}, this is q_{out}, input to the pump, this is q_{in} and this is a cyclic process. If you try to draw the corresponding T s diagram, then we have this is 1 to 2.

Till now we have discussed about the processes in T s plane, rather we also can represent all the processes in P-v plane.

Now, let me discuss about a few issues, probably we have seen that if we allow the power plant to operate following these ideal Rankine cycle, given the same heat input and heat rejection, that is if we consider these two different cycles, that is a ideal Carnot cycle and ideal Rankine cycle and if these two cycles are operating between two same temperature limits, that is the heat addition and heat rejection.

We have seen that the ideal Rankine cycle offers a few advantageous features, though we need to compromise the efficiency. What are those advantageous features we have discussed? We can see that instead of partial condensation which we have seen in case of the ideal Rankine cycle, here we are having complete condensation.

Second the work ratio, I mean significant part of the work output is required as the input power if a power plant is running following the ideal Carnot cycle; because instead of pump, we had compressor and when compressor is handling two phase mixtures, since the specific volume of the vapour is very very high.

So, the compression work does significant work input and as a result of which the work ratio will be less for the ideal Carnot cycle. But since here we are having pump, pump can only handle single phase liquid; so it is the work input to the pump is not that much and as a result of which we can have high work ratio for this ideal Rankine cycle. Not only that another important point I will be discussing today that beyond point 3 if we allow steam to expand in the turbine, that is the isentropic expansion process. Because the turbine walls are insulated; so, we are not going to have any heat loss theoretically and that to if we allow steam to expand following internal reversible process what we can do that there is a possibility, which we had not in case of ideal Carnot cycle; but here we do have that, so we can increase the temperature beyond 3. So, we can increase the temperature of the steam leaving the boiler, rather you can superheat the steam.

Ideally this is saturated vapour line, so this is the saturated temperature at point 3 T_{sat}; but what we can do, we can increase the temperature of the steam, rather we can super heat steam beyond point 3 essentially to increase the efficiency of the plant as well as we also will have another important advantage that I will be discussing soon.

Now, today we will be discussing about another important issues. See if you try to draw all the processes in P v plane, this is point 4 basically inside the vapour dome that is two phase mixture. So, then point 2 so, I can give this is 2`. So, as I discussed, if we try to compare the ideal Rankine cycle with the ideal Carnot cycle, here we are having heat addition, there are two components, one is sensible heat addition 2 to 2` and then there is the phase heat transfer following the phase change, 2` to 3.

So, the condition 2 is sub cooled liquid. So, this is form line, this is 3, this is 4. So, this is the diagram in the P v plane 2 point is sub cooled liquid. So, this is 2`.

So, this is 2` and then 3 that is also in the saturated vapour line and then 3 to 4 that is the isentropic expansion. Now, we have seen that efficiency of the ideal Rankine cycle is less than the ideal Carnot cycle, reason is very simple; because if you look into the concept of mean temperature of heat addition, here had it been the ideal Carnot cycle, the total heating is 2` to 3.

So, because of this ideal Rankine cycle, we are having the small component of heat addition that is the sensible heat transfer 2 to 2`. So, in particular this component of heat addition lowers the mean temperature of heat addition, which in turn results in a drop in the efficiency of the ideal Rankine cycle.

So, now we look into the concept of mean temperature of heat addition. By the way if we try to draw area under any process line in T s plane, it gives the heat transfer.

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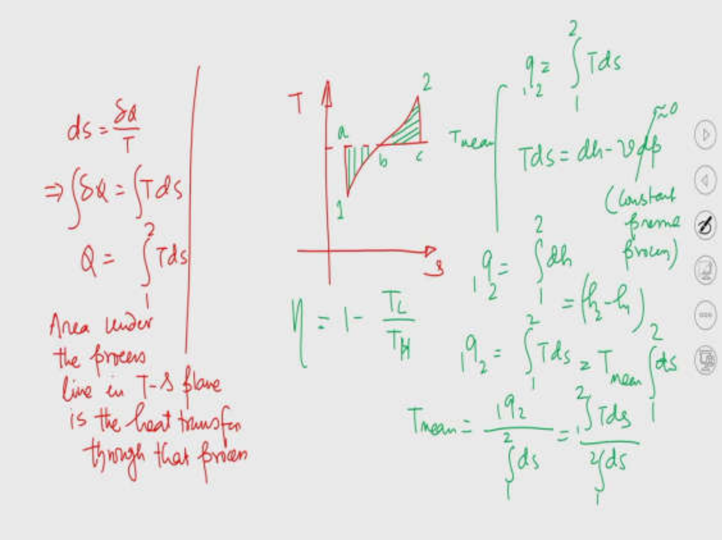

