Thermal Engineering: Basic and Applied
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Lecture – 10
Ideal Power Cycle and its Limitations, Introduction to Actual Power Cycle

I welcome you all to session of Thermal Engineering and today, we shall discuss about the ideal power cycle. Thereafter we shall see that the ideal power cycle is having a few limitations and discussing those drawbacks of the ideal power cycle, we shall also discuss about the actual power cycle and from there you will come to know the need of the actual cycle.

So you know that in the last class we have just introduced about the ideal power cycle that is the Carnot cycle. And we have also discussed that the steam power plants operate on the vapour power cycle. And since Carnot cycle is an ideal cycle, accordingly, the ideal vapour power cycle should be the Carnot vapour power cycle. Today we shall discuss about this particular cycle. Though we all know about this cycle and you have studied about it in thermodynamics course, but for the sake of completeness, as well as to discuss about some essential issues in the context of the operation of the steam power plants and also to highlight why this cycle is not suitable for the practical cycle, We would like to take up this particular aspect.

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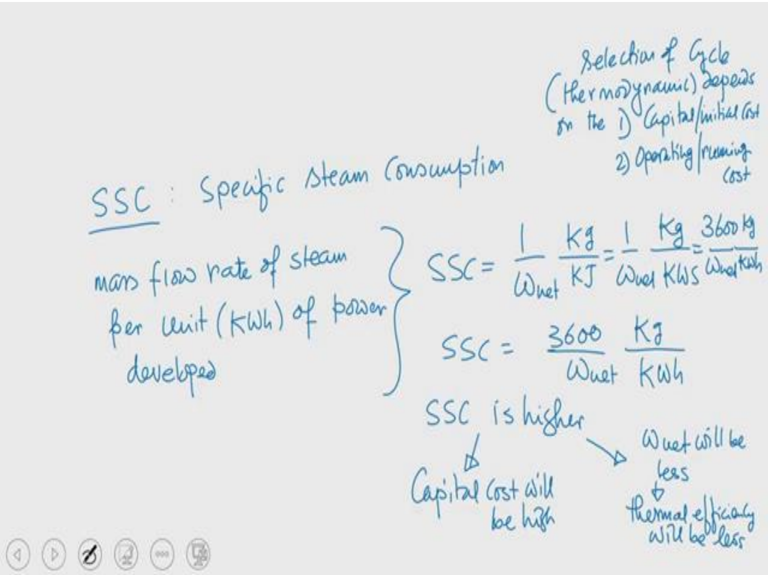

You know that in the last class we have discussed about one important index quality of the steam power plant that is specific steam consumption. So, before I go to discuss about the Carnot cycle, let us briefly review that particular term that is specific steam consumption. Why

I would like to discuss this? This SSC that is specific steam consumption is nothing but the mass flow rate of steam per unit kilowatt hour of power developed.

$$SSC = \frac{1}{W_{net}}\frac{\text{kg}}{\text{kJ}} = \frac{1}{W_{net}}\frac{\text{kg}}{\text{kWs}} = \frac{3600}{W_{net}}\frac{\text{kg}}{\text{kWh}}$$

Now. If you try to recall in the last class, I have mentioned that the choice of a particular cycle which should be used to compare the performance of the power plant depends on two important aspects. I mean we should consider these two aspects, while selecting a particular cycle for the comparison of the processes which are there in a power plant. What are those? So, one is the capital cost or the initial cost. Other one is running cost or the operating cost.

So selection of thermodynamic cycle depends on 1) capital or initial cost, 2) operating or running cost of the plant. See now, why this SSC is an important index for the quality of the plant? So, you know that

$$SSC = \frac{3600}{W_{net}}\frac{\text{kg}}{\text{kWh}}$$

So basically, if the plant size is very high that means W_{net} should be very high. So basically, you know that this SSC governs the capital cost; by how? You know that higher the specific steam consumption, higher will be the operating cost, higher will be the capital cost. Again, I am telling higher the specific steam consumption greater will be the size of the plant higher will be the capital cost.

