Engineering Thermodynamics
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Week-10
Lecture-43
Vapor Power Cycle

Welcome to lecture 1 of the Vapor Power Cycle. Till now, we have talked about the Gas Power Cycle in previous lectures. In which, all the processes involved in the cycle, the working fluid always remains in the gas form. Now we will discuss the Vapor Power Cycle, in which the working fluid considered can be vaporized or condensed. This means that it can remain in the gas, vapor form or liquid form. And in this way, we will utilize this process in the form of alternative vapor and condenses. And in particular we will talk about the basic ranking power cycle. The power cycle we will use, the vapor power cycle, the working fluid remains steam. Will it be vaporized or condensed? And you will ask the question, why is it steamy? It is easily available and is low cost. It has a high enthalpy of vaporization. You can give more heat when you are changing the phase. This becomes an important reason to use it. Steam will be used in the vapor power cycle. It will be a working fluid. Now the question is that when you take working fluid in a way that can be condensed, then what ideal cycle should you take in the form of a model? As you have seen, the Carnot cycle is the most efficient cycle if it is taken in a specific condition of 2 temperatures. But in this case, if the working fluid is steam If you want to apply this to Carnot principle, then you will get this form. In which you will get 1-2 The fluid is evaporating. This is your temperature versus entropy plot. Here it is in the liquid. Saturate liquid. And this is your heat input. And this is delivered to you in a saturated vapor. Then it expands. Isentropically. So, it is in the two-phase region. Then it is condensed. This is 3 to 4. This is also isothermally. and then 4 to 1 is isentropically compressed in the compressor. But is this cycle that we have just seen, this is the Carnot cycle, so can we use this in the dome, which is called a saturated dome, it is in the two-phase region, is it suitable? Practically, it will be very difficult to see, because you will have to work in the two-phase region in such cases. So, it is not very efficient, it limits it, if you are in the two-phase region, you have to heat transfer. This means that the Qin is fixed. Because this cable will only work on the 2-phase limit. It will become delta H or Hfg. So, this limits the heat transfer. This means that it has limited efficiency. Because your Qin is fixed. So, it has limited efficiency. The second reason is that your isentropic expansion This one, you see, the quality will not be 100% So, this is 90% less, so what is in this, it works as a turbine, expansion means turbine This is also a big problem because it is difficult to handle low quality steam. This is also problematic. Second is that compression 4 to 1. This is also a problem because you have to work in two phase regions in compression. This is also a problem. So, Carnot Cycle is not an ideal approximation of the actual device, and it is not realistic. So, we use this model. Can we do it up and down? There are more problems with this model. It was not practical. So, to approximate it, we have to think of something else. So, for this comes the ranking cycle. So, ranking cycle is an ideal cycle in your vapor power cycle. It tries to keep the temperature of the canola high. So, you have to keep the temperature high. So, it avoids these issues. It avoids the ranking cycle. You have to superheat the boiler. And complete condensing. That means it is complete condensing. So, if you want to use Carnot cycle, you have to maintain this condition. And these are very impractical conditions. That's why ranking cycle avoids this. It removes it from the cycle in a new way. So, let's take a look at what we do in the ranking cycle. The idea behind the ranking cycle is to