Steam Power Engineering

Prof. Vinayak N. Kulkarni
Department of Mechanical Engineering
Indian Institute of Technology-Guwahati

Lecture - 15
Low Temperature Power Cycles

Welcome, we have seen till time that we can use the Rankine cycle for electricity generation and also we can use the Rankine cycle for the effect where we are actually having waste heat or we are having the heat to be supplied where steam is the source of the high temperature, constant temperature source. So the examples were bypass turbine or the back pressure turbine and also electricity generation we had seen.

Then we had seen that there are some properties of ideal fluid. Looking at those ideal fluids we had come to a conclusion that there is need of binary or tertiary fluid cycles. In that case we had seen that okay we can club two Rankine cycles together and if we club two Rankine cycles together then we will have higher efficiency of the coupled cycle.

But we have also seen in last class that the Rankine-Rankine cycle coupling is a problem since it has issues like high cost and the leakage. So the most possible way to couple is coupling of Rankine cycle with Brayton cycle. So we had seen what do we mean by Brayton cycle. Further we are going to see in this class that how we can make use of Brayton cycle and Rankine cycle in coupling and also what are the possible low temperature cycle.

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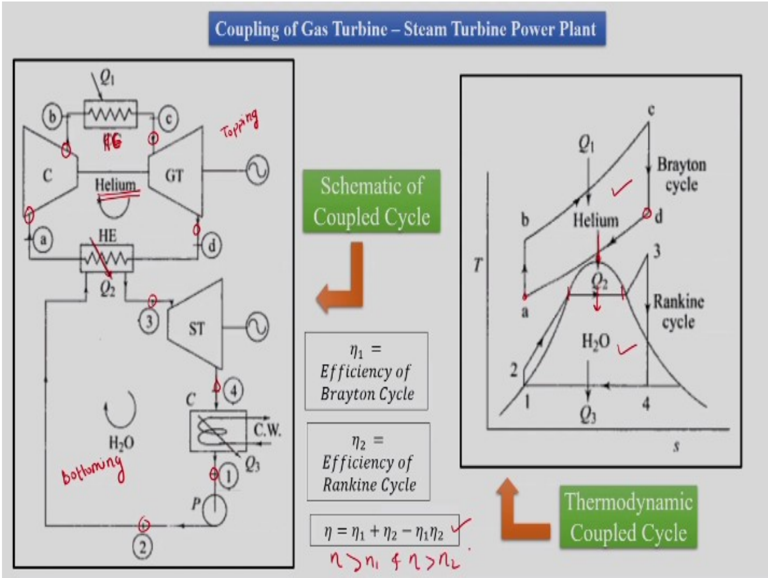

So coupling of gas turbine cycle and steam turbine cycle. So we had seen in last class that okay, we will have gas turbine cycle at the topping cycle. So this is our topping cycle and this is our bottoming cycle and in this topping and bottoming cycle, we have compressor from a to b where it is increasing the pressure of the gas which is the gas used in the gas turbine cycle.

Then we will have heat addition into the, we will have heat addition into the heat exchanger. This is heat exchanger. So in the heat exchanger, we will add heat. Once heat is added into the heat exchanger, then we will have expansion in the turbine and after expansion in the turbine the gas turbine cycle will lose the heat.

And this heat lost will be taken by the water which is pumped first to high pressure then it will take the heat into the boiler which is necessarily the heat exchanger for gas turbine cycle and then we will have expansion in the steam turbine. Then we have condenser which will reduce which will remove the heat. So having said this, this is the schematic we had seen.

And then we have this as the T-s diagram for topping and bottoming cycle where we have this as gas turbine cycle and this as Rankine cycle where we are supplying the heat from the gas turbine cycle to the Rankine cycle. Unless otherwise said we will consider the total heat to be exchanged in this process or we will have to be said otherwise that only latent heat is exchanged or latent heat is given from the Rankine Brayton cycle.

So if η_1 is the efficiency of Brayton cycle, η_2 is efficiency of Rankine cycle, we had proved that total efficiency or efficiency of the combined cycle is $\eta = \eta_1 + \eta_2 - \eta_1\eta_2$ and this η is actually greater than η_1 and η is also greater than η_2. We had seen this one. We had proved this.