$$ds = \frac{\delta Q}{T}$$

$$\Rightarrow \int \delta Q = \int T\,ds$$

$$Q = \int_1^2 T\,ds$$

Area under the process line in T-s plane is the heat transfer through that process

$$\eta = 1 - \frac{T_L}{T_H}$$

T_{mean}

$${}_1q_2 = \int_1^2 T\,ds$$

$$T\,ds = dh - v\,\cancelto{\approx 0}{dp}$$

(constant pressure process)

$${}_1q_2 = \int_1^2 dh = (h_2 - h_1)$$

$${}_1q_2 = \int_1^2 T\,ds = T_{mean}\int_1^2 ds$$

$$T_{mean} = \frac{{}_1q_2}{\int_1^2 ds} = \frac{\int_1^2 T\,ds}{\int_1^2 ds}$$

So, from the second law you have studied that ds is point function. So, this is the property. So, $ds = \frac{\delta Q}{T}$ therefore, $\delta Q = Tds$.

So, if we integrate, we will be getting $\delta Q = \int_{1}^{2} Tds$; so that means area under the process line in T-s plane is nothing but the heat transfer that we can write from this expression. So, area under the process line in T s plane, in T-s plane is the heat transfer through that process.

So, now just by looking into the concept of mean temperature of heat addition, we can understand why the efficiency of the ideal Rankine cycle is less than the ideal Carnot cycle. So, if I write this T-s plane, say this is the line and say this is the T_{mean}.

So, say the process is 1 to 2. For example, if we consider the process like this 2 to 2`, but I am now giving separate name, that is process 1 to 2 and this is T mean.

So, this is nothing but mean of T_2 and T_1. Now, you can see the area which is shown by the hatched portions is basically this two area are equal. So, basically if we compare the ideal Rankine cycle. So, this is 1-2`-3-4. So, this is ideal Carnot cycle. But in that case mean temperature of heat addition is this. Now, because of this sensible heat component, it lowers the mean temperature of heat addition; this you can understand from the schematic, because now the area under the curve, this is mean temperature. So, these two curves are equal and this is nothing but the area under the mean temperature.

So, mean temperature corresponds to the areas 1-a-b-1 and 2-c-b-2. So, this is the mean temperature.

So, you can understand ideally, had it been the Carnot cycle; then the mean temperature of heat addition would have been T_2` or T_3. But because of the presence of the small component, now it will reduce; because these area we also need to take into account.

So, as a result of which the efficiency of the Rankine cycle will decrease. We know that $\eta = 1 - \frac{T_L}{T_H}$. If we reduce T_L, that means the temperature of the heat sink at which heat is rejected; that if you reduce, then efficiency will increase, otherwise I have to increase the mean temperature of heat addition, but what we can see from the schematic that because of this presence of this component mean temperature of heat addition will decrease; if that decrease, then efficiency will reduce.

Now, just mathematically we can say as ${}_1q_2$. So, the total heat transfer in this process is nothing, but $\int_1^2 Tds$ and that is nothing but the area under the hatched portion. So, inside the boiler, this is constant pressure heat addition.

So, this 2 to 3 is constant pressure process and this is constant pressure line. Now, for the ideal Rankine cycle if it is constant pressure, we can write second Tds equation, $Tds = dh - vdp$. This component equal to 0 for the constant pressure process; that means we can write that ${}_1q_2 = \int_1^2 dh = h_2 - h_1$.

