Concepts of Thermodynamics
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Lecture – 64
Carnot Cycle and Rankine Cycle (Contd.)

In the previous lecture, we were discussing about the thermal power plant cycle and in that context we discussed about Rankine cycle; first simple Rankine cycle then Rankine cycle with super heat and rigid.

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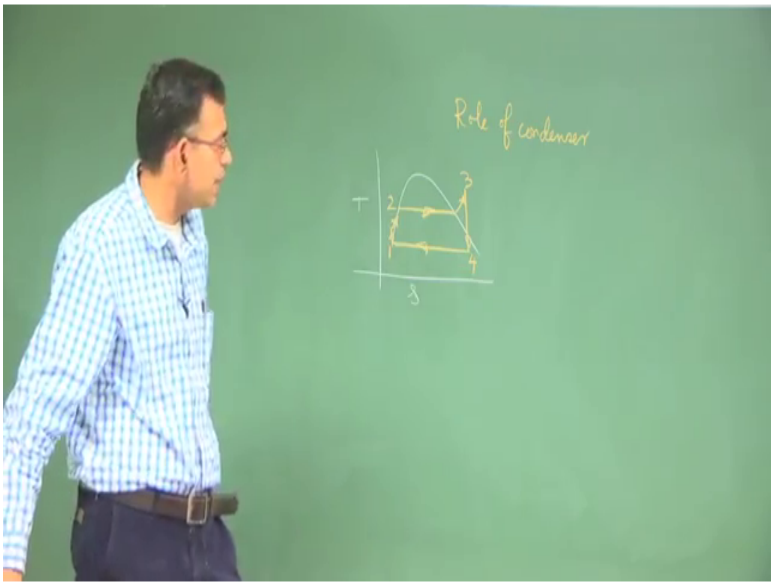

What we did not discuss is the role of the condenser. So, we will take we will consider a simple T-s diagram and just take an example of Rankine cycle with super heat and in this process understand the role of the condenser .

So, what happens if we reduce the pressure or temperature of the condenser? We have seen that increasing the efficiency of the cycle there are two possibilities; one is increase the mean temperature of heat addition which we tried to do with super heat, the other possibility is reducing the mean temperature of heat rejection for which we have to concentrate on the condenser. So, in the condenser what we are doing? In the condenser we are rejecting heat at what temperature? For that we have to build up a little bit of practical idea.

So, what is cooling the steam of the condenser? The cooling water is cooling the temperature cooling the steam of the condenser. What is the typical temperature of the water? Let us say 25 degree centigrade just as an example, I mean there is no sanctity about this 25 degree centigrade, but it is not abnormal also.

So, if it 25 degree centigrade, what is the steam temperature it would be greater than 25 degree centigrade for heat to be rejected from the steam to the water? Greater, but not too much different because higher temperature difference will result in more external irreversibility; so, if it is 25 degree centigrade the cooling water this steam let us say it is 30 degree centigrade. If it is 30 degree centigrade, what is its pressure? Had it been 100 degree centigrade, it is pressure would have been 1 atmospheric. So, if it is 30 degree centigrade its pressure is below 1 atmosphere.

So, the first understanding is that the condenser is under vacuum. Had there been no condenser and heat would have been rejected to the atmosphere then the temperature at which heat would have been rejected is 100 degree centigrade because, 1 atmosphere will correspond to 100 degree centigrade as the saturation temperature for liquid vapor water. Instead, here we are coming down to much lower temperature, but for the lower temperature we are having to give a penalty.

Penalty is that the condenser is under vacuum and because it is under vacuum the maintenance of the condenser is a very serious thing, otherwise what will happen if there will be air leakage from surroundings to the condenser because it is under low pressure or vacuum. Forgetting about that having the condenser itself working at a temperature less than 100 degree centigrade is advantageous because it will reduce the mean temperature of heat rejection and it will increase the efficiency.

So, having the condenser at a lower and lower temperature will actually increase the efficiency, but the problem is that I if you lower the condenser pressure of the temperature the state point 4 will go further and further away from the saturated vapor line. So, turbine blade erosion problem will coming. So, turbine erosion problem will come in and air leakage problem will come in more and more as you reduce the condenser temperature, otherwise reducing the condenser temperature is good for the thermal efficiency point of view.

