Thermal Engineering: Basic and Applied

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Lecture - 12
Analysis of Simple Rankine Cycle and its Design Modifications

We will start our discussion today on the simple Rankine cycle and we will discuss about the problematic issues which are involved with the cycle and then we shall go to discuss about the modifications of the Rankine cycle essentially towards the increase of the efficiency of this particular cycle.

So, you know that in the last class, we have discussed about the simple Rankine cycle. And we could establish the efficiency of the Rankine cycle in terms of the heat which is added to the cycle and the amount of heat which is rejected from the cycle before going to discuss about the design modifications of this particular cycle, first it is essential to understand the problematic issues involved with the cycle and only then we can look for remedial measures towards addressing those issues, for the enhancement of the cycle.

It would be wise to again draw the simple Rankine cycle schematic diagram of the steam power plant and then we shall go to discuss about the problematic issues.

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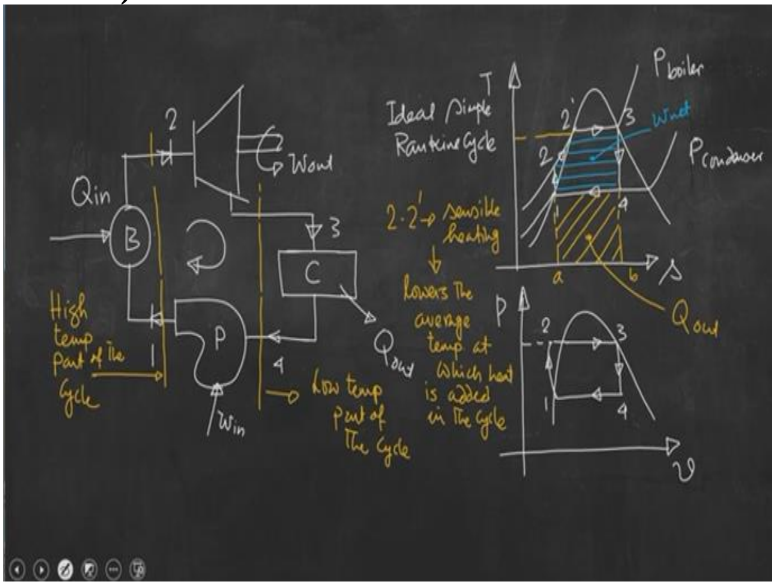

So, in the last class we drew the schematic, so, there is boiler, turbine where we are getting work output and pump where we need to provide work input. So, this Q_{in} amount of heat is added to the boiler and after doing work steam is taken to this mechanical device that is condenser and steam is the working substance in this part of the cycle that is the low temperature part of the cycle. So, this Q_{out} is the amount of heat rejected and we collect condensate and it is again pumped back to the boiler. So, this is a closed cycle.

So, if we try to describe all the processes by comparing them with the Rankine cycle, then we had drawn the T-s diagram in the last class. So, there is P condensate and P boiler plotted in the T-s diagram. So, this is basically the T-s diagram of ideal simple Rankine cycle. We have also discussed about the corresponding P-V diagram and h-s diagram. So, let me draw the P-V diagram today because it is very important.

So, the corresponding PV diagram is shown in slide. As I have used several points 1, 2, 3, 4 in the T-s and P-V diagram, it is essential to mark those points in the schematic. Now, if we compare this T-s diagram with the T-s diagram that we had seen for the ideal Carnot cycle, so, this 2-2' is the additional part in Rankine cycle. So, the total heat addition here is at the constant pressure that is at boiler pressure. So, this segment 2-2' that is the sensible heat transfer is the additional feature that we can see from the T-s diagram in the frame of this Rankine cycle. And probably I discussed that it is because of this segment of heat addition, I mean this particular segment lowers the average temperature at which heat is added to the cycle.

