Concepts of Thermodynamics

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Lecture – 63
Carnot Cycle and Rankine cycle

We have discussed about various thermodynamics cycles so far and we will continue with that. The thermodynamics cycles that we have discussed so far are mainly air standard cycles that means, the cycles which used air as working fluid under certain special assumptions. But practical cycles may not always have air as a working fluid, but they can use for example liquid vapour mixture or superheated vapour for achieving a particular purpose. And those kinds of cycles may be used for various applications or those kinds of cycles may find their applications in various sectors ranging from power plant engineering to refrigeration.

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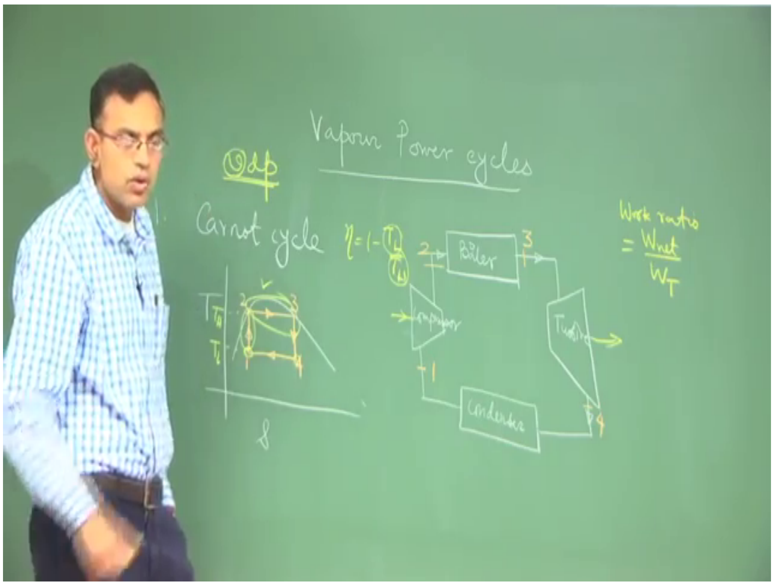

So, we will start with something which we call as vapour power cycles. The whole idea of dealing with vapour power cycles is to understand the thermodynamic aspects of power generation in a thermal power plant. And let us try to understand through the following analysis of cycles. First we consider an idealized cycle which we have discussed earlier; and for any thermodynamics cycle that is like a benchmark with respect to which we compare the performances of other cycles. And this is the good old Carnot cycle.

So, imagine that there is a boiler. So, remember that every cycle may not always have an engineering architecture to represent its functionality. At the same time, if we refer to an engineering architecture or an engineering block diagram which connects various components of engineering system to constitute the various parts of the practical cycle, it gives us a good practical perspective of where the cycle can be applied.

So, for understanding the Carnot cycle, bringing the boiler or turbine or condenser or compressor to a purview is not always necessary. You can have an abstract Carnot cycle where you have two reversible adiabatic and two reversible isothermal processes, but if you bring that in perspective with respect to certain physical devices connectivity's of physical devices, it explains the context much better.

So, you have a boiler. From the boiler, so in the boiler what happens? You transfer heat, so that water gets converted into steam or water vapour. Then it enters a turbine and it expands in the turbine. Once it expands in the turbine, the thermal energy of the fluid decreases; and the expands of this decrease thermal energy, the turbine get some mechanical energy, and the turbine blade start rotating. So, that is how thermal energy is converted into mechanical form of energy and subsequently to electrical form.

Then we have a condenser. The purpose of the condenser is that the steam condenses from a mixture of saturated liquid vapour, mixture of liquid and vapour to a state where it is more it is closer towards the saturated liquid. In other words, the liquids the mixture of liquid and vapour gives away heat to a fluid and then it starts condensing. So, it gives away heat typically to a fluid which is a cooling water. And I will discuss later on what are the practical perspectives to it. Then here the pressure is much lower than the boiler. So, to bring it back to the state of the boiler, you require a compressor.

So, let us try to imagine that there is a Carnot cycle like this, and plot it in a temperature versus entropy diagram. So, a Carnot cycle in a Ts diagram looks like a rectangular box. And let us draw that rectangular box, we have discussed this earlier. So, how does it look like a rectangular box that, I am not going to discuss over again, but briefly you have the steam entering the boiler, sorry water entering the boiler and getting converted into steam. So, from 2 to 3 is the process in the boiler, then this is a reversible isothermal process because the fluid here is a simple compressible pure substance. So, its phase change occurs at a constant temperature. Therefore, a isothermal process is clearly achievable between stage 2 and 3, this is not at all in practical.