So, we can understand one very interesting thing whatever is good for improving thermal efficiency may not be good from practical considerations and that is where we have to make a compromise in the thermal power plant design.

So, the most fundamental role of the condenser is not however, just to increase the efficiency. The condenser is there fundamentally to satisfy second law of thermodynamics for the cycle, the Kelvin-Planck statement for the cycle because had the condenser not been there, there would not have been a mechanism by which heat would be rejected in a part of the cycle and then it would violate the Kelvin Planck statement and it would not be able to produce work continuously in a cyclic process. And therefore, from the very basic need of the second law of thermodynamics a condenser type device is required whether it is under low temperature or relatively high temperature, that is from the efficiency consideration and other consideration but condenser type device has to be there to reject the heat.

Now, Carnot cycle is something with which we started in studying the vapor power cycles. The Carnot cycle being so interesting we could find that despite being so interesting and highly efficient it cannot be applied in practice. So, the question is could you imagine an alternative cycle in practice, which would give the same benefits of the Carnot cycle, although it could be imaginary, but it could give us a good clue of how to improve the efficiency of the cycle to bring it closer to the Carnot cycle and that brings us to the perspective of ideal regenerative cycle.

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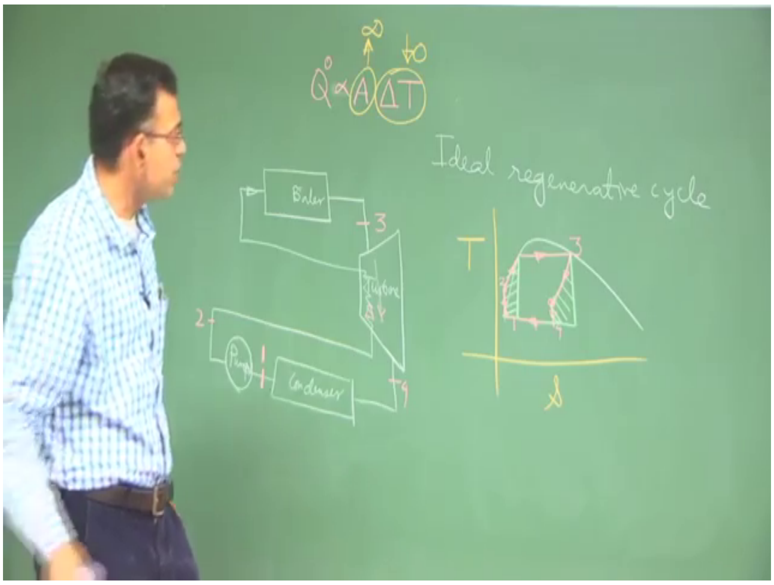

So, in the ideal regenerative cycle what is done is you have the boiler, then you have the turbine condenser very much similar to what was there for the standard Rankine cycle. Then you have the pump. After that the fluid will circulate across the external casings of the turbine and that then it will enter the boiler. What is the purpose? The purpose is to increase the mean temperature of heat addition. So, that the liquid which is going to be fed to the boiler, it is being fed by progressively increasing is temperature by bring it in contact with the steam in the turbine.

So, how it does it will be very clear if we can draw a T-s diagram. So, you have the state point 1, which is here the condenser then from 1 to 2 you have the pumping. Then it enters the boiler; from the boiler when the steam enters the turbine, now it is no more adiabatic for the steam because that steam gives heat to the water which is being now put into the boiler. See steam is coming on from this side and water is going from this side and they are exchange heat. So, we are trying to have an ideal counter flow heat exchanger where water is going along one side, steam is coming along the other side. Steam is rejecting heat to the water and to make irreversible at every stage the temperature difference between the steam and the water is kept delta t to be very very small 10 into 0.

So, when the steam rejects heat if it is an ideal counter flow heat exchanger it will heat exchanger it will follow exactly this line in parallel and you will have the T-s diagram like this. So, these are exactly parallel lines, everything is exactly parallel. These two are parallel and these are parallel. So, you have 1, 2 and 3 then 4.

So, why the efficiency of this cycle is equal to the efficiency of the Carnot cycle is quite obvious from this T-s diagram you consider a Carnot cycle like this. This amount of area is added to the Carnot cycle to make this new cycle, but this amount of area is subtracted also and this is equal to this. Therefore, the area under the T-s diagram for this ideal regenerative cycle is same as the area under the T-s diagram for the Carnot cycle and that makes their efficiencies exactly the same.