So, I have tried to mark in the schematic to distinguish between the high temperature part of the cycle and the low temperature part of cycle. This segment 2-2' lowers the average temperature at which heat is added in the high temperature part of the cycle and it is because of this reason the efficiency of the ideal simple Rankine cycle is lesser than the efficiency of the ideal Carnot cycle.

So, at least we have identified the particular segment 2-2' that is sensible heating which lowers the average temperature at which heat is added in the cycle, of course, in this high temperature part of the cycle. So, this is the reason for which the efficiency will be lesser. So, let us quickly revisit the mathematical expression of the efficiency of the Rankine cycle just by looking at the heat addition and heat rejection.

You know that heat is being rejected, so, as I mark over T-s diagram in slide, the hatched portion represents the amount of heat which is rejected. As I told you area under the process line in the T-s plane is the indicative measure of the amount of heat transfer whether it is transferred to the system or from the system. So, this $Q_{out}$is the amount of heat rejected. And if we give name to the points in T-s plane as ‘a’ and ‘b’, so the area under a22'3b would be the heat addition and heat rejection is the area of the portion that is a14b. So, if we subtract these 2, we will be getting W_{net}.So what is W_{net}? W_{net} is the area under the hatched portion shown in different colour in the diagram in slide.

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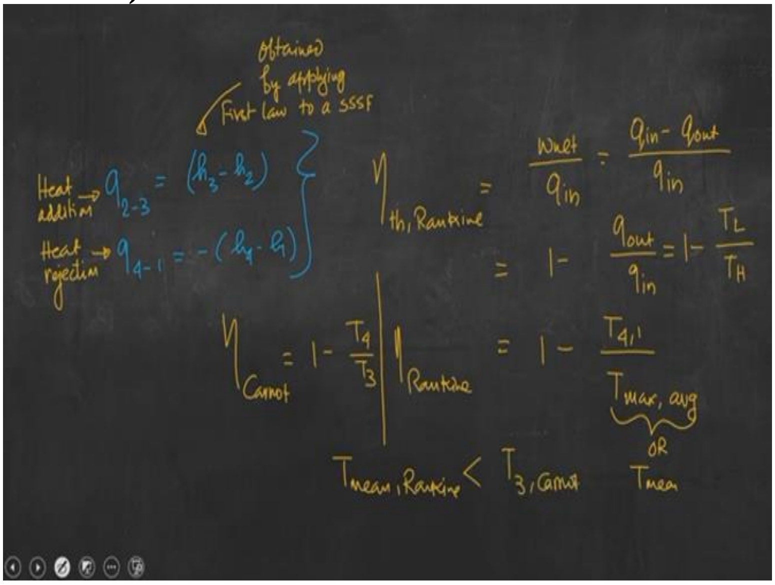

Obtained by applying First law to a SSSF

Heat addition → $q_{2-3} = (h_3 - h_2)$

Heat rejection → $q_{4-1} = -(h_4 - h_1)$

$$\eta_{th,Rankine} = \frac{W_{net}}{q_{in}} = \frac{q_{in} - q_{out}}{q_{in}}$$

$$= 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_L}{T_H}$$

$$\eta_{Carnot} = 1 - \frac{T_4}{T_3}$$

$$\eta_{Rankine} = 1 - \frac{T_{4,1}}{\underbrace{T_{max,avg}}_{\substack{OR \\ T_{mean}}}}$$

$$T_{mean,Rankine} < T_{3,Carnot}$$

Heat Addition: $q_{2-3} = (h_3 - h_2)$

Heat Rejection: $q_{4-1} = -(h_4 - h_1)$

So, these 2 expressions we can write easily by applying the first law of thermodynamics to a process which is steady state steady flow process. So, these 2 are the expressions of these 2 quantities that is heat addition and heat rejection. Then we can write

$$\eta_{th,Rankine} = \frac{W_{net}}{q_{in}} = \frac{q_{in} - q_{out}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

I am not going to write the expression of work that is added to the system and the expression of work that is coming out from the system. So, if we write these quantities in this specific form,

$$w_{out} = h_3 - h_4 \ \& \ w_{in} = -(h_2 - h_1)$$

So w_{in} is negative, because we have discussed about the sign convention. So, if the processes are reversible processes, then in the context of this particular cycle, we can write

$$\eta_{th,Rankine} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_L}{T_H}$$

So, you can understand Q_{in} amount of heat is added to the cycle in the boiler at a temperature that is the maximum temperature in the cycle that is T_H. And Q_{out} is the amount of heat which is rejected from the system at a temperature that is T_L that is the condenser temperature.