Now, cannot we write say that ${}_1q_2 = \int_1^2 Tds$? Cannot we write this is nothing but $T_{mean}\int_1^2 ds$? So, therefore, $T_{mean} = \frac{{}_1q_2}{\int_1^2 ds}$. So, that you have studied to calculate the average quantities; in fluid mechanics you have studied to calculate the average flow rate.

So, this is $\frac{{}_1q_2}{\int_1^2 ds}$. Now, what is this? So, this is nothing but integral $\frac{\int_1^2 Tds}{\int_1^2 ds}$. So, if we now go to the next slide, what about Tds?

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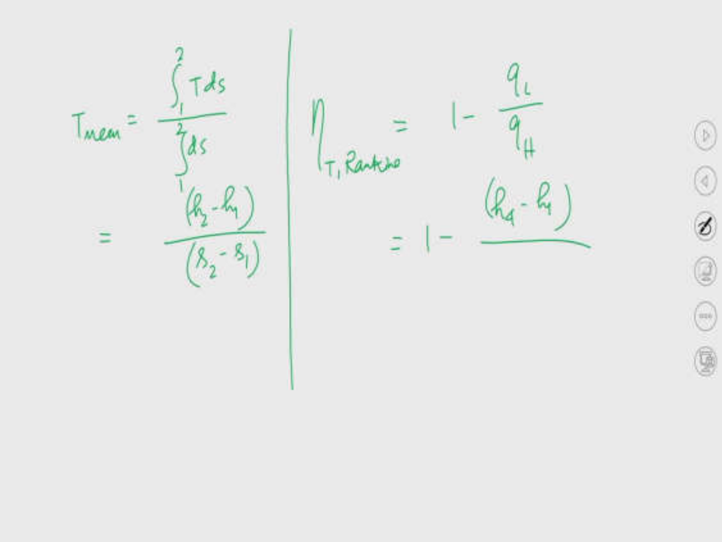

$$T_{mean} = \frac{\int_1^2 Tds}{\int_1^2 ds} = \frac{(h_2 - h_1)}{(s_2 - s_1)}$$

$$\eta_{T,Rankine} = 1 - \frac{q_L}{q_H} = 1 - \frac{(h_4 - h_1)}{\quad}$$

So, basically $T_{mean} = \frac{\int_1^2 Tds}{\int_1^2 ds}$. So, that is nothing, but what this Tds for the constant pressure line? Constant pressure process that is *dh*. So, that $T_{mean} = \frac{h_2 - h_1}{s_2 - s_1}$. So, we can write this is the Tmean expression. Now, if we look at the expression of $\eta_{T,Rankine} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_l}{q_h}$

If the processes is reversible cycle, we can write that is $1 - \frac{T_l}{T_h}$. Now, $q_l = h_4 - h_1$.

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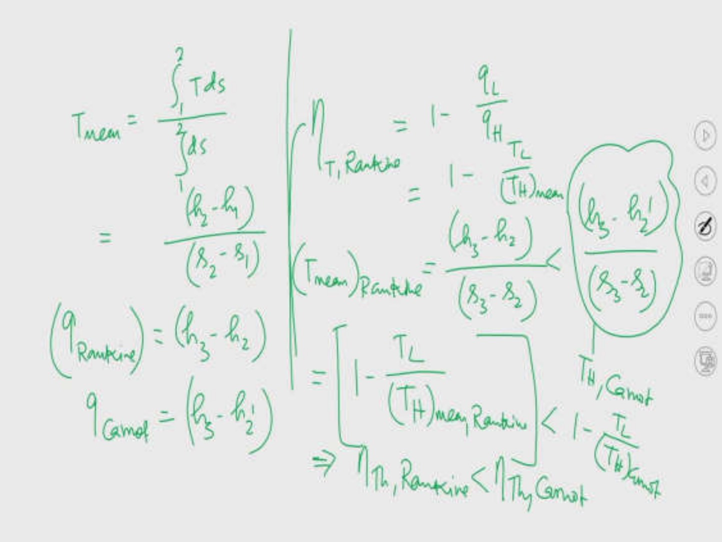

$$T_{mean} = \frac{\int_1^2 T ds}{\int_1^2 ds} = \frac{(h_2 - h_1)}{(s_2 - s_1)}$$

$$(q_{Rankine}) = (h_3 - h_2)$$

$$q_{Carnot} = (h_3 - h_2')$$

$$\eta_{T, Rankine} = 1 - \frac{q_L}{q_H} = 1 - \frac{T_L}{(T_H)_{mean}}$$

$$(T_{mean})_{Rankine} = \frac{(h_3 - h_2)}{(s_3 - s_2)} < \frac{(h_3 - h_2')}{(s_3 - s_2)}$$