For higher the SSC you know W_{net} will be less. We have seen that thermal efficiency is W_{net}/Q_{in}. So, for the given heat input rather given energy input in the form of heat, if we get less work output then efficiency will be reduced. So, for higher the SSC, greater will be the size of the plant, capital cost will be higher, on the other hand to have higher SSC you can see from the expression that W_{net} should be less.

If W_{net} is less for a given heat input, efficiency of the plant will be reduced, so, the operating cost or running cost will be high. So that is why this specific steam consumption is an important index for the quality of the steam that you can understand. Because thermal efficiency is

$$\eta_{th} = 1 - \frac{W_{net}}{Q_{in}}$$

So, if W_{net} is less for a given Q_{in} then efficiency will be reduced.

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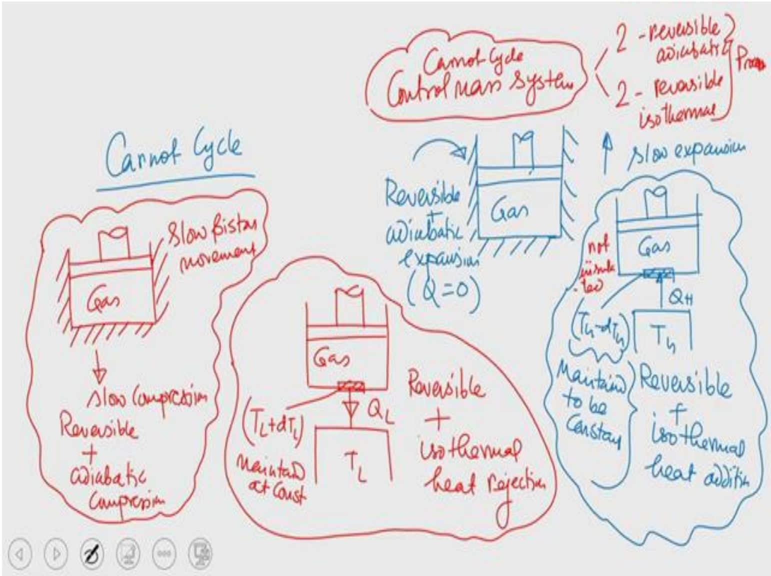

Carnot cycle

You have studied Carnot cycle for the control mass system in thermodynamics. You can imagine that a gas in a piston cylinder upon receiving heat is slowly expanding. And if we assume that the temperature of the boundary through which heat is supplied to the gas is remaining same, then you can assume that the process is isothermal and that too if the process is very slow process and if we do not consider the external irreversibility rather no external irreversibility is there, there is no heat transfer, then we can assume that this is reversible adiabatic expansion. Similar way we can also reduce the temperature of the gas. I mean there are three different cases.

First of all, if we consider that there is a cylinder and this is the piston as shown in slide. And we assume that this is piston is moving up so, it is slow expansion. This expansion of the gas can be made possible upon supplying heat from the external source. So, if we supply heat to this gas say from one temperature reservoir at temperature T_h and say, temperature of this particular surface over which heat transfer takes place is $T_h - dT_h$ and Q_h amount of heat is being supplied. So, in that case we can consider that the expansion is slow. Of course, the gas will expand and the temperature, pressure and volume of the gas will no longer remain in its initial state. So basically, that is the slow expansion; so, we can assume that the process is reversible isothermal expansion.

So, in this case we can assume, this is reversible adiabatic expansion. There is no heat loss, some amount of heat is being supplied to the gas and gas is slowly expanding. So, this is reversible adiabatic expansion. There is no heat interaction between system and surroundings, so, no external irreversibility. So, reversible plus adiabatic expansion.