Now, in many books you will find that if we reduce the temperature of the lower part of the cycle that means if we reduce T_L, then perhaps efficiency will increase or if we increase T_H, also efficiency will increase. So, for a fixed T_L if we increase T_H that means, we need to have the higher temperature of the high temperature part of this cycle at which heat is added to the system. If we can ensure that efficiency will increase.

We will be discussing soon that this T_L cannot be reduced below a particular value. If you would like to increase T_H then there are many other issues. So, basically we by having some suitably designed combustion process, we can increase the temperature at which heat is added to the system. But again we cannot increase T_H beyond a particular value and that is restricted by the metallurgical consideration of the several components which are there in the power plant.

$$\eta_{th,Rankine} = 1 - \frac{T_L}{T_H} = 1 - \frac{T_{4,1}}{T_{3,2}}$$

So, this T_H is $T_{4,1}$ because this is either T_4 or T_1 because you know that this is simple compressible pure substance, so, during phase change temperature remain constant. So, the process can be also approximated by the isothermal process that is what we have seen in the context of the Carnot cycle. So, in the context of the Carnot cycle the amount of heat is rejected at a constant temperature. So $T_4 = T_1$.

Now, in this particular case though it is constant pressure heat rejection, but as long as we are working inside the vapour dome, the process is isothermal basically there is no change in temperature. So, basically the phase change occurs at a constant temperature, so $T_4 = T_1$. But can I write $T_H = T_3 = T_2$? No, basically this T_H is neither T_3 nor T_2. So

$$\eta_{th,Rankine} = 1 - \frac{T_L}{T_H} = 1 - \frac{T_{4,1}}{T_{max,avg}} = 1 - \frac{T_{4,1}}{T_{mean}}$$

So, in the conclusion we can write

$$\eta_{Carnot} = 1 - \frac{T_4}{T_3}$$

$$\eta_{Rankine} = 1 - \frac{T_4}{T_{mean}}$$

$$T_{mean} < T_3$$

So, try to understand the mean temperature at which this amount of heat is added to this Rankine cycle is less than the temperature at which it is added to the Carnot cycle. If this mean temperature becomes lesser then definitely you can understand that efficiency will be less. So, why $T_{mean} < T_3$? Because this is the Carnot cycle, you can understand from the T-S diagram you cannot write this as the T_3. Because this particular segment lowers the temperature at which heat is added. So, it is because of this reason this T_{mean} for the Rankine is less than T_3 for Carnot cycle.

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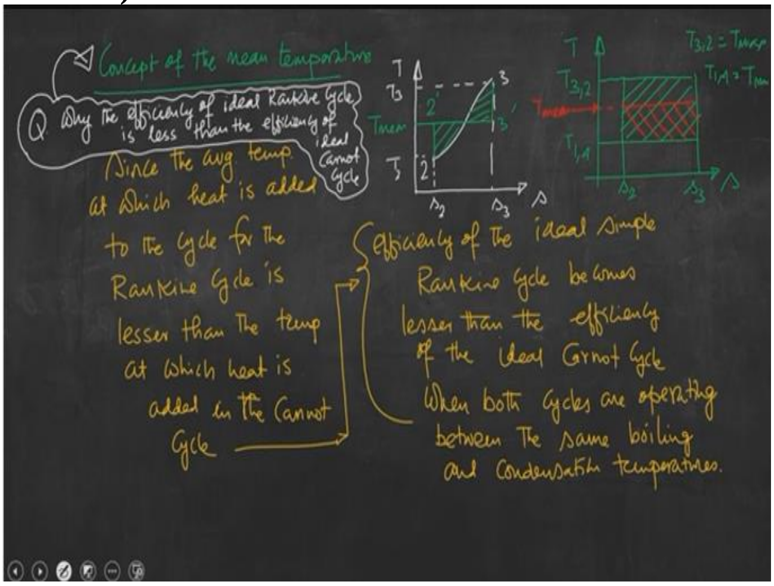