use turbines, pumps, condensers, boilers, etc. You have to use these four devices in any power cycle. So how can we make it? So, there is a simple modification in this. First, this point, the boiler. Let's say, it takes up to 2 to 3. So, it's not like 3 ends up on saturated vapor only. Here, what we do is, it ends up at a higher temperature. So, why do they supply so much? That these 2 liquids, which is supposed to be here, we take it from 2 to 3. So, from 2 to 3. and this is the pressure, this is the P boiler pressure we put this much heat on the boiler pressure then from 3 to 4 expansion happened and at this point the quality is close to 100% so it brings the lead very close to the saturated vapor so this is your turbine work and from 4 to 1 complete condensation has happened which is on the liquid, so this is the saturated liquid and pump 1-2 is used to bring the pressure to higher pressure this is lower pressure and this is on P Boiler So what you have done is that you have avoided first you have done this in a complete dome which they were doing and now you can put more Qin second is that you wanted to achieve complete condensation but you don't have the requirement of this condition that both 1 and 2 are at a higher temperature that means 4 to 1 you have to compress at a higher temperature now there is no requirement So, the way you compressed the 1 to 2, you did compress it, but not so much that it took you to the supercritical condition. So, in this way, you made the cycle effective. And since our purpose is that the work is power out, net power out is the area under the curve, so eventually it is not so efficient, in fact, it is more efficient, so it meets our purpose. So, in the ranking cycle, you have 4 processes. 1 to 2 is the isentropic compression in a pump. Second is the constant pressure heat addition in a boiler which is 2 to 3. This one is 2 to 3. Then the isentropic expansion in a turbine means that 3 to 4 will work as a turbine. It will work isentropically. Since these are ideal conditions, we are calling them ideal cycle and ranking cycle. Constant pressure heat rejection, here you have heat rejection 4 to 1, where condensation is happening. So practically what will happen is that the saturated liquid will go into the pump. and compress it so that the pressure will be applied to the P boiler the pressure of the boiler will be fixed P will be fixed on P boiler and when the water comes out of the boiler, the superheated will come out of the boiler and when it expands, the pressure and temperature will drop and it will reach the 2 phase region and it will reach the saturated liquid vapor so here we have 2 phase saturated liquid plus vapor and comes out on saturated liquid. So, this is your ideal ranking cycle. Now you can apply energy balance on this. Since these are steady flow devices, you can apply energy balance on every steady flow device. Assume that kinetic energy potential changes are negligible. So, Q in minus Q net in minus Q net out will be equal to delta H. And you can say that Q in plus Q out plus W in minus W out. So, your net is in. It is a plus. It is equal to change in. It is enthalpy. You can use this on any device. If you talk about pump. If your adiabatic is in pump. Q is equal to zero. So, W pump in will be a simple change in. Enthalpy will be H2 minus H1. Okay. In this way boiler. In the boiler, there is no work. The Q in is simple. S3 minus S2 Because Q out is not there. In the turbine, Q is 0. So, W turbine out is equal to S3 minus H4. And in the condenser, again there is no work. Only Q out. So, Q out will be changed to enthalpy. H4 minus H4 So you will take this as a balance of each device. You will take it out through the energy balance. Now this is the ideal condition, you can also calculate the thermal efficiency by definition. The thermal efficiency of the network is divided by Qin, which is 1 minus Qout by