In this later case, this is reversible plus isothermal expansion, why? Isothermal expansion is reversible and slow expansion. So basically, this expansion takes place due to infinite small temperature difference. So basically, the heat is being supplied from this higher temperature reservoir to the gas through the boundary wall and the temperature of the surface through which heat is supplied or transferred from this reservoir to the gas is remaining same. So, the temperature of the boundary is remaining same and that is $T_h - dT_h$. So, this is somehow maintained to be constant. In this case, we can assume that the process is reversible isothermal expansion process. This is slow heat transfer process due to infinite small temperature difference and the process is reversal isothermal process. So this two processes we have discussed.

Similarly, we also can assume that heat will be supplied from the gas to another source. Now, also we can discuss like this. Say you know that heat is transferred from the gas to the reservoir and temperature of this particular surface through which heat transfer takes place, is $T_L + dT_L$ and it is also maintained to be constant. And this is reversible plus isothermal heat rejection.

I should say that this (the 2nd case) is not isothermal expansion to be precise, let us say for the time being we are writing this is isothermal heat addition. So, we are supplying heat to the gas through the surface and the surface temperature is maintained at $T_h - dT_h$. And this heat transfer takes place due to infinite small temperature difference. And the process is reversible isothermal heat addition; this is slow process, infinite slow process.

Upon receiving that amount of heat if cylinder expands very slowly and there is no heat leakage through the walls of the cylinder then this is reversible plus adiabatic expansion (1st case). Why adiabatic expansion? Because Q = 0 in this particular case.

And for this (3rd case) particular case you can see that this is reversible isothermal heat rejection. Now, we also can assume that another process where the cylinder is insulated. But in the previous (2nd) case the surface is not insulated. So, this substance inside cylinder is gas in all cases and this is also slow compression. Reason is simple, you know this is reversible isothermal heat rejection if we reduce the temperature of the gas by taking certain amount of heat away from the system and if you assume that the piston is moving in very slowly. So, again the process is reversible that is simple compressible pure substance and if we move the piston very slowly so that is reversible plus adiabatic compression. So, this is adiabatic compression.

So, you know that this is reversible adiabatic expansion in this particular case, the temperature, pressure and volume of the gas will no longer remain at the initial state so, PVT will change. So basically, this is the concept of the Carnot cycle for the control mass system. If we imagine that in the piston cylinder arrangement this is the cylinder which contains gas, we will supply heat and that is reversible isothermal heat addition will allow gas to expand slowly and it will follow the reversible adiabatic expansion. Because if we insulate the surface, then there will not be no leakage of heat from the system to the surroundings.

(3rd case)We can use the same cylinder but now we remove the insulation. We can take certain amount of heat away from the system by connecting one thermal reservoir. And we are maintaining that the temperature of the boundary through which heat will be transferred from the gas to the temperature reservoir is constant that is $T_L + dT_L$. And this heat exchange will takes place through this infinitely small temperature difference. So, process is reversible but isothermal heat rejection. Why heat rejection? Because heat is getting rejected from the system to the surrounding. Process is reversible because very slow process and isothermal as the temperature is maintained constant at the boundary at which heat is transferred from the system to the surroundings.

And next if we remove this and if we allow so basically, what will happen? You know that the slow expansion will slow compression. So basically, what will happen? If we take away certain amount of heat from the gas then piston will come down, as if the gas is getting compressed. So, if we now remove this particular arrangement and the continuous movement of the piston towards the bottom of the piston will be there and basically the movement of the piston is very slow. So, it is, it is nothing but the compression. So, movement is very slow, so, reversible. Now what is done? Surfaces are insulated, so, there will not be no heat leakage or heat interaction between system and surroundings, so it is reversible adiabatic compression.