So, the ideal regenerative cycle has efficiency exactly as same as that of the Carnot cycle. Despite that you will find that the ideal regenerative cycle does not find any application in practice. First of all it is extremely difficult and practically impossible to run the water across the turbine casings and expose that to the steam, which is already expanding in the turbine. Hypothetically you can draw to parallel lines, but practically to make it happen it is not feasible. Even if it is feasible, that would not give rise to a reversible heat transfer.

Why? The rate of heat transfer is equal to is proportional to the surface area across which the heat transfer is taking place and the temperature difference between the two fluids hot fluid and cold fluid. So, if this temperature difference is trending to 0 then this difference is tending to 0, then this must tend to infinity to make a finite heat transfer; that means, that turbine casing surface has to be infinitely large to accommodate for a finite heat transfer in this process and that kind of having an infinitely large heat transfer area on the surface of a turbine, it is not practically feasible and that is why you will not get ideal regenerative cycle working in practice.

Although you do not get ideal regenerative cycle working in practice, still you get some lessons out of these. This is just like a Carnot cycle; cannot be implemented in practice, but gives a very important lesson. What is the lesson? You try to heat the water that is being pumped by the pump before it enter the boiler that is the message. Why you heat it? To increase the mean temperature of heat addition to increase the mean temperature of heat addition, heat the pump outlet water before it enters the boil. That is the message that we get from the ideal regenerative cycle.

So, the message is that we get from idea cycles are not because we want to make them implement exactly in practice, but we get their usefulness utility and fundamental principle and try to implement that principle in the form of mode idealistic cycle. So, that for example, is a real regenerating cycle. So, I will try to make a schematic of real regenerative cycle and show that how it borrows the lessons of ideal regenerative cycle that make the implement.

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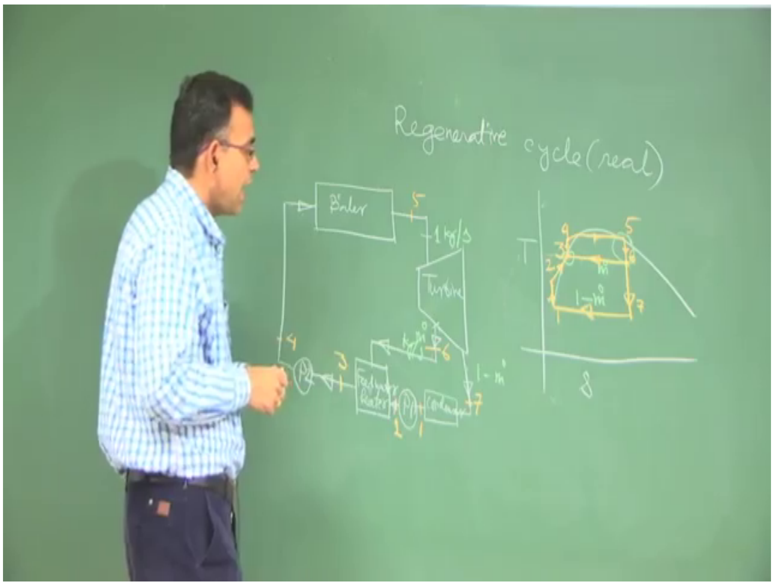

So, regenerative cycle real; remember, that this course is not a course of power plant engineering. So, the whole idea is to make you understand the role of thermodynamic cycles in practical engineering. Here the role is to figure out that by taking model hypothetical cycles, how we can increase the mean temperature of heat addition or decrease the mean temperature of heat rejection without compromising certain things like turbine blade erosion so on.

So, in the regenerative cycle sorry, regenerative cycle regenerative so you have the boiler. Then in the turbine so, this is called as multi stage turbine you always have a high pressure stage, this you also saw in re heat that there is a high pressure stage, there is a re-heat pressure and there is a low pressure. There could multiple re-heat pressure stages.

So, here there is an intermediate pressure stage at which the steam is extracted. Why? This steam still very hot, it is not as cold as what or it is not relatively colder as compared to what would have been the case had it been fully extracted from here. So, the steam is partly extracted from here why because it is still hot. So, the fluid that comes out of the pump will be exposed to this hot steam to make it hotter before it enters the boiler again.