Qin. Now in this you can calculate the work of the network Qin minus Qout is equal to turbine out minus Wp in. You can also calculate the back ratio in this. We discussed the ratio in the last lecture. In the case of gas turbine cycles.

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i$$

Pump(q=0): $w_{pump,in} = h_2 - h_1$

Boiler(w=0): $q_{in} = h_3 - h_2$

Turbine(q=0): $w_{turb,out} = h_3 - h_4$

Condenser(w=0): $q_{out} = h_4 - h_1$

Thermal Efficiency

$$\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

$$w_{net} = q_{in} - q_{out} = w_{turb,out} - w_{turb,in}$$

Now, let's try to understand this concept through a question. And apply this concept in a question. But we will take the ideal ranking cycle only. and we are saying that it has a steam power plant which operates on a simple ideal ranking cycle which we just discussed and steam enters the boiler at 3 MPa in this condition, in saturated liquid condition and comes out at 350 degrees Celsius and at 3 MPa which is more in turbine and it expands from turbine to 75 kPa and comes out at state 4 which is in saturated liquid vapor and it condenses on this pressure but it condenses on the liquid saturated liquid vapor. This is the saturation liquid plus vapor. It is a two-phase region. Now I have to tell you how much the thermal efficiency of this is. So, this is your Qe and this is your Qout so how will we do this? Basically, we have to take out the flour. And Q in will be H3 minus H2 And Q out will be H4 minus H1 So you know this So you have to find this And how will you find this? You will find this from the steam table So first of all, if you can get all this information from the steam table Then everything can be done easily So now let's try to see from the steam table Let's start. First, Let's talk about the one. This is P1 75 kPa. And this is saturated liquid. You have to extract all this data from the table. Let me list the tables that I have to use. Table A5, A4 and A6. These are the steam tables. From here you will get H1. kilo Pascal. And this is V1 which is VF at 75 kilo Pascal. This is your 3 MPa fan. Let's pass 3MHz to state 2. Note that this is a pump, so we are assuming that it is isentropic. So S2 is S1, its entropy is constant. Note that if you balance the work, the work that we are pumping in, this will be S2 minus S1. If you balance it, this is working and according to S2 flow, it is S2 minus H1. And we can consider this pump as V1 delta P. We have derived this before. So, this is V1 P2 minus P1. So, we know the pressure, this is P2. So, we know P2, P1 and we have taken out V1 from here. So, you will get this expression. So, this work comes out as 3.3 kJ per kg. So, this way you will get H2 from here. So, you have H1 from the table. H2 came out from here. H1 came out from the table. Now we come to state 3. This is your outlet. The balance that came out is 3 MPa. 350 degrees Celsius so from here you will get H3 will be found from table, from superheated table Okay, superheated table will be found This is your Data is given in tables, so you can insert it, so you also got H3 We will go to state 4 which is here, which is at the exit of the turbine. Before the condenser. So, this is state 4. Here you get the condenser pressure which is passing 75 kg. And we are saying that this is already a saturated mixture. Saturated liquid plus vapor mixture. The turbine is also isentropic, which means S3 is equal to S4. Now you can extract from here, S4, which is a saturated liquid, will be S4. What will be the quality of this? It will be S4 minus Hf divided by Sfg. You can extract from here, so this will come from your table. From the saturated table, you get this information at 75 kPa So you will get it from here because you already know the S4 value from here and SFG will be found from the table So this x4 comes out here 0.8861 From here you can get h4 So, Hf and Hfg you can get at 75 kPa and X4 you can use here. So, from here you will get H4. Now you have Enthalpy, you have Enthalpy in all conditions. Now you can easily extract Q-in. Q-in is on boiler. 3 minus H2 and Qout will be H4 minus H1 So you can get your Qin and Qout from this Which is 2728.6 kJ per kg and this is 2101.8 kJ per kg And the question was asked from us that how much is its thermal efficiency Q out by Q in. So, from here it comes out. 0.260 or 26%. So, these are the questions. Now here we have done it like this. We can also do it with Wnet. Wnet is also available to use. Out minus Pump in If you remove that, then this is your Wnet W turbine out which is H3 minus H4 This is your H3 minus H4 This is your Pump you have already removed Which is H2 minus H1 So from here this is Wnet Even if you do this, the same value will be obtained. So, in a way, ETA says that 26% of your heat is converted into the network. 26% of the heat that comes into the boiler is converted into the network. Now the back ratio is back work ratio W in by W out means that the pump you are using and the turbines you are removing, it is approximately 0.004 which is 4%. Now that is why the back work ratio of steam is very low. If you remember, the gas turbine we discussed last time, the back work ratio of your vapor is 40-80% whereas here it is 4% that's why we prefer it more so that's why it is very less and that means you have to use very less percentage to run the pump another interesting question is if you consider that this whole vapor If you had run the power cycle on the basis of Carnot, then what would have happened? So, if we assume thermal efficiency according to Carnot, operating between T minimum and T maximum So we write it as T minimum by T maximum which we call T zero or low divided by T high So we write it as T minimum by T maximum So T minimum is your temperature Notice that T maximum is 350 and the corresponding temperature of the T-minimum is 750 kPa so if we look at that if we put the value of this then it is 1 minus 91.76 plus 273 Kelvin and this is 350 plus 273 Kelvin so this is 0.415 so note that what we have done is We can see that the Carnot cycle has a lot of efficiency. And our ranking cycle efficiency is less than the current one. It is 26% and this is 41.5%. So, if we were to go according to Carnot then this limit is too much so what is the reason for this? So, one big reason is that Carnot outside the cycle its irreversibility is also neglected.