Concept of the mean temperature

Q. Why the efficiency of ideal Rankine Cycle is less than the efficiency of ideal Carnot Cycle

Since the avg temp at which heat is added to the cycle for the Rankine Cycle is lesser than the temp at which heat is added in the Carnot Cycle

Efficiency of the ideal simple Rankine cycle becomes lesser than the efficiency of the ideal Carnot Cycle when both cycles are operating between the same boiling and condensation temperatures.

Since the average temperature at which heat is added to the cycle for the Rankine cycle is lesser than the temperature at which heat is added in the Carnot cycle, efficiency of the ideal simple Rankine cycle becomes lesser than the efficiency of the ideal Carnot cycle, when both cycles are operating between the same boiling and condensation temperature. So, if you would like to have comparison between 2 cycles, we must secure a common basis for this comparison. So, you can see that if 2 cycles are allowed to operate between the same boiling and condensation temperatures, then only the efficiency of the ideal simple Rankine cycle will be lesser than the ideal Carnot cycle.

So, now, let me draw the T-s diagram for Rankine Cycle. So, we have 1 particular process 2-3 and the maximum temperature T_3 and T_2, S_2, S_3 has been plotted in the diagram. Now the average temperature is the mean temperature that is T_{mean}.

So, Suppose we mark two points 2' & 3' on the T_{mean} line such that the resulting two areas in the T-s diagrams are equal, So, now we can consider drawing T-s diagram for the Carnot cycle. We can plot $s_2, s_3, T_{3,2}, T_{1,4}$ in the T-s diagram.

Now, if we try to superimpose the average temperature at which heat is added over there so, you can understand heat is added at T_3. So,

$$T_{3,2} = T_{max}; \;\; T_{4,1} = T_{mean}$$

And the hatched area in the diagram is basically W_{net}. This is what we have seen for the Carnot cycle. Now, higher the W_{net}, higher will be the efficiency for the given heat input.

What you can see that these 2 cycles are operating between same boiler temperature and condensation temperature, but the temperature at which heat is added to the Rankine cycle is now less than $T_{3,2}$. So, if we try to superimpose, then we can plot T_{mean} as shown in the slide.

So, now W_{net} for the Rankine cycle is the area under the new hatched section as shown in the slide, provided the temperature at which it is rejected is remaining same. So, that is why I have written that if the power plant is operating between same boiler and condensation temperature that is for both the cases the temperature at which it is rejected is remaining same, but in one case it is added to the cycle at $T_{3,2}$that is the T_{max} & in other case, though the boiler temperature is remaining same, but this particular segment at which heat is added to the cycle lowers the average temperature and it becomes T_{mean} as if the heat is added at this average temperature and it lowers W_{net}. Since W_{net} that is net work output from the cycle becomes less, so we can expect that the efficiency will be less. So, this is the concept of average temperature or mean temperature. So, the concept of mean temperature is important when we try to analyse for why the efficiency of the ideal Rankine cycle is less than the efficiency of the ideal Carnot cycle. So, this is very important question that is why the efficiency of ideal Rankine cycle is less than the efficiency of ideal Carnot cycle. So, to address this question we need to understand the one important concept that is the concept of the mean temperature at which it is added to the system.