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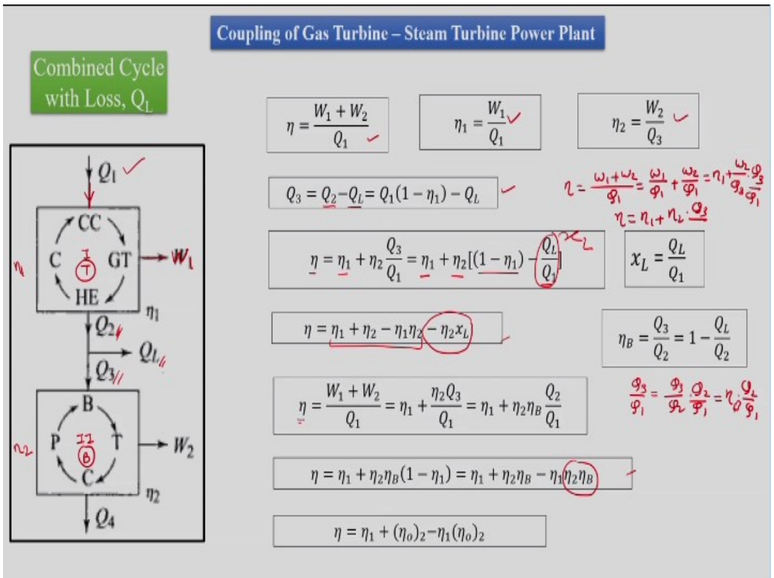

Having said this, let us consider that we have now Rankine and Rankine cycle or Rankine and Brayton cycle with some loss. That means, we have topping cycle, this is 1 is a topping second and this is 2 is a bottoming cycle. So we will say this as T and then this as B, topping and bottoming cycle. So Q_1 is the heat taken by the topping cycle. It loses Q_2 amount of heat and does W_1 amount of work.

But in this process, it loses Q_L amount of heat before passing the heat Q_3 to the bottoming cycle. So in the last expression where we had proved that η_1, we have proved here that $\eta_1 + \eta_2 - \eta_1\eta_2 = \eta$. In this case, we had assumed that $Q_L = 0$. So we do not have any loss. But now if we have loss then we will have to prove what is the efficiency.

So efficiency we know that total efficiency of the combined cycle is equal to $\eta = \frac{W_1 + W_2}{Q_1}$. Q_1 is the heat taken total from the atmosphere surrounding where η_1 is the efficiency of topping cycle and η_2 is the efficiency of bottoming cycle. $\eta_1 = \frac{W_1}{Q_1} \wedge \eta_2 = \frac{W_2}{Q_3}$ *where* Q_3 is the heat taken by the bottoming cycle.

Then we have Q_3 is equal to from the heat conservation $Q_3 = Q_2 - Q_L$. But $Q_2 = Q_1(1-\eta_1)$ okay. So this is Q_2. Since we know that $W_1 = Q_1 - Q_2 \vee \eta_1 = 1 - \frac{Q_2}{Q_1}$. So this formula can give us that $Q_2 = Q_1(1-\eta_1)$. This we can opt in from here. So we know now what is Q_2. So $Q_2 = (1-\eta_1)(Q_1 - Q_L)$.

So this is formula for Q_3. So we can say that we have now $\eta = \eta_1 + \eta_2 \frac{Q_3}{Q_1}$ *but* $\frac{W_2}{Q_1} = \eta_2 \frac{Q_3}{Q_1}$. Since we know that we can express this expression $\eta = \frac{(W ¿¿ 1 + W_2)}{Q_1} = \frac{W_1}{Q_1} + \frac{W_2}{Q_1}$ ¿.

But $\frac{W_1}{Q_1} = \eta_1$ and $\frac{W_2}{Q_1} = \frac{W_2}{Q_3} \times \frac{Q_3}{Q_1}$. So $\eta = \eta_1 + \frac{W_2}{Q_3}$. So this is $\eta_2 \frac{Q_3}{Q_1}$. And this is what we have written here. So this is $\eta_1 + \eta_2 \frac{Q_3}{Q_1}$. But $\frac{Q_3}{Q_1}$ can be expressed from this expression as $\frac{Q_3}{Q_1} = \left((1-\eta_1) - \frac{Q_L}{Q_1} \right)$.

So this is what expressed over here in the bracket. So we have got total expression for $\eta = \eta_1 + \eta_2 \left((1-\eta_1) - \frac{Q_L}{Q_1} \right)$. So having said this, we will represent suppose $x_L$as a factor, loss factor is equal to$x_L = \frac{Q_L}{Q_1}$. So this term is said as loss factor. Having won this we can write down the expression as $\eta = \eta_1 + \eta_2 - \eta_1 \eta_2 - \eta_2 x_L$. So this comes an extra term with loss.