So, imagine all these four processes are constituting to form a cycle and that cycle is the Carnot cycle. But mind it, it is for a control mass system, there is no flow. So, the concept is like this if we can now think of a cycle for a flow process rather, we are trying to apply whatever you have learned for a flow process, so, this is basically Carnot cycle which is having two isothermal processes and two adiabatic processes. So, two reversible adiabatic processes are reversible adiabatic expansion, reversible adiabatic compression. And another two reversible isothermal processes. So, we are having total four processes, out of these four processes, two are reversible adiabatic processes, and other two are reversible isothermal processes. So, all these four processes constitute this control Carnot cycle for the control mass system.

If we can conceptualize such an ideal cycle like Carnot cycle for a flow process that would be the Carnot cycle for the flow process and that is a hypothetical power plant which will operate on using this cycle.

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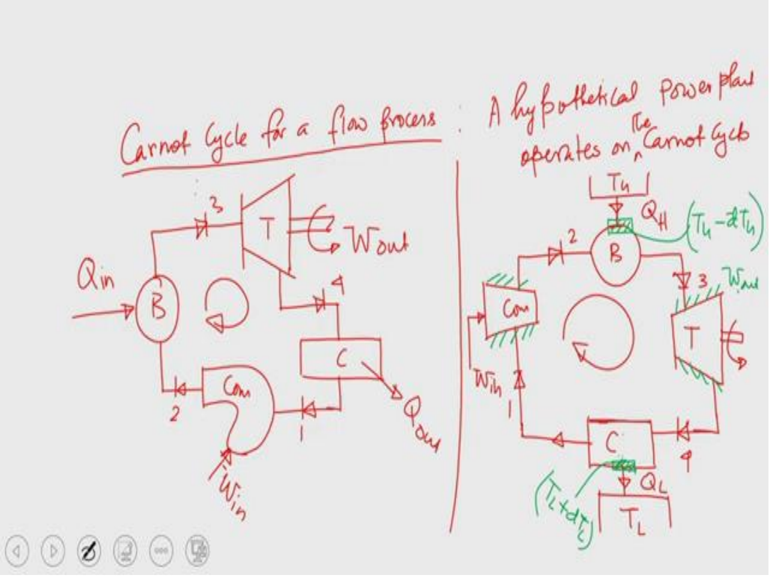

So now, we are going to discuss about Carnot cycle for the flow process. And this is nothing but a hypothetical power plant that operates on the Carnot cycle. So, now what we have seen is that we have discussed about four major components.

So, I have discussed about the Carnot cycle. The last example that I have illustrated only to make you understand that the Carnot cycle is essential and an ideal cycle and this is for the control mass system. So, if we try to conceptualize all these four processes but for a flow system, then we will get the Carnot cycle for the flow process and a hypothetical power plant can be operated by using this Carnot cycle.

So now, let us draw the schematic depiction of the power plant. So, there is boiler, turbine, pump and condenser and this is a cycle. So, all processes are getting executed in a cyclic manner. So you know that Q_{in} is Q heat addition to Boiler, then W_{in} is the work input to the pump, W_{out} is the work output from the Turbine and Q_{out} is the heat rejected from condenser. As I told you that this power plants operates on vapour power cycle, but we shall definitely discuss about the actual power cycle which can be used to predict the performance of the plant by mapping all the processes in thermodynamic coordinate diagram and then by calculating the performance or efficiency of all the individual processes.

But, I told you that though it is very difficult to achieve ideal cycle in practice but we need to study it. And in the context of this discussion, we also introduced one definition that is known as efficiency ratio or relative efficiency. So, this is an important measure of the performance of the actual power cycle. So, in actual power cycle we can understand that efficiency will not be 100% and that is not possible at all. But our objective should be to increase the efficiency of the actual cycle so as to reach closer to the ideal one and that is why the ideal cycle is important to be discussed.

So basically, you have learned from the previous discussion about all these four processes. So, now what we can see is that heat is being added in the boiler and then it expand in the turbine and then it is coming to the condenser wherein by rejecting heat, the working substance changes its phase. And that liquid is again taken back to the boiler.