So, this goes to device which is called as feed water heater, but the remaining steam expands it goes through a condenser and then the condenser is pumped buy a pump number 1 to this intermediate pressure because the fluids which mix in the feed water heater directly they should be brought to the same pressure. So, this is already at a higher pressure than this.

So, these pump elevates the pleasure of the condensate to this pressure at which this steam is extracted. So, this fluid which is relatively cold now mixes with hot fluid and it becomes hotter and then it is pumped by another pump to the boiler pressure. So, this is just one feed water heater as an example, but you could have several feed water heaters. In many power plants the another purpose that this feed water heater serves is getting rid of air and that is why dissolved here and that is why this is called as deaerated also.

So, now, I will draw the T-s diagram for this cycle. So, from the boiler so, let us say this after pump 1 it is feed water. So, let us say this is one traditionally the condenser we are calling as state point 1, this is state point 2. So, 1 to 2 like this, pump is considered to be a small enough device to have very high level of irreversibility. So, reversible adiabatic process for pump is more or less not very impractical from 2 to 3 you have the feed water heating. So, that increases the mean temperature.

Then, from 3 it has to be pumped to boiler pressure so there has another pump 2. It pumps it to the boiler pressure and then it undergoes the process in the boiler. So, it comes to the state point 5 then it expands from 5 up to 6. Pressure of 6 is same as the pressure of 3 right because it is a constant pressure process; so, because it is in the 2-phase region there temperatures also the same; so, you have. The remaining steam expands to 7 and then 7 to 1 is the condensation process.

So, this is, remember this is not technically a correct cycle diagram, thermodynamics cycle diagram. The reason is that all the streams do not have the same mass flow. So, if you consider say 1 kg per second of steam flowing through this and if this is m dot then this is one minus m dot, this is m dot kg per second. So, from 5 to 6 you have one the expansion here what it comes out is 1 minus m dot sorry, that is m dot right and this is 1 minus m 1. Together they intermingle and form become 1 here at this stage, no to ensure that 3 is a saturated liquid this m dot is that is a design problem that you select the m dot in such a way that by a steady state steady flow analysis of the feed water heater as a device what comes out at 3 is saturated liquid, a correct choice of m dot will do that ok.

So, that can be ensured, but the more problematic part so far as technically constructing the correct cycle diagram is that here because different masses are flowing across different parts of this. This is not technically correct thermodynamics cycle many power plant engineers will not appreciate this because for them the sole purpose of this diagram is to identify state points. They will not care whether it is a thermodynamic proper cycle or not, but technically not. So, this cycle has an elevated efficiency if considering that the mean temperature of heat addition is elevated because of steam which is heating the feed water ok.

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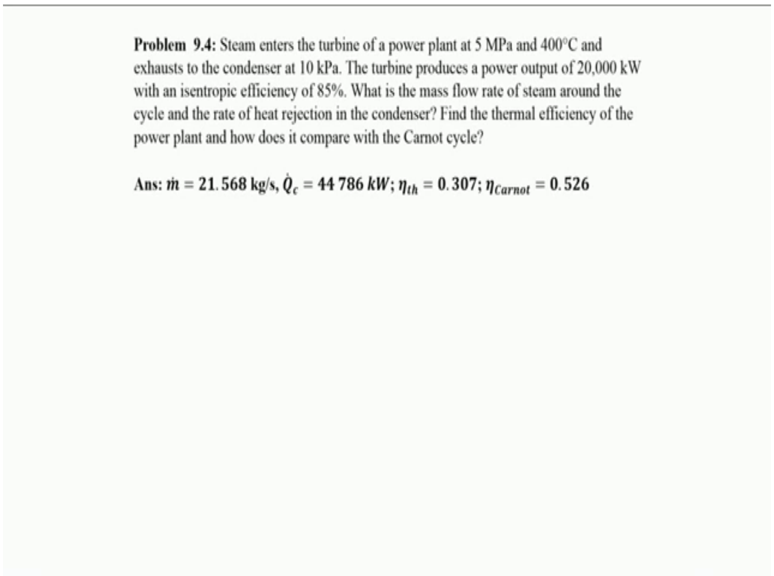