From 3 to 4, you are having a reversible adiabatic expansion in a turbine. So, this is 4. From 4 to 1, you have the condensation process. So, now, if you present the cycle to somebody, the first question that will come is that so many people say that the Carnot cycle in a practical consideration is not visible, but here you are showing that there is a Carnot cycle based on a power plant may work. So, where is the fallacy? We have discussed about this Carnot cycle, but we have not discussed the practical feasibility of this side, and let us discuss about that.

So, practical feasibility wise 1 to 2, sorry 2 to 3 is ok, 3 to 4, what is the problem with 3 to 4, first of all achieving a reversible adiabatic process is difficult. But even if you achieve that you see that as the steam is expanding, the state 4 is coming more and more away from the saturated vapour line, that means, if you expand it more and more, you will see it goes closer, it goes closer and closer to the saturated liquid line in the liquid vapour dome, that means, the liquid fraction in the steam that comes out of the turbine maybe quite high. What it can do? It can erode the blades of the turbine and that can be pre detrimental for the performance of the turbine.

So, turbine blade erosion is a very, very practical problem. And because of such problems, you cannot really go on expanding the state from say 3 to further and further down. Had you been able to go to lower and lower temperature, it would actually been better so far as efficiency is concerned, because efficiency of the Carnot cycle is 1 minus T L by T H; and this is T L and this is T H. So, point 4, had it got lowered; that means, T L would have been lowered and had T L been lowered efficiency would have been higher, but practical considerations do not permit that.

However, the most impractical part of these Carnot cycle based thermal power plant is that suddenly stopping the condensation at the point one to achieve a Carnot cycle. So, in a practical plant, how would you know that where is this point one. So, it is very, very difficult, I mean you cannot have a physical mechanism by which you suddenly stop the condensation at 1, so that is another practical point. The other important practical limit is the 1 to 2, this compression it handles what it handles a mixture of liquid and vapour. And it is quite a power consuming process to compress a mixture of liquid and vapour.

First of all the compressibility of the liquid and vapour they are different, so compressing their mixture as a whole is difficult and because there is significant amount of vapour in the mixture remember that for a reversible process steady flow process the work done is v dp. So, the compressor work is v dp because there is significant vapour in this, this is not completely liquid. So, vapour has a high specific volume. And therefore, the work input to compress the vapour component at least is quite high.

So, why do you bother so much about the work input? You bother so much about the work input because the network is the difference between the turbine work output and compressor work input. So, if you require large compressor work input, then the net work output decreases. And how much it decreases, it is given by particular parameter called as work ratio, defined as the network by the turbine work.

So, in practice, you want the compressing device demanding as less amount of energy input as possible. In other words, you actually want the work ratio to be as close to 1 as possible. It will definitely be less than 1, but closer to 1, the better it is. So, here because of mixing of because of compressing this liquid vapour mixture, there a practical difficulties as well as there is a reduction in the work ratio. So, we have identified various shortcomings associated with the Carnot cycle, but this despite the shortcoming the Carnot cycle give certain basic understanding that if you decrease T L and if you increase T H, you could increase the efficiency of the cycle.

So, in reality if you do not have a constant T L and constant T H that is constant temperature of heat rejection and constant temperature of heat addition. You could work out an average temperature of heat addition and average temperature of heat rejection, and replace this in instead of the T L and T H; you write average T L and average T H. I will define that so called mean temperature of heat addition and rejection later on. And we can clearly see that lower the mean temperature of heat rejection or higher the mean temperature of heat addition more will be the efficiency. So, now given that the Carnot cycle is not very much practically feasible. We will study a variant of this called as Rankine cycle.