This term is giving us the efficiency without loss and this efficiency gets subtracted due to loss. Further we can also find out using different method where we will see that η_B is some loss coefficient which is equal to $\eta_B = Q_3/Q_2$. Q_3 is the heat taken by the bottoming cycle and Q_2 is the heat lost by the topping cycle. So Q_3/Q_2 and then that is equal to $\frac{Q_3}{Q_2} = 1 - \frac{Q_L}{Q_2}$.

So this eta is as if we are running a cycle and then that has an efficiency which is operating between $Q_2 \wedge Q_3$ or we can also say this as a equivalent loss coefficient, which is equal to $1 - \frac{Q_L}{Q_2}$ since $Q_3 = Q_2 - Q_L . So\, 1 - \frac{Q_L}{Q_2} = \eta_B$. So having known this we can write down $\eta = \frac{W_1 + W_2}{Q_1} = \eta_1 + \eta_2 \frac{Q_3}{Q_1}$.

So this is equal η_1 + $\eta_2 \eta_B$ $\frac{Q_2}{Q_1}$. Again the same thing here $\frac{Q_3}{Q_1} = \frac{Q_3}{Q_2} \times \frac{Q_2}{Q_1} where \frac{Q_3}{Q_2} = \eta_B \frac{Q_2}{Q_1}$. So we get the expression $\eta_1 + \eta_2 \eta_B \frac{Q_2}{Q_1}$. Having known this, we can represent $\eta = \eta_1 + \eta_2 \eta_B (1 - \eta_1) = \eta_1 + \eta_2 \eta_B - \eta_1 \eta_2 \eta_B$.

So these two expressions are the representations in terms of the loss coefficient or loss factor. Overall, we can also write this efficiency which is a gross efficiency is equal to $\eta = \eta_1 + (\eta_o)_2 - \eta_1 (\eta_o)_2$. So this is, this term is called as $(\eta_o)_2$. And then that is where we can get the efficiency as η_1 + $(\eta_o)_2 -¿\, \eta_1\, (\eta_o)_2$.

So this gives us an idea that how much loss inefficiency we will have if the heat lost by one cycle is not equal to the heat gained by the other cycle.

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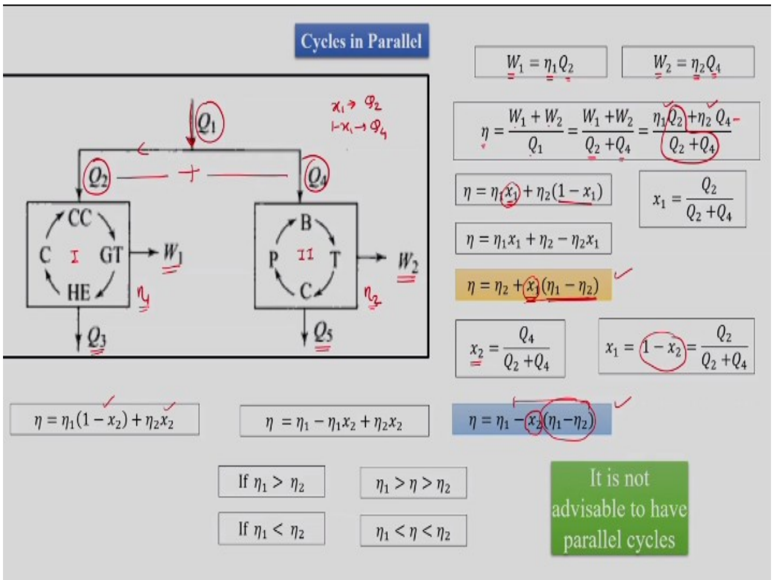

Now we had seen that we are coupling two cycles where one is topping cycle and other is bottoming cycle. But then obvious question, which would come to our mind that why do we not have two cycles in parallel. And this would be the example for that where we have two cycle, cycle 1 and cycle 2 and, these two cycles are in parallel, where they are getting heat from a common source which is having supplying heat Q_1.

Among that Q_2 amount of heat is supplied to cycle 1, Q_4 amount of heat is supplied to cycle 2. Cycle 1 does W_1 amount of work, cycle 2 does W_2 amount of work where cycle 1 rejects Q_3 amount of heat and cycle 2 rejects Q_5 amount of heat. Let us see what will happen if we have η_1 and η_2 are efficiencies, then what would happen as a total efficiency of the cycle.