So, with this little bit of practical background on to thermal power plant what I would like to do is to work out a problem on thermal power plant cycle which is given as problem 9.4 as you see in the screen. Steam enters the turbine of a power plant at 5 mega Pascal and 400 degree centigrade and exhaust to the condenser at 10 kilo Pascal. The turbine produces a power output of 2000 kilowatt with isentropic efficiency of 85 percent. What is the mass flow rate of steam around the cycle and rate of heat rejection to the condenser? Find the thermal efficiency of the power plant and how does it compare with the Carnot cycle. So, this is a very standard problem but let us try to solve this problem. Before that let me the erase the board and write the problem data here.

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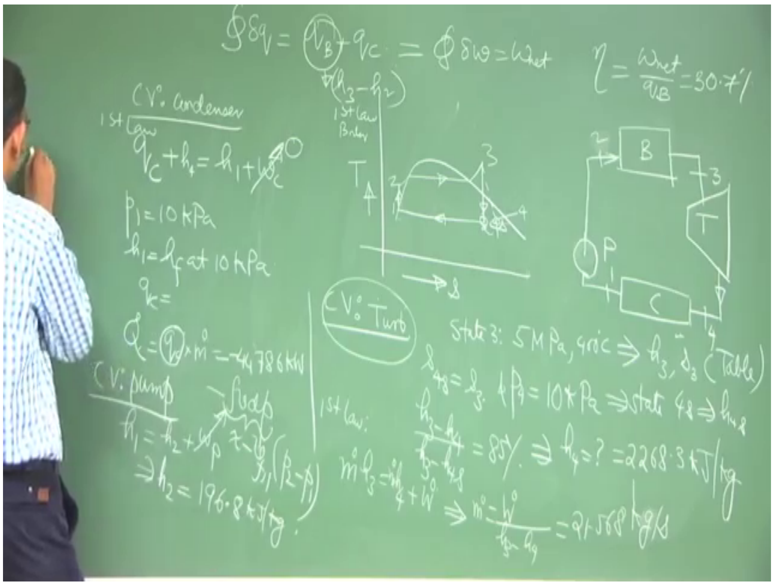

So, this for solving this problems I am not drawing it again, but you also have to physically draw the architecture, boiler, turbine, condenser and pump. So, will quickly let me draw it with schematic boiler, turbine, condenser, pump; sorry, pump so, 1, 2, 3, 4 ok. So, let us make the. So, it is essentially a control volume analysis for each of these components that we have to do. So, first we make a control volume analysis for the turbine. State 3 it is given 5 MPa, 400 degree centigrade this will imply what is h 3 and essentially solving a problem will require evaluating the enthalpies of all the state points, then all the relevant data you can figure out.

So, h 3 you know and s 3 you know, this is from the steam table. Then remember that this is not the actual state 4, I am not completed the T-s diagram drawing. This is 4 for reversible adiabatic process. It is given that this turbine has isentropic efficiency of 85 percent. So, the actual process actual state point 4 will be this. This is state point 4 s ok.

So, now from the definition of the turbine definition of the isentropic process in the turbine you have s 4 s is equal to s 3. So, you know s three; that means you know s 4s and p 4. What is p 4? p 4 is 10 kilo Pascal. So, this will give you what is state 4 s and this will give you what is h 4 s. So, h 3 minus h 4 divided by h 3 minus h 4s. This is the actual work. This is the reversible adiabatic work; this is 85 percent; that means, what is h 4? It is 2 to 68.3 kilo joule per kg.

So, what is the mass flow rate of steam around? So, m dot; so we have already done this if you use the first law, then you have m dot first law for the turbine. So, m dot h 3 is equal to m dot h 4 plus w dot neglecting changes in kinetic energy and potential energy. So, m dot is W dot by h 3 minus h 4, right. So, this is 21.568 kg per second that is the first question.

Second question is what is the heat rejection in the condenser? So, then we go for control volume as condenser. So, q c per unit mass flow rate plus h 4 is equal to h 1 plus w c the work in the condenser is this is also. So, we are fundamental using the first law, second law analysis of the cycle will require use of second law. This requires the first law.