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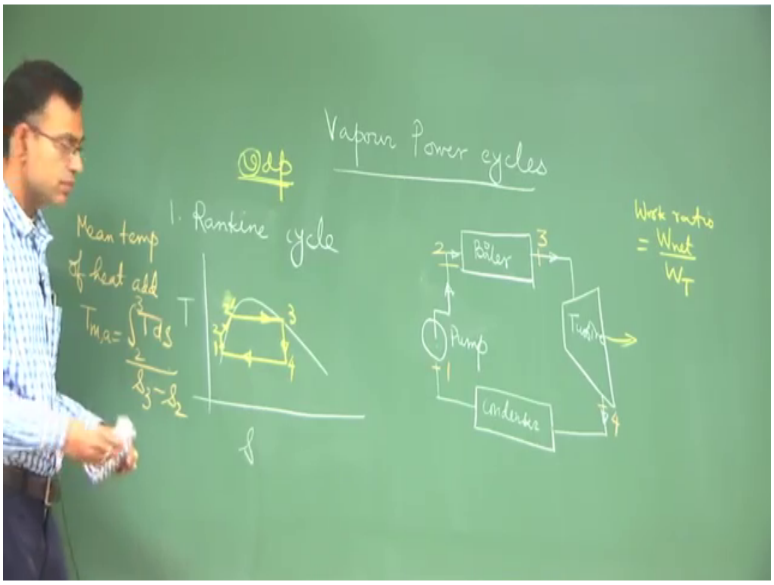

So, I will try to draw the Rankine cycle in the T s diagram first, and then we will change the hardware to accommodate for that. So, in the Rankine cycle, what we do is, we have similar process like the Carnot cycle, but we replace the compressor with a pump, and the pump net generally will handle only the liquid. So, the abrupt stoppage of the condensation process from 4 to 2 in between somewhere which was there for the Carnot cycle. Now that is replaced by a complete condensation from 4 to 1. This is the major difference between the Rankine cycle and the Carnot cycle.

So, from 4 to 1, 1 is not in between, 1 is at the saturated liquid state. And then from 1 to 2, there is a pump which pumps it to pressure to the boiler pressure. So, what it does is that it achieves something very interesting, it replaces the compressor with a pump which consumes much less power than the compressor. So, that is the game that the pump handles only the liquid, it does not handle the liquid plus vapour mixture. So, operation wise also pump is much more convenient than a compressor; power input wise also a pump requires much less power input because in integral v dp the such the specific volume which comes into the picture that is much less for a liquid as compared to a vapour, but in reality you know life is always like a balance.

So, when you gain something you also lose something. And what is that we lose here instead of heat addition at a constant temperature, now the heat addition starts from state 1 to state 2, sorry state 2 to state 3. So, earlier the state 2 was here, now the state 2 is here. So, from 2 to 3, it is not the entire heat addition at the T H previous T H, some heat addition from 2 to 2 prime is at a temperature lower than T H. So, the average temperature of heat addition which is defined as this mean temperature of heat addition. So, it is defined as the area under the Ts diagram from during the heat addition process. So, integral T ds from 2 to 3 divided by the change in entropy.

So, as if had it been a constant temperature process, what would be the equivalent constant temperature; and here that mean temperature of heat addition will be something between the temperature at 2 and temperature at 3. Say this is the mean temperature of heat addition. So, because the mean temperature of heat addition is less than what would have been there had it been a converse cycle clearly the efficiency will be less. But efficiency is not everything in life, you also have to see other practical constraints. And regarding replacing the compressor with the pump, the practical advantage of getting a high work ratio is very much there.

The reason is that the pump consumes very little work, so that the net work by turbine work is very close to 1. You can make it closer and closer to 1 by making other or by taking other measures but efficiency wise we have to sacrifice. So, this sacrifice in efficiency can be compensated by other arrangements. And we will make those arrangements subsequently. So, this is an ideal Rankine cycle so called ideal Rankine cycle, but you can have a Rankine cycle where the heating in the boiler does not stop at state 3. And the heating continuous in the superheated region at the constant pressure which is the boiler pressure, so that is called as Rankine cycle with superheat.

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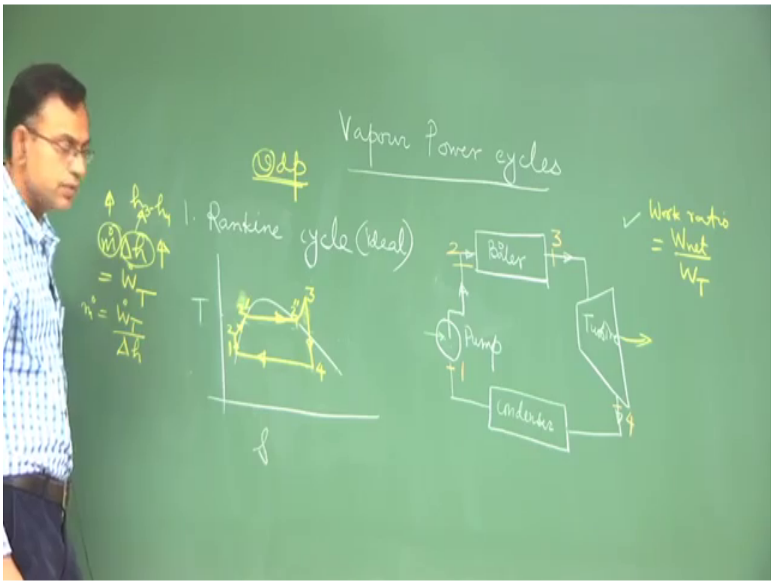