$T_{H, Carnot}$

$$= \left[1 - \frac{T_L}{(T_H)_{mean, Rankine}}\right] < 1 - \frac{T_L}{(T_H)_{Carnot}}$$

$$\Rightarrow \eta_{Th, Rankine} < \eta_{Th, Carnot}$$

Now, what about q_{Rankine}? $q_{\text{Rankine}} = h_3 - h_2$. So, for this particular cycle, this is the schematic depiction. Here, T mean is equal to $\frac{h_3 - h_2}{s_3 - s_2}$. Now, this is basically less than $\frac{h_3 - h_2'}{s_3 - s_2}$. So, I can write $\eta_{T,\text{Rankine}} = 1 - \frac{T_l}{(T_h)_{\text{mean}}}$.

So, now, if we consider the efficiency of Carnot cycle we write that $\eta_{T,\text{Carnot}} = 1 - \frac{T_l}{T_h}$. So, if we allow the temperature of the heat sink to be same, then $1 - \frac{T_l}{(T_h)_{\text{mean, Rankine}}} < 1 - \frac{T_l}{(T_h)_{\text{mean, Carnot}}}$

So, from this simple mathematical expression we can see that, T_H Carnot is higher than the T_H Rankine, that is essentially we can see from the mean temperature of heat addition; but only to have this from the concept of mean temperature, I have done this exercise.

So, efficiency of the Rankine cycle will be less than the efficiency of the Carnot. Now, I am writing $q_{\text{Carnot}} = h_3 - h_2'$. So, if these two cycles are allowed to operate between two same temperature limits; it is because of this reason, that is the mean temperature at which heat is supplied to the system cycle, the efficiency differs.

So, since the mean temperature at which it is supplied to the system is less than the Carnot cycle; so, this quantity is less than the heat addition, the efficiency drops.

So, though we have seen that the ideal Rankine cycle though offers a few, advantageous features like complete condensation, work input is less as compared to the work input to the compressor as it was for the ideal Carnot cycle. But only disadvantage is that efficiency is less and that is only because of the lower mean temperature of heat addition.

So, now, the time has come to look at the aspects by which the efficiency of the Rankine cycle can be increased; it may not be possible to reach efficiency of the ideal Rankine cycle equal to the efficiency of the idea Carnot cycle.

But still we may explore the possibilities by how the efficiencies can be increased. One important aspect is that if the temperature at point 3 can be increased. So, temperature of steam can be increased beyond point 3 before it enters into the turbine and that is known as super heating.

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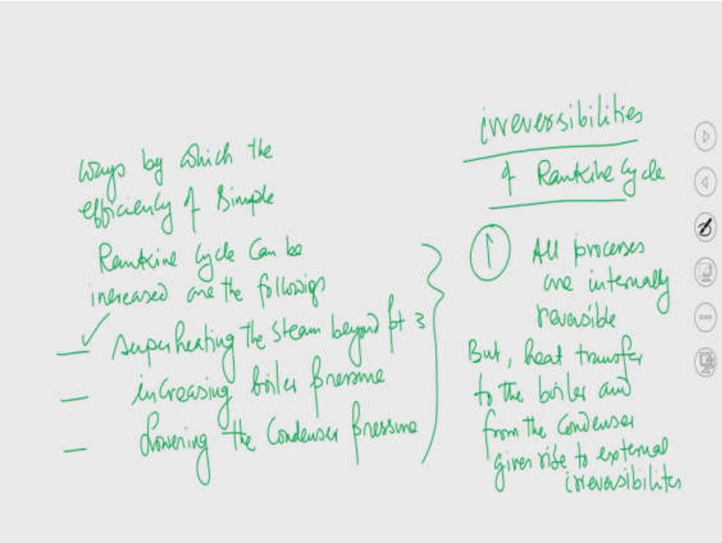

ways by which the efficiency of simple Rankine cycle can be increased are the followings