So, what is h 1? State 1 it is given state 1 is p 1 is equal to 10 kilo Pascal. So, p 1 is equal to 10 kilo Pascal. So, h 1 is h f at 10 kilo Pascal because h 1 is saturated liquid state. So, you will get q c from here and the q c will be whatever I do not have the answer with me, but q dot c is q c into m dot the rate of heat transfer this is minus 44786 kilowatt. This is minus because heat is rejected.

Then what is the next question? Find the thermal efficiency and how does it compare with the Carnot cycle. So, you have calculated h 1 only enthalpy state that is required to complete the description of the heat transfer are work done is h 2, right. So, the control volume if you make it pump, if it you can assume it is a reversible adiabatic steady state steady flow device. So, h 2 so, h 1 is equal to h 2 plus w pump, right; w pump is minus integral of vdp right.

So, if you do that so, this is roughly minus the specific volume is v f at 1 into p 2 minus p 1. This approximation is very much correct. So, v f at 1 means v f at 10 kilo Pascal; p 2 is 5 MPa and p 1 is p is 10 kPa. So, you get this you substitute it here you will get what is h 2 from here you already know what is h 1. So, h 2 is 196.8 kilo joule per kg.

So, now, only aspect is what is left is the thermal efficiency. So, what is the cyclic integral of heat this is q boiler plus q condenser with proper algebraic sign right. So, what is q boiler? q condenser is this q small c. What is q boiler? q boiler is h 3 minus h 2 if you apply the first law to the boiler. This by first law is a cyclic integral of work, this is w net. So, efficiency is w net by q boiler and this is 30.7 percent.

The next part of the question is how does it compare with the Carnot cycle. So, this question itself is little bit faulty because how does it compare with a Carnot cycle is like comparing an apple with an orange. Carnot cycle you have to specify the temperature at which the Carnot cycle is defined. There could be Carnot cycle define at some T L some T H for which this efficiency is actually more than the Carnot cycle. What this question actually intends is possibly that by taking T H as T 3 and T L as T 1, what is the efficiency of the Carnot cycle?

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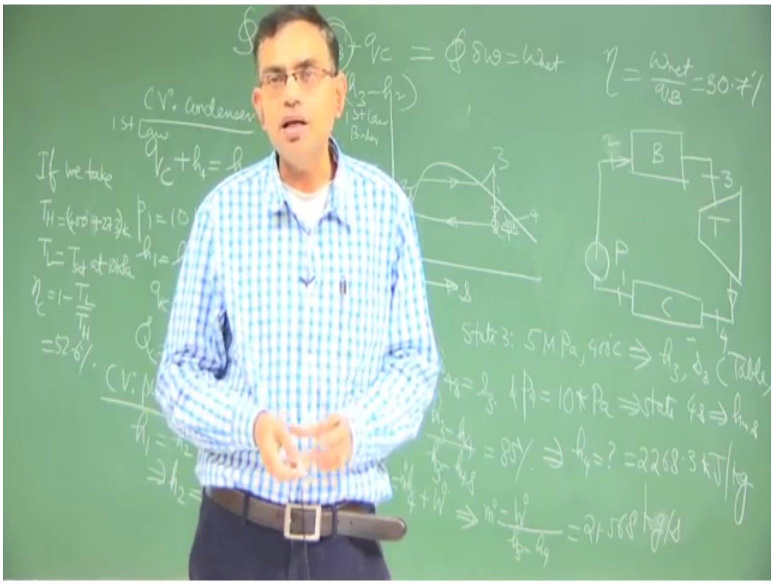

So, if we take this much be clarified if we take T H as 400 degree centigrade. So, this plus 273 Kelvin and T L is T sat at 10 kilo Pascal whatever Kelvin; then the eta Carnot what is that, that is the question. So, they remember that it is a very poor question that is the Carnot cycle efficiency greater than Rankine cycle efficiency or not? This in this way the question setter is prompting you give an answer the yes the Carnot cycle efficiency is greater than Rankine cycle efficiency.

But, this question has no meaning question is Carnot cycle efficiency between which temperatures that has to be specified and then only it can be compared with any other cycle. So, given two different other temperature limits this could be even less than the 30 point whatever answer that we have got. So, this answer will be 52.6 percent. So, to summarize we have discussed about vapour power cycles and some practical considerations as well as thermodynamic consideration related to that.

Thank you very much.