So, I have written P, as P stands for pump in the last class. So, today I should not write it pump, I am writing it as compressor. See I have written Com for us to denote condenser. So you know that I can arrange it in a bit different way as shown in the slide. So, there is compressor and boiler and then it is expanding in the turbines and after doing certain amount of work, it is again coming to another device that is condenser and it is rejecting heat to another reservoir say T_L. And then this condensate is taken to this compressor to be compressed back to the boiler at the boiler pressure.

So, there is the surface of the particular device as shown in slide through which heat is added to the boiler and heat is rejected to the low temperature thermal reservoir from compressor. So, you know that Turbine is a work producing device, so, there is W_{out} as shown in the slide. And this compressor is absorbing W_{in}. And this is a cyclic process and this device Boiler received Q_H from this high temperature thermal reservoir and reject Q_L to the low temperature thermal reservoir.

So, you do not look at the schematic which I have drawn in the slide at the right panel. This schematic which is shown at the left panel is basically the schematic of the power plant. That right one is too. But the concept is upon receiving certain amount of heat, the working substance will change its phase and after the working substance phase conversion, that substance will be taken to another mechanical device, Turbine in which it will expand and it does work on the rotating part of this device.

And again that working substance is taken to another mechanical device wherein by certain arrangement it rejects heat to the surroundings. And after rejecting heat again its phase will be changed. And finally, that substance is again compressed back to the boiler. So, the concept is taken over here. So, we are compressing. So, what I am writing, so, this is 2, this is 1, this is 3, this is 4. 1-2-3-4-1 cyclic process is shown in the schematic diagram in the slide.

So, upon receiving work input from the external source the working substance will be compressed back to the boiler wherein upon receiving heat from this external thermal reservoir. So, the temperature of this thermal reservoir is $T_h - dT_h$. This is exactly what we have shown in the reversible isothermal heat addition process where the temperature of the surface through which heat is supplied to the gas is $T_h - dT_h$. So we are supplying heat from this high temperature thermal reservoir to this device through the surface where the temperature is $T_h - dT_h$. And we are maintaining the temperature to be constant during the process.
And then the working substance upon receiving the heat will change its phase and for this particular cycle working substance is water and steam. When steam is coming out from boiler, it will expand and it does work. And after doing work, when the steam is taken back to the condenser, as we have discussed that it is very difficult to extract the enthalpy at state point 3 is very, very high than the enthalpy at state point 4. And it is because of this reason you are

getting work output W_{out}. But still enthalpy at state point 4 is sufficiently high that it cannot be directly taken to another device for the rejection of heat.

You know that if you would like to have complete you know we cannot. That is what we have seen from second law of thermodynamics. So, there must be a provision of heat rejection of the working substance. So, it is taken to the condenser and through the condenser it is taken to the (low temperature reservoir) so, heat is taken away from the working substance through this bounding surface, where temperature is $T_L + dT_L$.

And we are assuming that the temperature is maintained at $T_L + dT_L$ and heat is getting transferred from the flowing steam to the surroundings. And again, it is compressed back to the boiler. So, now you may ask me a question, we can try to use or utilize all the enthalpy which is there in a turbine. But again, in that case, what will happen you know that we do not require this condenser. So, it is difficult because in that case you need a turbine whose length should be abnormally very high and that would not be possible physically. So, that is the problem from mechanical operation point of view. So, this is the case.

So, we can go one step further to the compression process and you know that the surfaces of the compressor are insulated. Surfaces of the turbine are also insulated. If the surfaces are insulated and if the process is very slow, we can assume that the process is reversible adiabatic compression. In the Boiler you know that heat transfer takes place due to infinitesimal temperature difference and if we assume that the process is very slow, so it is reversible isothermal heat addition.