Let us say that η_1 is efficiency of cycle 1, η_2 as efficiency of cycle 2. So we know that W_1 work done by the first cycle is equal to efficiency of the first cycle into heat supplied to the first cycle. Similarly, heat work done by the second cycle is equal to efficiency of second cycle into heat supplied to the second cycle. Then we know that total efficiency of the cycle is equal to $\eta = \frac{W_1 + W_2}{Q_1}$.

But Q_1 is the total amount of heat supplied which is equal to $Q_1 = Q_2 + Q_4$. So which is $Q_2 + Q_4$. But W_1 can be written from here as $\eta_1 Q_1$ and W_2 can be written as $\eta_2 Q_4$.

Having known this we can write down this expression using a constant where we will say $x_1=\frac{Q_2}{Q_2+Q_4}$. So $\frac{Q_2}{Q_2+Q_4}=x_1$. So this is x_1.

So x_1 is a fraction of amount of total heat which is received to the cycle 1. So obviously Q_4 will if x_1 is the received heat corresponds to Q_2 then 1 – x_1 is the fraction of heat which will be received which is Q_4. So 1 – $x_1=Q_4$. Then $\eta=\eta_1 x_1+\eta_2-\eta_2 x_1$. So we will have $\eta=\eta_2+x_1(\eta_1-\eta_2)$.

So let us keep this equation in our mind and then again derive for the coefficient which is x_2. The same expression eta we will try to derive with respect to coefficient x_2 and then we will now that $x_1=1-x_2$ and that is equal to$x_1=\frac{Q_2}{Q_2+Q_4}$. Having said this, we can write down the expression as $\eta=\eta_1(1-x_2)+\eta_2 x_2$. Now $x_1=(1-x_2)$. And this is $1-x_1=x_2$.

So this is done. So knowing this, we can expand this and we can write down it as $\eta=\eta_1-\eta_1 x_2+\eta_2 x_2$. This leads to this formula, which is equivalent to this instead only fact that we have now it in terms of x_2. And this formula is in terms of x_1. So let us analyze these two formulas.

By analyzing we mean that let us feel that if η_1, efficiency of cycle 1 is greater than efficiency of cycle 2 we can use this formula, where $\eta_1-\eta_2$ terms come into picture. So this leads to a number which is a positive number, but this is a fraction. So this number will be less than 1. And since this number is less than 1, η is going to happen to be not greater than η_1.

So we will have $\eta_1>\eta>\eta_2$. Similarly, let us feel that η_1 is less than η_2. So we can use this formula, which leads to this number as a positive number but it will be less than 1, small number. And then this gives an impression, which says that η_1 is less than eta less than η_2. So it turns out with the fact that we should not consider two cycles in parallel since the resultant cycle will have efficiency intermediate to the efficiency of two cycles.

So this was an exercise where we had thought to see what would happen if two cycles are in parallel to each other. So understanding this, we will note the advantages of coupled cycle.

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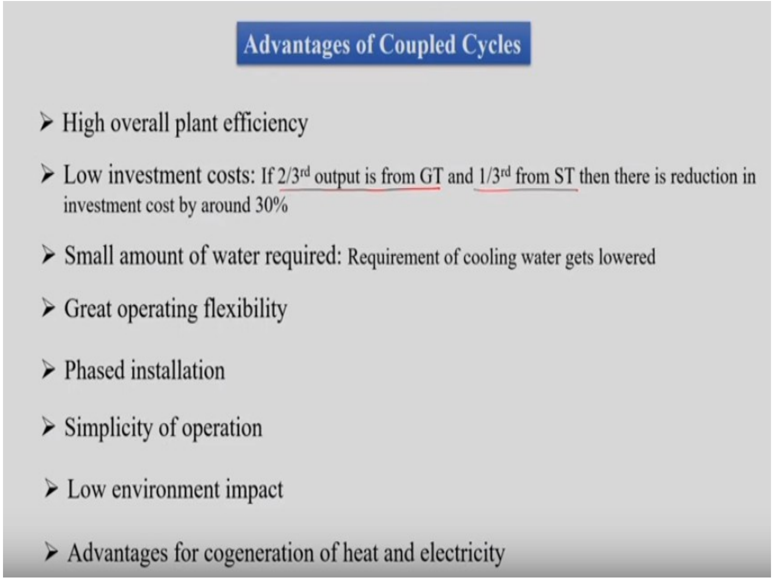

We have seen that when two cycles are coupled like topping and bottoming cycle this is what binary or tertiary cycles then we will have overall efficiency higher than any cycle. This is in particular for the gas turbine and steam turbine cycle. When we combine these two cycles basically two-third output is from gas turbine, one-third output is from steam turbine.