- ✓ superheating the steam beyond pt 3
- increasing boiler pressure
- lowering the condenser pressure

irreversibilities of Rankine cycle

① All processes are internally reversible

But, heat transfer to the boiler and from the condenser given rise to external irreversibilities

So, the ways by which efficiency of simple Rankine cycle can be increased are the followings; 1) super heating the steam beyond point 3, 2) increasing boiler pressure, 3) lowering the condenser pressure. So, these three are the ways by which we can really increase the efficiency of the ideal Rankine cycle.

But in this course we will be discussing about the first one, that is superheating the steam beyond point 3; that means superheating the steam before it enters into the turbine.

Now, the word ideal is used essentially to signify that, all the processes that is constant pressure heat addition, reversible adiabatic expansion, then constant pressure heat rejection and finally, reversible adiabatic pumping, all these processes are assumed to be internally reversible.

But we are still having sensible heat component. So, this is basically 2 to 2`, we are having sensible heat transfer and also we are having heat rejection in the condenser. So, when heat is getting rejected from steam, heat is supplied to the coolant. So, we are having finite temperature difference, otherwise the efficient heat transfer will not be justified. So, to have efficient heat transfer during condensation also, the heat transfer to the boiler is due to finite temperature difference. In these cases external irreversibilities are there. So, though we can assume the processes are internally reversible, we can assume that it is frictionless, processes are internally reversible; but external irreversibilities due to the heat transfer is there at boiler also here at condenser, we cannot say that this is purely ideal cycle.

So, the irreversibilities get associated with the Rankine cycle even if you keep the turbine walls insulated, if we allow steam to expand following reversible process; if we even allow the steam to expand following quasi static process.

Though we can consider that the process is internally reversible, we also can consider that this is frictionless; but to have efficient heat transfer inside the condenser, there must be heat transfer due to finite temperature difference. Also here we are having heat transfer outside the boiler, that is due to finite temperature difference.

So, external irreversibilities are associated with the cycle; so if we try to list down the irreversibilities of Rankine cycle. So, this is all processes are internally reversible; but heat transfer to the boiler and from the condenser gives rise to external irreversibilities.

So, we need to have efficient heat transfer in the boiler, also in the condenser and this two heat transfer due to finite temperature difference makes the process to be externally irreversible. So, these irreversibilities we cannot cannot eliminate; but our objectives should be to minimize, we shall discuss that part again.

Now, as you have seen that the efficiency of the ideal Rankine cycle is less than the ideal Carnot cycle; so there are several ways by how we can increase the efficiency of the ideal Rankine cycle. So, efficiency is nothing but thermal efficiency which is equal to $1-\frac{q_l}{q_h}=\frac{w_{net}}{q_h}$.

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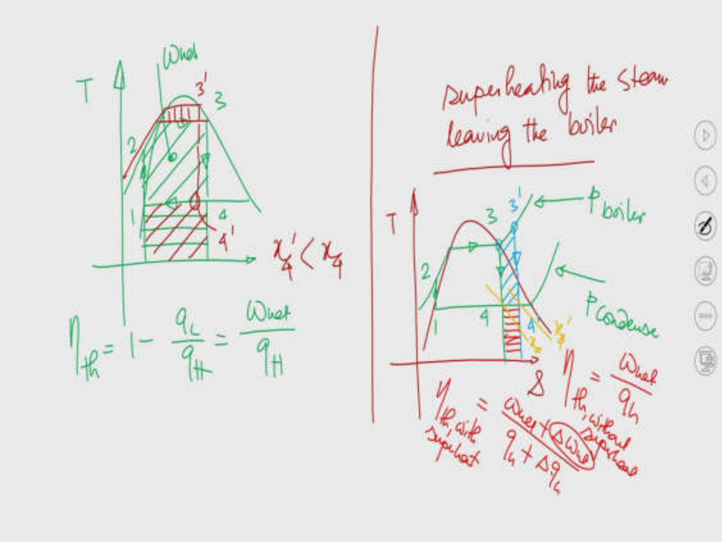