So, what is the conclusion? Conclusion is if we go back to the previous slide & try to mimic all the processes by using this Rankine cycle, the problems which are there in a Carnot cycle are not there in this particular case. But the process of constant pressure heat addition lowers the temperature at which heat is added to the system and the concept of mean temperature is coming into the picture. And it is because of this particular segment of heat addition to the system we need to go for this concept of mean temperature and we have seen that it reduces the efficiency of the cycle.

So, we have established or understood that the efficiency of the ideal Rankine cycle is less than the efficiency of the ideal Carnot cycle. This is quite obvious because you know Carnot cycle is the ideal cycle. We have studied this particular cycle only to understand that the report should be given for the betterment or for the improvement of the actual cycles, essentially to achieve the efficiency of the ideal Rankine cycle. It is not possible at all to achieve the efficiency of the ideal cycle, but objective should be to reach as closer as the efficiency of the ideal cycle.

So, in this particular Rankine cycle, at least we can understand that efficiency becomes really less though we can really address several issues like design of compressor, which will handle 2-phase mixture, it consumes a high amount of power, partial condensation at point, designing a condenser which will you know allowed to have partial condensation, it is also an important issue. So, the problem associated with the Carnot cycle can be eliminated by using this Rankine cycle. That means, if we design the power plant to operate following this Rankine cycle, we can address all those issues, but we are also going to invite another problem that is efficiency becomes really less.

So, efforts should be taken to address these particular aspects, so that we can increase the efficiency of the Rankine cycle to make it more practical. I mean though it is not possible to get efficiency of the ideal Carnot cycle, but at least we can increase the efficiency of the ideal Rankine cycle.

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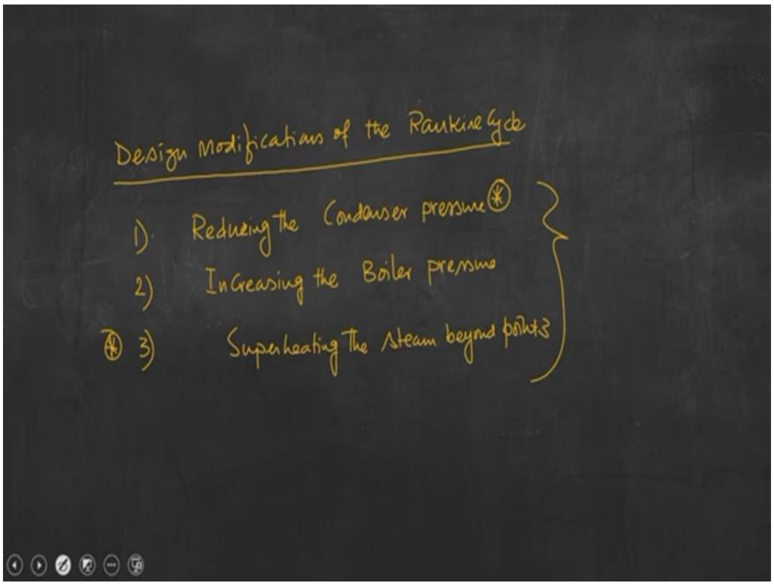

Design Modifications of the Rankine Cycle

1) Reducing the Condenser pressure ⊛

2) Increasing the Boiler pressure

⊛ 3) Superheating the steam beyond point 3

Design modification of the Rankine cycle

So, there are avenues by which efficiency of the Rankine cycle can be increased by modifying the system in several ways.

1) Reducing the condenser pressure.
2) Increasing the boiler pressure.
3) Super heating the steam beyond point 3.

At least the 3rd point we have discussed that one important flexibility of the Rankine cycle is that we can go super heating this steam up to any particular state beyond point 3. So, it is not mandatory that steam will be taken to the turbine at the saturated state rather we can super heat the steam beyond point 3. If we super heat the steam beyond point 3, without going into further analysis, you can just imagine that if we try to super heat the steam beyond point 3 say up to 3', you can see that this additional amount of W_{net} we can get.