Then there is reduction in investment cost by around 30%. This is statistical input. Small amount of water is required for cooling the water. So water requirement gets reduced. We have great operating flexibility when we have two cycles coupled with each other. Then we can actually have installation in phases for the coupled cycle. Then we have also simplicity of operation of decoupled cycle and we have lower environmental impact since our exhaust temperature will be lower in that case.

We further have advantages of cogeneration of heat and electricity. We can use it like the case where we are having two cycles, one cycle is losing the heat or we can have also usage like cogeneration where the water is source or steam is source of high temperature. Such are the advantages of coupled cycles. Now we are going to see what do we mean by low temperature cycle.

Practically we had seen that till time we work with the Brayton cycle or the Rankine cycle where the temperatures under combustion chamber or in the heat exchanger T_{max} of the cycle is very high. And then that is where we had put the limit on the metallurgical case or metallurgical limit for the T_{max}. But it is such T_{max} was possibly obtained by combusting the conventional fuels, where we are having the coal or oil kind of fuels to be burnt.

However, we might have some readymade source of heat available from the industry's waste heat or maybe from radiation of sun. So we can make use of such heat and we can run the Rankine cycle to obtain electricity from that. So in such case, where we have limited amount of the temperature difference available or limited amount of heat is available, then still we would like to execute the Rankine cycle.

Such cases we are terming them as a low temperature cycles. So let us see how the low temperature cycles would be operating.

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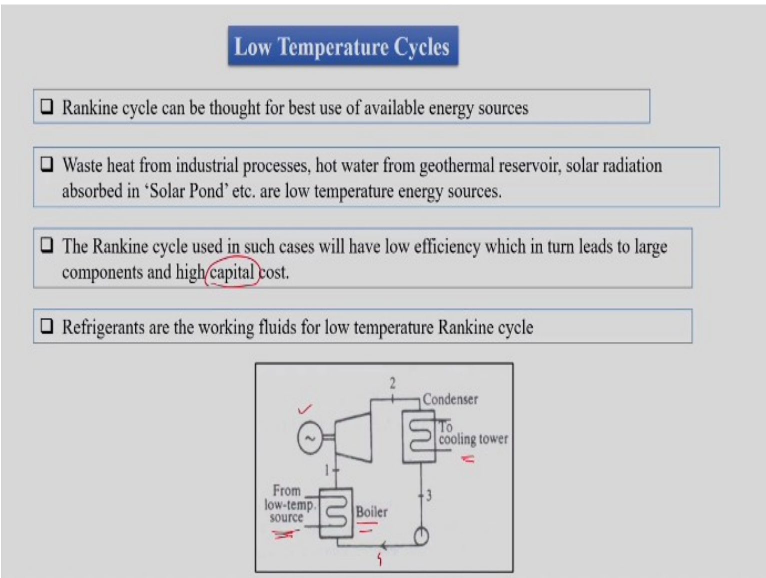

So as what expected, we will have 1 to 2 in the case of turbine, then we have 2 to 3 in the condenser and then 3 to 1 is in the pump and then we will have 4 to 1 into the condenser, boiler. So this was the routine operation of our Rankine cycle, this was for electricity generation. But here you should see that in the boiler, we have low temperature heat source, which is heating our working medium.

And obviously, when we are seeing that we are having this special topic of low temperature cycles, we will see that water will not be the first choice for these cycles. Then this is the source of heat for low temperature and similarly we have cooling tower for the condenser. Or we might have the low temperature sink also. Then Rankine cycle can be thought to be best used for the available energy resources.

Then what are the possible energy available energy resources? We can have some industrial process which is having heat as loss to the atmosphere, we can have hot water from the geothermal reservoir, we can have solar radiation absorbed in solar pond and then these will give us required small or sufficient temperature difference where we should be able to run a Rankine cycle.

Rankine cycle in such cases will have low efficiency and in turn would lead to large components and high capital cost. This is the disadvantage, but we are trying to use the available energy as the waste energy or the available energy in the form of solar or geothermal for electricity generation. So we are not burning any extra fuel. So with the most cost which is over here is in capital sense.

So we are saying that capital cost would only be higher and running cost will obviously be less since we are not in need of fuels. Having said this refrigerants are the working fluids for low temperature cycles, where we would demonstrate that why refrigerants would be good in low temperature cycles.