So, I will draw the Rankine cycle with super heat in the same Ts diagram to explain you that what happens with the super heat. So, which superheat you will continue with heating in the boiler up to point 3. And then if you make a reversible adiabatic expansion, instead of the point 4 here, you will have the point 4 towards the right. So, what are the advantages with this? Clear advantage is that the mean temperature of heat addition again had gone up which had gone down because of this part, by the way in the real power plant architecture the points 2 to 2 prime, this takes place in a zone called as economizer, 2 prime to this one say 2 double prime this takes place in the so called boiler, and 2 double prime to 3 this is called as super heater.

So, what we loosely called as the boiler part has essentially three sub parts, economizer, boiler and super heater. Now, this point 4 being earlier it was much more away from the saturated vapour line, now it is closer to saturated vapour line. Earlier it was here, now it is here. So, when it comes closer to the saturated vapour line, then what happens, then the turbine blade erosion problem is also reduced and that is a big thing because if you reduce the turbine blade erosion problem, then the blade life is increased, and manufacturing turbine blade this one of the costliest things for setting up a thermal power plant, so that would make a lot of relief.

Not only that the enthalpy drop between the previous start point and endpoint of the turbine and the present enthalpy drop. The enthalpy drop now with superheat is much higher that means you get much more specific enthalpy drop across the turbine. If you get much more specific enthalpy drop that means you require less amount of steam consume to get the same amount of power, because the mass flow rate into the enthalpy drop is the power output of the turbine W dot turbine.

So, if you have greater delta h, delta h is here h 3 minus h 4, then you have less m dot, so m dot, so m dot is W dot turbine by delta h. So, this is called as steam consumption at the rate of steam that needs to flow across the device. So, more this is what is it is because you have to burn more coal or any fuel to get a particular amount of power. If you get sorry you have to run more fluid in the not the coal I have mistakenly said that, you have to basically learn more fluid more working fluid in the system, because m dot is the working fluid which is running across the system. So, have to run more working fluids to get the same amount of power ok. So, this is steam consumption not fuel consumption, by mistake I have told fuel ok.

Now, the question is that superheat gives all good effects right. It increases so three positive effects. One is increasing the efficiency; the second is reducing the turbine blade erosion problem; and third is reducing the steam consumption ok. So, I mentioned about the fuel, and the fuel is indirectly related to the steam consumption, because more is the steam consumption more amount of fuel you need to burn, because for converting from liquid to vapour, the amount of steam the amount of fuel is required is proportional to the mass of liquid that is being converted to vapour, so that is what I am coming.

So, I have mentioned about three points which are very positive. The question is had it been so you should have increased the temperature to temperature of the state point 3 higher and higher, because had your point 3 been here you would have got more efficiency. Had your point 3 been here, you could have got even more efficiency. And not only that the turbine blade erosion problem will also be much less everything will be positive, but we do not do that. The constraint is not thermodynamics, but material that turbine blade has to be good enough in terms of withstanding the very high temperature at that state.

So, the maximum limit of temperature is restricted not by thermodynamics constraints, but by material constraints. By material constraints, if you go to higher and higher temperature, although you will get greater and greater efficiency, but the material of the turbine blade may fail, so that brings us to a perspective, where you are not able to go to a very high temperature which you wanted. Had you been able to do that, it would have been a delight. If you cannot do that, so this is Rankine cycle with superheat, you simply super heating may not work.