In Rankin, outside the cycle which is our furnace and the temperature difference between the gas combustion and the Carnot is very high. The difference between the Carnot and the ranking cycle is only because of the temperature difference between the gas power cycle and the steam power cycle. So, the irreversibility associated with it will be more compared to your gas-based combustion. So, in general, you will notice this. So, the efficiency of the ranking cycle is 26% and the Carnot base is 41.5%. So, what is the reason for this? So, Carnot is totally reversible. It will be externally reversible. Whereas, if you talk about ranking, the ranking is externally irreversible. The irreversibility of the pump is quite high because the temperature difference between the steam and the gas is very high due to which the irreversibility is high. Let's move forward. The actual power cycle will deviate from the ideal ranking cycle. So, entropy will not be constant. If we compress the liquid from saturated liquid in 1-2, then 2 will shift to higher entropy. And due to this, higher temperature will also come. So, it will go up on this line, on this particular pressure. But in general, pressure will drop in boiler also. and also in condenser, so that's why we give dashed line in actual cycle Second, your turbine is also connected to irreversibility so that's why your actual line will not be this it will be like this, or it will not be this, it will be this so that your entropy will increase So if we ignore the pressure drop of this then suppose that this one will be after coming out of condenser so here condenser and the condenser outlet will be 1 to 2S which we expect is isentropic but because there is irreversibility with the pump it will land here which will be actual note that it landed here in the isolator and it operated at constant pressure till reached 3 and after 3 the boiler came out of the exit at this pressure and the temperature became high Now it expands on turbine But it is not an isentropic expansion And the errors are connected here So its entropy will increase and land here So its eta According to the second law of efficiency Eta power of Ws Isentropic work divided by Wa And its Wa divided by isentropic So eta, we have already discussed We can use it If you know Eta, you know that H2Ss minus H1 is change in enthalpy across pump's one end to other end but in isentropic condition divided by actual condition same second law of efficiency of turbine is Eta will be H3 minus H4 which is actual which is at end point of turbine, exit point and entry point divided by the same difference in isentropic condition,