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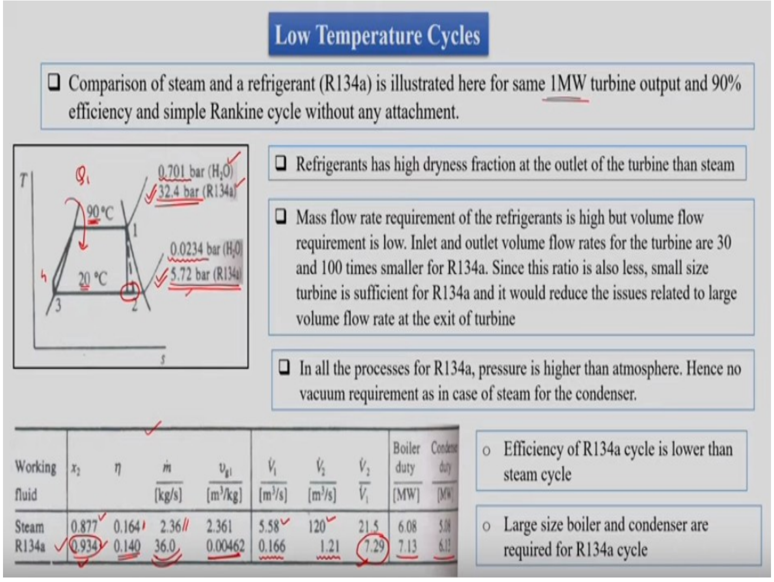

So we will see the comparison of steam and R314a which is a refrigerant when they are used for 1 megawatt turbine output and 90% efficiency of the turbine in case of simple Rankine cycle without any attachment. We mean here the attachment as super heater, reheater or regeneration. So if no such attachment is available, then in that case, we are considering that okay we will have two working mediums and we have limited amount of temperature difference between the boiler and the condenser.

So let us see this. So we have said that okay we are having 90°C as the saturation temperature in the boiler. We have 20 °Ctemperature in the condenser. Then we run our Rankine cycle. Then there are two working mediums. One is water and one is R134a. Then having said this, we have our usual conditions 1 to 2 here is in the turbine, 2 to 3 is in the condenser, 3 to 4 is in the pump, and 4 to 1 is in the boiler.

And here we mean that we are getting heat Q_1 added which is from waste heat or from solar pump. Then these are the outcomes which we are going to get based on the properties of steam and properties of R134 corresponding to these two saturation temperatures. Looking at this the first thing what we can see over here is the dryness fraction over here.

We can see that the dryness fraction for steam is much lower than in case of R134a. So R134a gives good dryness fraction at the outlet. This is good and this is not good. Further, we can see here that mass flow rate requirement of the refrigerant is high, but mass flow requirement of air of steam is less, but we should not just see the mass flow rate requirement.

We can see the volume flow rate at the entry to the turbine and volume flow rate at outlet of the turbine. Since specific volume of the refrigerant is very low, we can see over here that the volume flow rate at the entry to the turbine is very low for the refrigerant. Similarly volume for it at the exit of the turbine is low in case of refrigerant in comparison with the steam.

So it leads to that exit to inlet volume flow rate ratio is very less in case of the refrigerant. So this gives us a very small requirement of a turbine. Turbine becomes compact since the volume flow rate is small in comparison with steam. So these two we can notice as advantages of use of refrigerant. Further, we can notice over here that we are saying that we are having 20°C as the temperature for condenser. For that saturation temperature, the R134 is having pressure 5.72 bar.

But water will have pressure 0.234 bar. Similarly steam will have pressure, saturation pressure corresponding to 90°C as 0.7 bar. But in case of refrigerant, we have pressure as 32.4 bar. So these two pressures one high pressure one low pressure or one boiler pressure, another condenser pressure both the pressures are more than the atmospheric pressures in case of our refrigerant as the working medium.

So we have good dryness fraction, we have lower volume flow rate, we have higher pressures. So these three things comprise to the advantages of use of refrigerant for low temperature cycle. But two disadvantages what we can see that efficiency of refrigerant based Rankine cycle is lower than the efficiency of steam based Rankine cycle.

Further we can see that the boiler duty means heat added into the boiler and condenser duty means heat lost in the condenser both are high in case of the refrigerant. That means we need more heat interactions for the, more heat interactions in the condenser and the boiler if we want same 1 megawatt amount of work output using the refrigerant as the working medium.