Here(In turbine) also it is expansion but the expansion takes place slowly, so, it is assumed that the process is reversible internally and also there is no heat loss from this turbine to the surroundings, so it is reversible adiabatic process. Finally, when the steam is coming to condenser, we are maintaining the temperature of the surface of the condenser at $T_L + dT_L$ and through that heat is transferred. If the process is very slow and you are assuming that the temperature is same during the process, then this is reversible isothermal process. So, exactly all the processes that we have discussed in the context of the control mass system, we can visualize or conceptualize all the processes, even for a flow system. So, this is the Carnot cycle for a flow system and a hypothetical power plant that we will operate using this cycle.

Why hypothetical that will be discussing soon. So, we can go one step further and we can draw the schematic again in another form.

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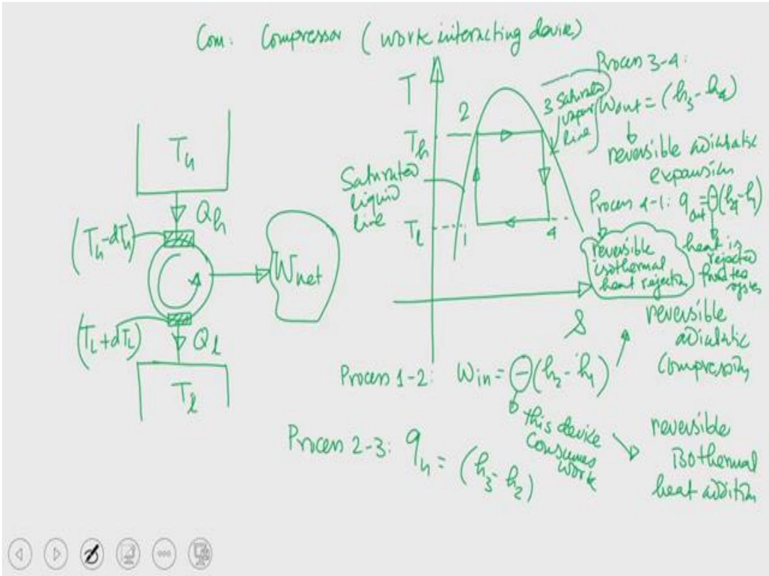

So, what we can say from this particular schematic is that we are supplying W_{in} to the compressor we are getting W_{out} from the turbine. So basically, there will be a net work output from this cyclic process. So, all the processes are getting executed in a cyclic manner. So, for a particular cycle, we are getting net work output at the cost of the heat addition in the Boiler and heat rejection in the condenser.

So, we can reduce that like this. There is the high temperature reservoir at T_h and all the processes are getting executed in a cyclic manner and we are assuming that at the surface temperature is $T_h - dT_h$ and we are getting W_{net}. Of course, to get this W_{net}, there must be a provision of heat rejection that is Q_l. The amount of heat addition is Q_H. And this the sink temperature is T_l. And we are assuming that the temperature of the surface through which heat is taken away from this system is $T_l + dT_l$. So basically, if we look carefully, in a particular cycle, we are getting net work output while exchanging heat between these two temperature thermal reservoir and that is what we have tried to represent over here.

So that is the second law which states that it is impossible to construct a thermodynamic device which will operate in a cycle and the net effect would be to produce work continuously, while exchanging heat with a single temperature thermal reservoir. So, that is not possible. So, if you would like to get this W_{net} in a cyclic manner that is what the symbol indicates, then there must be a provision of heat rejection.

So, this is how the Carnot cycle works. Now again, we need to map the processes of the Carnot cycle in thermodynamic plane, that is T-s plane. Why T-s plane? There are many such thermodynamic coordinate diagram like T-s, h-s, p-V, p-T, T-V. So, what is special about this T-s diagram? Because you have studied from thermodynamics that if we can identify any process and if we can map the process in T-s plane, the area under the process line in T-s diagram will give you the heat transfer for the reversible processes.