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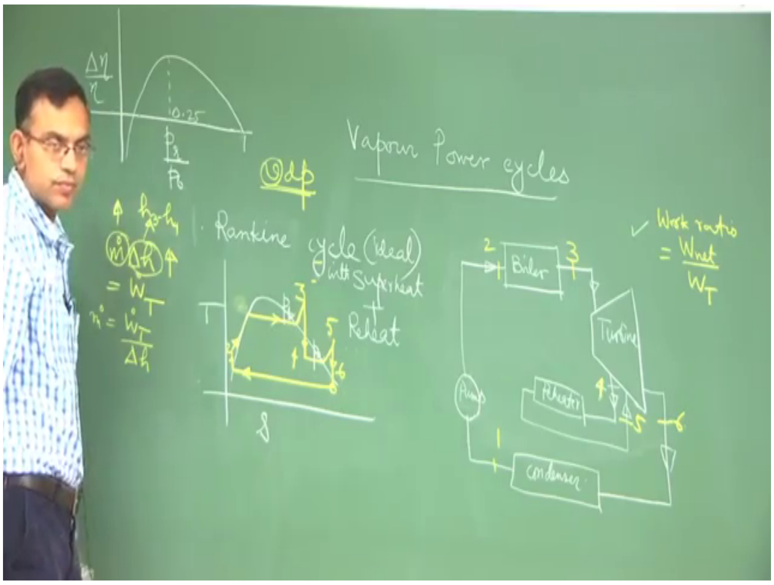

And then to derive all these advantages you consider, so we considered Rankine cycle, ideal Rankine cycle with superheat, and we will add another factor which we call as Rankine cycle with superheat and reheat. So, what is reheating? So, what we will do is we extract the steam not at this state, but at a somewhat intermediate pressure state, say this state which state 4, then we heat it in the reheater, this is physically a reheater.

So, this is called as reheat, but you know it could be integrated with the boiler itself. So, you can in principle just to make a discernible architecture. Let me draw a phase diagrams, so that it is easier. So, you can have a boiler a turbine there is a extract from the turbine it goes to a device which is called as a reheater which may be physically integrated with the boiler, but you may just for clarity show a reheater like that. And then that reheated steam enters the turbine, and then from the turbine the exit state comes.

So, you have so we start with the Ts diagram, by drawing the Ts diagram, I will not draw on the same diagram again and draw phase diagram. So, boiler 2 to 3; boiler to turbine - expansion, the first level of expansion from 3 to 4; then at that intermediate pressure, heat is again added in the reheater. Here we are showing it as a separate block just for clarity. And the reheater itself may take it to a super heated state, but to what temperature maximum. So, if we considered superheat plus reheat, then your 0.3 could be beyond the saturated liquid saturated vapour state so some here may be. So, this is 0.3; this is 0.4.

So, what I mean is that now from here when it goes up maximum temperature could be this, because you stop heating beyond this for the material constant. When you reheat, you cannot heat it beyond this. So, you go from here to a point 5, where it enters the turbine. And then from 5 it expands in a turbine 5 to 6. And from 6 to 1, in the condenser, so this becomes your point 2 and you have the process like this. So, this is the Rankine cycle with reheat and superheat. You could have multiple stages of reheat, but here in this diagram we are showing only one stage of reheat. Remember that had the turbine blade hypothetically not have any material constraint, reheat is not necessary, alone superheat would have done the purpose because of separate attachment and extracting the steam from the turbine in between and heating it again all these are problematic.

So, we are taking that problem because we have no way of heating this further in a single shot. So, we are heating it in a sequence of shots, in this way one significant gain that we are getting is that we are going more and more closer to the saturated vapour line that means so this is the 0.6, that means, the 0.6 is having much closer existence to the saturated vapour line, and the turbine blade erosion problem is less.

What about the efficiency with reheat? See your average temperature of heat addition is the average temperature of heat addition during the super heat part plus the average temperature of heat addition during the reheat part. So, these two effects together can actually have a higher mean temperature of heat addition as compared to without reheat or could even have a lower mean temperature of heat addition as compared to that without reheat.

So, if you, so this is this pressure is called as reheat pressure, and this pressure is may called as the boiler pressure. So, if you make a plot of the change in efficiency with respect to the original efficiency as a function of the reheat pressure by boiler pressure, you get a curve like this. This is around 0.25, from practical thermal power plant data. So, you actually have a deduction in efficiency if the reheat pressure is very low, because if the reheat pressure is very low then the mean temperature of heat addition because of low reheat pressure you also have a lower temperature at which heat is added that will reduce the overall mean temperature of heat addition. And the efficiency instead of gain has a fall; beyond that the efficiency starts increasing, but you get the maximum benefit when this is around 0.25.

What is this? So, zero benefit when the reheat pressure is same as the boiler pressure, that means, it is no reheat. So, this value is 1 ok. So, to summarize we have discussed about Rankine cycle, simple Rankine cycle, Rankine cycle with reheat with superheat and with reheat. What we have not discussed is what is the role of the condenser in the Rankine cycle, and we will take up in the next lecture.

Thank you very much.