These two disadvantages are also there in the bracket of the refrigerant cycle. But here as we should note again that we are using the waste heat available from the industrial process. We are either using geothermal energy or we are trying to use the energy from solar radiation. So energy which is said to be boiler due to is freely available for us and we are not had burning any fuel for that.

So noting this low temperature cycles are used for electricity generations. Although they supposed to have higher capital cost.

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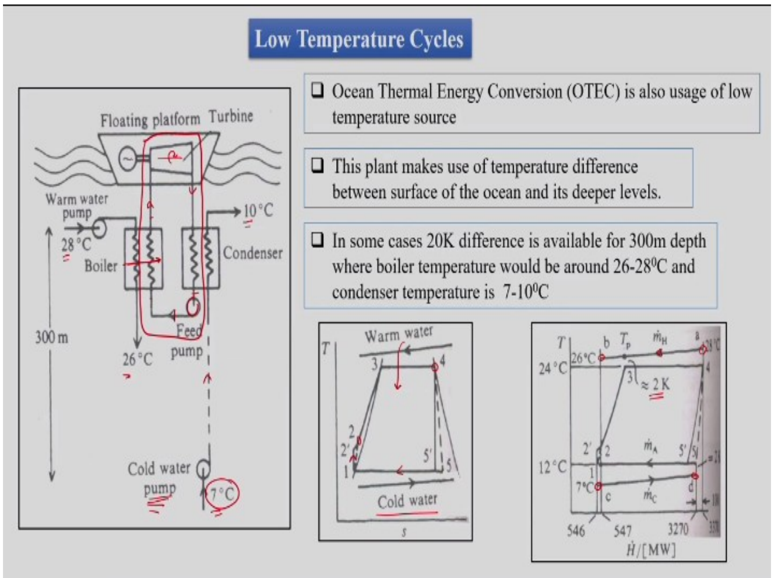

There is one more option of low temperature cycle and then that is called as ocean thermal energy conversion. Basically, we can think of having small temperature difference in the ocean between the surface of the ocean and its deep inside. If surface of the ocean and deep inside if we try to consider then there will be temperature difference.

Temperature difference of 20°C Kelvin or 20 Kelvin is available, if we go 300 meter depth, then in certain places, we can get this difference where 26 to 28°C will be our boiler temperature and 7 to 10°C will be our temperature inside the condenser. So this temperature difference can also be thought to be extracted for the work output or electricity generation where such conversion of ocean energy is called as ocean thermal energy conversion.

This is a possible power plant where we are passing our refrigerant in the circuit where this is the refrigerant circuit. This is the refrigerant circuit for us, where we have pump. Refrigerant is getting pumped from low pressure to high pressure. Then heat will be added into the refrigerant in the boiler, where basically boiler is comprised of the water which is taken from the surface of the sea and that surface of the sea water is going to give heat to the working medium of our Rankine cycle.

Then it will be passed into the turbine. It will rotate the turbine and it will rotate the generator, will generate the electricity and then turbines exhaust is given to the condenser. But in the condenser, we are going to pass the water which is from the deep inside the sea, which we have stated around 300 meter. So that water which is a coolant will rise its temperature, maybe from 7 - 10 °C.

The high temperature water will lose the temperature from 28 to 26°C. Having said this, we can roughly plot our Rankine cycle over here, where we will have pump from 1 to 2, where we have pumping process from low pressure to high pressure. Then we have warm water from the surface of the sea giving its heat to the refrigerant and the refrigerant by all this means would go from this point to this point which is saturation vapor line.

Then we will have extraction of the work in the turbine. And then this refrigerant will lose it but for that we will fetch the water from the deep bottom and then this will use a cold water which will be gaining the heat. In this case with the references where we will consider TTD which is terminal temperature difference to be the 2 Kelvin.

If that is considered then we can see that okay, our cycle will have this kind of heat loss for the water from the sea surface which will reduce its temperature from 28 to 26 °C and it would gain the temperature from 7 K to 10 K. And then we would run the Rankine cycle of ours for electricity generation.