So, if we try to represent the processes, then we can plot T_l and T_h. If we go to the slide and look at the schematic diagram shown in the right panel, we can see 1-2 is compression process. Then we can map process 1-2 in the T-s plane. So that is the compression process and we need to supply work into the compressor for its smooth operation.

$$\text{Process } 1-2\text{: } W_{in} = -(h_2 - h_1)$$

From where we can write this expression? You know that in the previous class, I have discussed about the application of combined first and second law to the steady state steady flow processes. If we assume that the process which in the compressor is steady state steady flow process and then we apply first law for the flow process. We know that this is not a heat interacting device because surfaces of the compressor are insulated. So, there is no heat loss from the system to the surroundings. So, this is not a heat interacting device rather, this is a work interacting device. Because it absorb work for it is operation, so, this is also called as work absorbing device. So, $W_{in} = -(h_2 - h_1)$ why negative? This negative sign indicates that this device consumes work. So, this work is not produced rather this device consumes work.

Now what about this process 2-3? 2-3 is the heat addition and we have assumed that the process is isothermal heat addition, because constant temperature is maintained during the process. So, this is reversible isothermal heat addition process.

$$\text{Process } 2-3\text{: } q_h = (h_3 - h_2)$$

So, this is heat addition to the system. So, you know process 1-2 is work consuming device. This device consumes works that is why it is negative. So, 2-3 process is heat addition. So this

1-2 process is reversible adiabatic compression, and 2-3 process is reversible isothermal heat addition process.

So, you know 3-4 is expansion process but it takes place reversibly because process is very slow but there is no heat interaction between the device and the surroundings. So, it is again work producing device and we can map this process as 3-4 and this process is reversible adiabatic expansion.

$$\text{Process } 3-4\text{: } W_{out} = h_3 - h_4$$

So, you know that this is basically reversible adiabatic expansion, so, we will be getting W_{out} from the application of the first law applied to the flow process rather steady state, steady flow process.

And you can understand that 4-1 is again heat rejection process but it is at constant temperature. Because the temperature of the surface through which heat exchange takes place is remaining constant at $T_l + dT_l$ during the process. And the process is very slow because heat transfer takes place due to infinitesimal temperature difference. So that is why this is hypothetical. In reality, it is very difficult to ensure that the heat transfer will takes place due to infinitesimal temperature difference both at the condenser as well as at the boiler. So that is why the word hypothetical came into the picture.

$$\text{Process } 4-1\text{: } Q_{out} = -(h_4 - h_1)$$

So, this negative sign again because heat is rejected from the system. And this is again reversible isothermal heat rejection. So, we could identify four different processes from this particular cycle and this is known as Carnot cycle. So, this is the ideal vapour power cycle that is the Carnot cycle.

So we have discussed that heat addition to the system is positive and heat taken away from the system is negative. That is how the signs in above expression are assigned. So, in process 1-2, the amount of heat is taken away from the system, that is why the negative sign is coming. Similarly, work extracted from the system is taken to be positive, that is the sign convention. But W_{in} is the work which is added to the system that is why it is coming as negative. So, we have identified all these four processes. We could map all these four processes in T-s plane.
Though points 2 and 3 are shown on the saturated liquid line and saturated vapour line, but in general, these two points could be shown to the inside the vapour dome.

And with this if you would like to summarize today's discussion then we have tried to understand the Carnot cycle, starting from the control mass system then we have extended our concept to the flow system and then we have tried to compare the processes which are there in a power plant using this Carnot cycle. And we could identify all the processes and we have mapped all these processes in T-s plane. From there we have quantified the mathematical expression for heat which is added to the system or which is taken away from the system and similarly for work which is added to the system and work which is extracted from the system. From this next what we can do? We can at least try to frame the efficiency of the plant following this Carnot cycle and then we will see what are the drawbacks associated with this cycle. So, with this, I stop here today and we shall continue our discussion on this particular aspect in the next class. Thank you.