So, probably when you have discussed about the advantageous feature of the Rankine cycle, one of the features is that we can super heat the steam beyond point 3. If we can super heat the steam at least we can see that we will be getting this amount of additional work output. If we are getting this amount of additional work output, probably we can increase the efficiency of the cycle. But to get this amount of W_{net} we also need to compromise the heat rejection

So, we need to go for a detailed discussion whether this W_{net} is relatively higher than this amount of heat rejection. If that is the case, then definitely we can increase the efficiency of the cycle.

Not only that, also important point is that if we can super heat steam beyond point 3 that is up to 3', the quality of the steam at the exit of the turbine becomes good. So, basically you know that the point 4' is closer to the saturated vapour line and if the point becomes closer to the saturated vapour line quality will increase. So, by super heating steam beyond point 3 we are getting additional amount of W_{net} and I am telling you that this relative increment of W_{net} is higher as compared to this heat rejection. Though heat rejection amount will increase, but the relative increase in W_{net} will be high and the resultant effect will be the increase in efficiency of the Rankine cycle.

On the top of that, the most important feature is that we can increase the quality of the steam at the exit of the turbine. So, the expected deterioration of the turbine blades due to pitting and erosion can also be prevented. So, this is one of the reason by which we can increase the efficiency of the Rankine cycle.

So, reducing the condenser pressure, increasing the boiler pressure and superheating the steam are the different modifications. I would like to discuss only 1 today that is reducing the condenser pressure & we will discuss all these 3 so, one by one.

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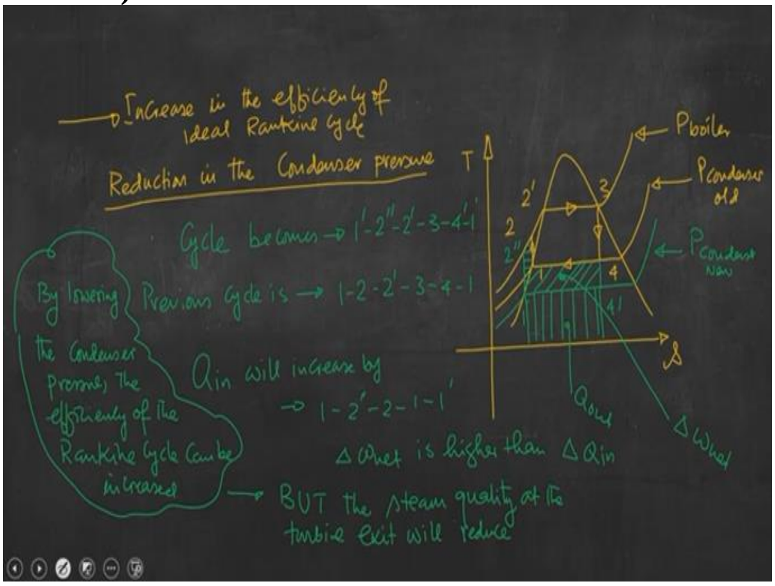

→ Increase in the efficiency of ideal Rankine cycle

Reduction in the Condenser pressure

Cycle becomes → 1'-2''-2'-3-4'-1'

Previous cycle is → 1-2-2'-3-4-1

Q_{in} will increase by → 1-2'-2-1-1'

ΔW_{net} is higher than ΔQ_{in}

By lowering the condenser pressure, the efficiency of the Rankine cycle can be increased → BUT the steam quality at the turbine exit will reduce

Reduction in the condenser pressure

So, let's quickly draw the TS diagram as shown in slide. We have plotted the point 1, 2, 2', 3, 4. So, we are looking at the possible way by which we can increase the efficiency of the ideal Rankine cycle. One of the possible ways is the reduction in the condenser pressure.

So, this is the simple Rankine cycle 1-2-2'-3-4. Now, what will happen if we reduce the condenser pressure? Say we are reducing the condenser pressure up to this particular point that is $P_{Condenser\ new}$ from $P_{condenser\ old}$.