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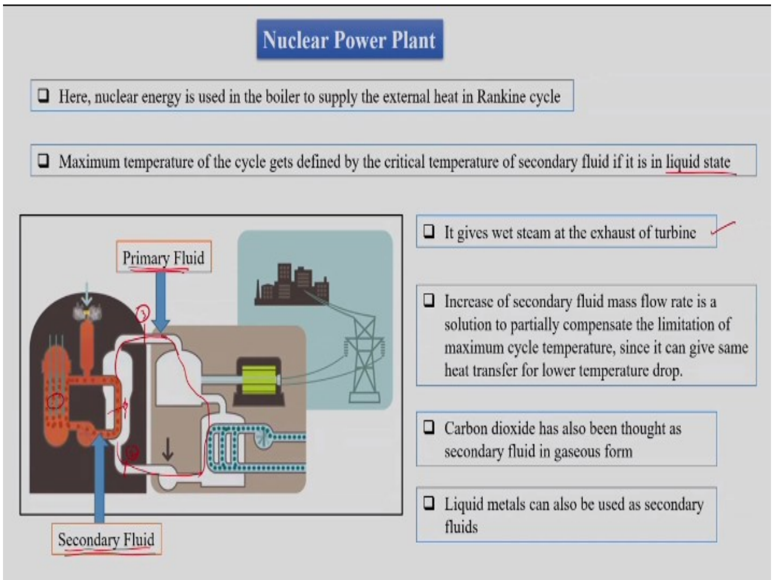

Having said this, we can talk about the next point where we are talking about nuclear power plant. So this is a typical nuclear power plant, where we are having our Rankine cycle as the basic cycle. But again, we are considering nuclear power plant for the fact that we are having the boiler where we are supposed to burn the fuel and having heat exchange is getting replaced.

So the point to be noted over here that we are trying to get a nuclear energy for the process of heating into the boiler. So nuclear energy is our source of heat for the Rankine cycle. So having this as our source of heat, we will see maximum temperature. In such case we will have basically based upon critical temperature of the secondary fluid.

Here we are saying that there is water or steam which is getting passed in the circuit which is basically boiler, pump, condenser, and turbine. So that circuit is called as primary circuit and working medium is primary fluid. So in this case parallelly there is one more fluid which is basically passing the heat from the nuclear energy or nuclear rods to the water, which is our primary fluid is called as secondary fluid.

So secondary fluid basically takes heat from the nuclear energy and nuclear source and then it gives the heat to the water. Here we mean that in case of ours, when we try to plot our Rankine cycle, in such case, we will have it like this we will have T-s diagram, we will have the dome and then we will have such as our Rankine cycle which is very primary Rankine cycle.

And that Rankine cycle will not be able to have superheat which we have already discussed. Since we are trying to say that we are having secondary medium as liquid and if that is a working that liquid is water, then water's critical temperature is known to us then we cannot cross this temperature as the T_{max} since we are using water itself as the heat source. So that water may be at high pressure.

And then that high pressure water will supply the heat where we will go from 2 to 3 in the boiler. This is what we will go from 2 to 3 in the boiler. So if we are trying to use liquid in case of nuclear power plant, then we have to be watching out with the critical condition of that liquid beyond which we cannot have cycles T_{max}. But what we can do, this same amount of heat we can gain if we try to increase the mass flow rate of the same secondary fluid.

We know that heat lost by the secondary fluid will be $Q = mC_P dT$. So we want same temperature difference between the secondary fluid and the primary fluid in heat transfer, then we can increase the mass flow rate. By increasing the mass flow rate we can basically increase the amount of heat transfer to the primary fluid and by that means we can increase the T_{max}but still we cannot increase the T_{max} beyond the critical condition.

Having said this, we can think of gaseous fuels also as the, gaseous fluids also for the heat transfer. But if we have liquid fluids, then we can know that for the simple Rankine cycle turbine exhaust will be very wet. So we will have very small dryness fraction at the outlet of the turbine. So keeping this point in mind, we can think of other material than water liquid as the source.

Then we can think of carbon dioxide as one of the materials for which is in gaseous format can be thought as the medium for transfer of heat from the nuclear energy to the boiler. And similarly, we can also think of liquid metals for transfer of heat from the nuclear source to the boiler.

So this would help to run the nuclear power plant where we are trying to avoid the use of conventional fuels like coal or oil to be used to generate the fluid gases, which would pass over the water and generate the steam. So instead of that, we are trying to run two circuits, primary and secondary circuit, where primary circuit is our steam cycle. And that would receive the heat from secondary medium, which can either be gases like CO_2 or water, liquid, or maybe liquid metals as well.

So this is the gist of nuclear power plant, how we can replace the conventional boiler. So this ends the discussion on this topic, which is binary cycles and the nuclear or low temperature power plants. So we will see the next topics in the next class. Thank you.