$x_4' < x_4$

$\eta_{th} = 1 - \frac{q_L}{q_H} = \frac{W_{net}}{q_H}$

superheating the steam leaving the boiler

$\eta_{th,\text{without superheat}} = \frac{W_{net}}{q_h}$

$\eta_{th,\text{with superheat}} = \frac{W_{net} + \Delta W_{net}}{q_h + \Delta q_h}$

See, basically area under the process line 2 to 3 that gives heat addition to this system that is the q_H and if we subtract this q_L; which is hatched by this red color, that will be nothing, but W_{net}.

So, you can see, if we need to increase Wnet, perhaps we can increase the boiler pressure;

So, this is 3` and say this point is 4`. So, if you increase boiler pressure, you can see we can have this is the extra net amount of work, but again the point 4 that is the exit steam quality, which is becoming more away from the saturated vapour line. So, the quality of the steam will deteriorate.

So, x`$_4$ is less than x_4. So, if we increase the boiler pressure, perhaps we are getting this much amount of extra work output, we can have slight or little increase in efficiency; also operating boiler at high pressure, need special operational arrangement.

But what we can see that, at the cost of the increment in Wnet; we are going to have compromised with the quality of the steam at the exit of the turbine. So, increasing boiler pressure, though it leads to increase slight increase in the efficiency; but the quality of the steam leaving the turbine will be deteriorated.

So, next we will be discussing about super heating the steam leaving the boiler. So, this is now saturated vapour line, the point 3 is on the saturated vapour line; but what we can do? We can increase the temperature of the steam before it enters into the turbine by having special arrangement that is called super heating.

So, when steam is producing inside the boiler, it is taken through some special device called super heater. So, there are arrangements which are known as radiant super heater, convective super heater.

So, when steam is coming out from steam drum or from the steam tube; then steam is taken through the super heater, which are placed in a hemispherical dome of the boiler.

So, the roof of the boiler is a hemispherical in shape. So, those super heaters are placed in that hemispherical dome. So, steam coming out from the steam drum or steam tube is taken through those super heaters, only to increase the temperature beyond point 3. If you increase the temperature of steam beyond point 3; then what effect does it have on the efficiency?

So, if we now look into that. So, if we do not consider super heating, we have seen from point 3, it will expand and you will be getting 4. If we now allow steam to pass through those special arrangements like super heater; then say I am allowing steam temperature to go up to this point 3`. And if 3` is the thermodynamic state of the steam before it enters into the turbine and then if we allow steam to expand and then this is 4`. So, if we super heat steam beyond point 3, we can have this amount of additional net work.

So, this additional net amount will lead to an increase in the efficiency of the cycle of the plant. But at the cost of that increase in Wnet, we also having heat rejection in heat input. So, this area also will lead to the heat rejection amount, the amount of heat which is getting rejected inside the condenser.

Now $\eta_T = \frac{w_{net} + \Delta w_{net}}{q_H + \Delta q_H}$. So, that means if we increase the temperature of steam before it enters into the turbine; we are also going to have extra amount of heat input in the system. Maybe we are getting additional amount of work, but $\frac{\Delta w_{net}}{\Delta q_H} > \frac{w_{net}}{q_H}$.