So, if we reduce the condenser pressure cycle becomes 1'-2"-2'-3-4'-1'. So, the previous cycle is 1-2-2'-3-4-1. So, we can see that if we lower the condenser pressure, then we are going to have additional amount of work that can be seen from area hatched in the T-s diagram.

The T-s is very important. Because again I am telling that by drawing the process line in T-s plane we can get $W_{net} = Q_{in} - Q_{out}$. If we reduce the condenser pressure you can see that Q_{in} will increase. So, Q_{in} will increase by the area that is 1-2"-2-1-1".

So, this ΔW_{net} is higher than ΔQ_{in}. So, if we reduce the condenser pressure we can see that we are going to have a slight increase in Q_{in} that is ΔQ_{in}, but that increment is not larger as compared to the increment in the W_{net}. In other way, the increment of W_{net} is more than the increase in Q_{in}. So, the resultant effect will be the increase in the efficiency of the Rankine cycle.

So, again I am telling if we lower the condenser pressure, though there will be slight increase in Q_{in} but that increment in Q_{in} is insignificant as compared to the increment in W_{net} that we are getting. The hatched area under 1-1'-4'-4 is ΔW_{net}. So, the resultant effect will be the increase in efficiency of the Rankine cycle.

So, we can increase the efficiency of the Rankine cycle by lowering the condenser pressure. Though we can increase the efficiency, the problem is if you look carefully at this T-s plane, now, state of the steam at the exit of the turbine is 4'. So, the quality of the steam at the exit of the turbine deteriorates. So, if we reduce the condenser pressure, the efficiency of the cycle will increase, but we can see from the T-s plane that the quality of the steam at the exit of the turbine will be poor. So, the chances of having turbine blade erosion will be there. Not only that, another important problem which is associated by lowering the condenser pressure is there.

What is the main problem? See now, if we reduce the condenser pressure which is also known as the turbine back pressure. So, the pressure of steam at the exit of the turbine is also known as the turbine back pressure. So, if we try to reduce the condenser pressure we cannot reduce condenser pressure drastically. Because, if we reduce the condenser pressure drastically and it becomes less than the atmospheric pressure, then there will be leakages of air from the surroundings into the condenser and that air will cause mechanical problem with the pipe through which coolant is circulated. So, we cannot reduce condenser pressure drastically.

Condensers are normally operated below atmospheric pressure, but we cannot operate condenser at a pressure difference which is very, very high. Pressure difference is the difference in pressure at which condenser is operating and the atmospheric pressure. So, if the condenser pressure becomes very, very less than the atmospheric pressure, then chances of air leakage from the surroundings to the condenser will be very high and that air will create a mechanical problem in terms of the coolant, which is circulated through the pipe. Not only that, the air will try to reduce the heat transfer coefficient.

Also, another important point that I would like to mention is that whether you would like to operate condenser pressure sufficiently below the atmospheric pressure or not that will be dictated by the temperature of the water which is available near the plant site. Because this pressure is the saturation pressure corresponding to the temperature of water which is available at the plant site. So, based on the temperature of the coolant, which is available near the plant site, the condensate pressure should be decided.

So, the summary of the today's discussion is we have discussed about the concept of mean temperature. And we have seen that by invoking the concept of mean temperature, we could explain why the efficiency of the ideal simple Rankine cycle is lesser than the efficiency of the ideal Carnot cycle. Then we have discussed about a few possible ways by which we can increase the efficiency of the ideal simple Rankine cycle. And we also have discussed one of the 3 important ways that is by lowering the condenser pressure.

If we reduce the condenser pressure we can see that the efficiency of the cycle can be increased, but for that increase in efficiency, we need to compromise the quality of steam at the exit of the turbine. So, we need to have a judicial balance between these 2. Not only that, we also have discussed about critical issues about the selection of the condenser pressure in the context of the operation of the steam power plant.

So, with this I stop here today and in the next class we shall discuss about the remaining 2 points that is by increasing the boiler pressure and superheating the steam beyond point 3. Thank you very much.