PUMP: $\eta_p = \frac{w_s}{w_a} = \frac{h_{2s}-h_1}{h_{2a}-h_1}$

Turbine: $\eta_T = \frac{w_a}{w_s} = \frac{h_3-h_{4a}}{h_3-h_{4s}}$

We will take this. The problem we had done earlier, we should consider that the turbine we used, the pump we used, its efficiency is not 100% its isentropic efficiency is 87% of the turbine and the isentropic efficiency of the pump is So, this is the efficiency with respect to the ideal condition. So, from here you have to find out the total thermal efficiency of the total cycle and net power output of the plant if the mass flow rate is given. So, these are the two things that we have given. So, we will assume that there is a steady operating condition, kinetic potential energy, negligible changes are happening in it. So, now the question is how to do it? So now because the pump is W-Pump In, if we show the actual, what will happen is, notice that the pump, W, if we see, in, then in will be your S2, and we know that eta P is this So S2A minus H1 is what? S2s minus H1 divided by S2A minus H1 This means You have given that eta Wpump in We can write it as well. h2s minus h1 divided by eta p. In isentropic conditions, you call it Ws. Which will be pumping in isentropic conditions. We can write it in this way also because we can apply it in this condition V∆P, eta P This means Vp2 by p1 eta P So you will get it from here We know V, how do we know V? Because we have written V as V1 And V1 is Vf at 38 degrees Celsius So you will get this information from here, so this is the result of pump in 19.0 kJ per kg. Now let's talk about turbine workout. So, this is the W turbine out. Again, see the definition. The actual turbine out will be eta t multiplied by Ws. So, this is your eta t Ws turbine. The turbine of the ideal condition. In this you can say that this is H6 and H5. So, this is H6. minus H5. So again, you can get this information from the table. This is the table. The actual condition is 10 kPa saturated mixture. So, this is H5 instead of 6. This is actually H5 minus H6, i.e. in isentropic condition. So, you can get this. This will be the same as we used earlier. We used 2115 but we have not added any values in this. This is the turbine output. Note that we have differentiated the diagrammatically. The actual losses are shown but this is the part we are concerned with. Now we need the boiler information. because we have to extract the Qin and ETA so what is the boiler? boiler is H4 minus H3 so we will get this easily then we have to extract Wnet is WT out minus W pump in so we extracted this just now, so we got this also got extracted for extracting ETA, you have Wnet divided by Qin. We have noticed that only the values wtout and pump in are not in the isentropic process so the values will change. We are measuring that, and we have also taken out the value of h5 from here. W in and Q in will give 36.1% Power produced by this plant will be W net which is M dot into W net This is the data You have to multiply this in mass flow rate That's why, So This is the thing We have solved it like this. We have taken the main data from here. This is the schematic diagram of the product. It was given that your pump is working at 85% Isotropic efficiency turbine is working at 87% And the rest is given to you. And of course, we have to use the table. So we had to get the thermal efficiency which is Wnet divided by Qin So to get Qin we did simple H4 minus S3 To get Wnet we had to get turbine out minus Wp in To get turbine out we have to get actual 15 minus this but eta is given So from here you got a lot of information on the basis as we did here So, you have to use all this information in your notes, like H5 So, H5 information was known And H6S was to be used Because if we look at the actual information We have not given the rest of the information If we talk about the actual information So, if we talk about H6X So, you know this information Because you know that it is asymptotic S6 Is equal to S5 So, in this acid-tropic condition, you will get this. And H5 is known to us already. So, with this information, we can calculate this with the alarm. And you will get to practice a lot in the examples given to you. So, naturally, there should be no problem. So, this case is not exactly what we have seen here. If you pay attention, there are 2-3 things that are different. We have changed the efficiency and some conditions. The idea is more or less the same. The pressure has also changed. The idea is more or less the same. But you have to understand that the process is similar. Wherever you get inefficiency or value, you have to use it. where you have a table, you need to use it because to use the table you need complete information where there is no complete information you have to see what is available like in this case you had a brick that's why we used this otherwise if we had all the information then we would have done H6 minus H5 and we would have got the actual turbine work but H6 we can't get it out So, we had to adopt this strategy in this form because we have been given the eta. So, you will have to solve some things like this. Let's move ahead. An important question arises that how can you increase the efficiency of the ranking cycle? To increase the efficiency of the ranking cycle, you have to increase the area under the curve. One way is to reduce the pressure of the condenser, then you will get this additional area. The second option is to shift the temperature and superheat the oil. As I have done here, you will get this additional area. And third is that you increase the pressure of the boiler. In this case, the T average increases. So, by increasing this, this will increase, but since it will shift to the left, then this will decrease. And in that, moisture content will increase. So, in this, of course, competitive, no matter how much, how much, one is your value will be more but you will have to struggle a little bit operationally. As I said, it will be a problem for the operation if you increase the boiler temperature. But now it is majorly handleable, it is done easily, there is no problem. And now the pressure of the major boiler, which used to be 2.7 MPa, is now 30 MPa. So, the pressure has increased so much, so naturally this increase is preferred in the industry, that you increase the pressure. So, nowadays, the maximum power plant sometimes works super critically, it means that it will work like this also, it will run straight like this, supercritical means straight from here to here, so it will work like this also. And its thermal efficiency is especially 50% if it depends on fossil fuel play. But when we use it on nuclear plants, we do it at low temperatures. For safety reasons, because of this, its efficiency is low. And fossil fuel, petrol, coal etc. On all these things, your efficiency is up to 50%. So, I hope you have understood the purpose of this ranking cycle. How this ideal is made, ranking cycle, The concept of power cycle is where the working fluid is steam which is sometimes liquid and sometimes vapor depending on the process and this alternative phase change takes the form of a cycle and we will understand how to use it under the dome and how to use its area under the curve and how to use the parameters to increase its efficiency So I hope you got the clarity. We have understood to some extent from the example of the medium. But there is a little subtleness, a little trick, you will have to pay attention to it. And the exam, in general, the questions of the exam staff, if you take coffee, then you will have to understand it fundamentally. So, the questions of the example will be focused on this step, that you can practice. In the next lecture, we will talk about the reheat and regenerative power cycle. And then we will take this uncle ahead. Till then, I bid you farewell and will meet you in the next lecture.