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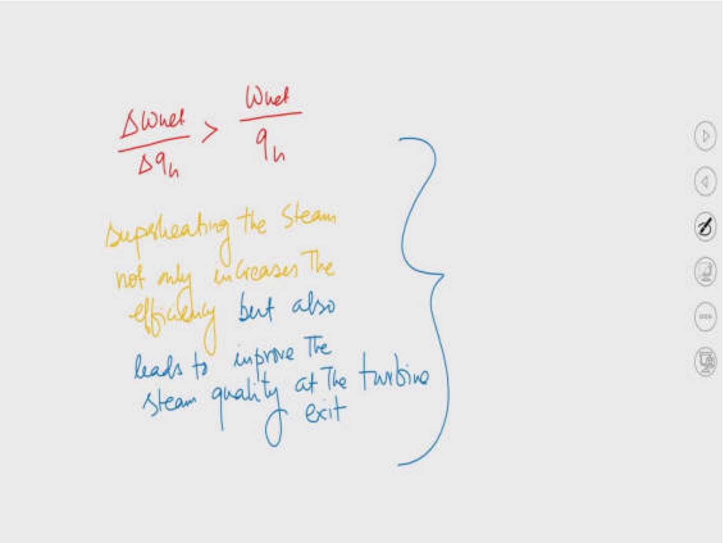

$$\frac{\Delta W_{net}}{\Delta q_h} > \frac{W_{net}}{q_h}$$

Superheating the Steam not only increases The efficiency but also leads to improve The steam quality at The turbine exit

So, this is very important to understand at this point of time. You can see that we are going to have additional amount of heat input because of the small line q`$_3$. So, because of the small line, that is area under this process line will give the heat transfer. So, 3 to 3` because of the superheating we are going to have additional heat energy as input energy.

At the cost of this additional heat input energy, we are getting extra amount of Wnet. Now, which is more? This Wnet is more as compared to Δq_h, so the amount of heat which is additionally added to this system to get this amount of Wnet. So, if we take the ratio between these two quantities greater than this; as a result the efficiency with super heat, will be higher than without super heat.

So, if you increase temperature of the steam beyond point 3, which in a sense indicates that steam is super heated inside the boiler, which is done essentially when the steam is coming out from steam drum, then steam is allowed to pass through the super heater.

If we increase that, maybe we are going to have additional heat input to the system and that is nothing but Δq_h; but at the cost of that increase in heat input, we are getting Wnet. And $\frac{\Delta w_{net}}{\Delta q_H} > \frac{w_{net}}{q_H}$, as a result the overall effect will be an increase in efficiency of the cycle.

So, this is one aspect. But as I told you that to get this slight increase in efficiency maybe 4 to 5 percent; we also need to have additional arrangement like placing up those super heaters, which will be hanging from the roof of the hemispherical dome of the boiler.

So, operational cost as well as the installation cost may not lead to significant increase in efficiency. But which is most important here, if you look at this T s diagram we can see; if we do not have super heating, then if we allow steam to expand inside the turbine, then quality of the steam leaving the turbine is x4.

But if we super heat steam beyond point 3, then the quality of the steam x`4 which is very close to the saturated vapour line. So, not only we can increase the efficiency of the plant, but also what we can do; we can increase the quality of the steam leaving the turbine which in turn will help in increase the life time of the turbine blade.

As I told since this is two phase mixture; so higher the moisture content of the steam coming out from the exit, the turbine blade will be more vulnerable to pitting and erosion. So, if we increase the quality of the steam at the exit of the turbine; then the problem associated with the turbine blade erosion and pitting can be avoided.

So, super heating the steam not only increase the efficiency, but also also leads to improve the steam quality at the turbine exit considering the life time of the turbine blade, or turbine blades.

So, to summarize, today through very simple mathematical analysis we have shown that efficiency of the ideal Rankine cycle is lesser than the ideal Carnot cycle. We have tried to see this from the concept of mean temperature of heat addition; then we have tried to explain several ways how we can increase the efficiency of this simple Rankine cycle.

We have also discussed about the irreversibilities associated with the Rankine cycle and finally, we have seen that by increasing boiler pressure, we can increase the efficiency of the Rankine cycle.

But when we are trying to have increase in efficiency by increase in boiler pressure; we are also trying to invite another problem of having turbine blade erosion. Using superheating the steam, we have seen efficient way of increasing the efficiency; it not only improves the efficiency, but also leads to the better quality of steam leaving the turbine and which will be very helpful to prevent the turbine blades from the undesirable effect that is erosion and pitting.

So, with this I stop here today and we shall continue our discussion in the next class.

Thank you.