Engineering Thermodynamics
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Week-05
Lecture-27
Carnot Principal

Welcome to the second law of thermodynamics part 4. In this lecture we will discuss the Carnot principle. and how absolute thermodynamic temperature is defined by that principle called Kelvin scale so we will discuss about this as you have read in the previous lecture that second law of thermodynamics puts a limit condition on the operation of cyclic device which we call Kelvin Plank or Clausius statement. And two statements are like this. The first Kelvin Plank statement says that the heat engine cannot operate, it interacts with only one reservoir. It's not like you have only one single reservoir, you have exchanged heat and produced work. This is not possible.

Similarly, the refrigerator cannot operate until a net energy input is obtained from outside. Without energy input, it cannot release heat from low temperatures. These two statements are the statements of the second law of thermodynamics. If any of them is wrong, you can show that the other one will also be wrong. So, you can understand it as a conditional limit of any cyclic device. There is a limit which depends on it. Let's move ahead. So, we will bring the concept of Carnot principle with this. There are two statements on this. The first statement is that your irreversible heat engine, which is the actual heat engine, is always irreversible. So, if you have made a heat engine using the two different temperatures of the reservoir as we have written here 1, this is the actual heat engine which will be normal. So, we will call it irreversible heat engine. And this is reversible in which all your processes are very slow which is an ideal system. So, efficiency is the capacity of irreversible is always less than the capacity of reversible. So, the real power of the heat engine is always the efficiency of the engine will be less than the efficiency of the engine. This is a rule of the Carnot principle. The thermal efficiency of the reversible heat engine Eta will always be more than the irreversible heat engine. This was your first statement. If you have two reversible heat engines, one is number 2 and number 3, these two are the heat engines which operate between temperature TH and TL. Since these are the same for high thermal and low temperature reservoirs, the efficiency of these two and three will be the same. So, this is another statement of this. The power of all the current heat engines is the same. So, the efficiency of both the heat engines is the same. Because both the heat engines are using the same reservoir. So, the efficiency of both the heat engines is the same.

Now we can prove it. So, the first statement is that the efficiency of the irreversible is less than the irreversible. So, if you keep on assuming that this is not the case, then you can see that the flour is the thermal efficiency is W net out if there is heat. Plus, QH and Wnet out you can write it in QH-QL. If this is not true, or the assumption written here is not true, that if eta's thermal efficiency is irreversible, if this is not correct, let's assume that this if not correct. Let's assume that if this is correct, then what will happen? So, what does this mean? If you are taking heat, then more heat If eta is more in reversible and irreversible case, then the loss of energy will be less. QL is irreversible. We are proving that QL is irreversible. If we assume QL is irreversible, it means we are losing more energy in the case of QL. QL in irreversible case, they are losing less energy and in reversible case, they are losing more energy so this condition will be there. Now, what we can do is, we have a heat engine here, and we have another heat engine here, which we can use as a refrigerator. So, we assumed that This work will be directly input in this engine, which we will use as a refrigerator. So, we will put the heat back in the tank. And we are extracting the QL. So, this is a combination of heat engine plus refrigerator. If we combine both of them, then what will happen is that since it has been returned, we can remove it internally. Because it will be cancelled if we combine both of them. so, this combination will work like this that your this is QL irreversible and this is QL reversible but the direction is different so what will happen in this direction QL reversible this one is in this direction minus the irreversible one and this net out This is reversible and this is reversible, so it will work like a net out. So, since we are using this also, so if you are both subtracting, then note this that if this statement is greater than 0, Because this is definitely greater than zero. Because we have assumed that QL reversible is more. It is losing more energy in the reversible case. Because we assumed that eta is the opposite. And when we combine this, we get to the state where you have taken out energy from only one reservoir and converted it into work. So, this is not possible, it violates Second, thermodynamic. This is not possible. So, it will be reversible. The efficiency of reversible will be higher than irreversible. You can also do this proof concept in the second case. You can assume that it is different. And again, you can combine it with a heat engine. You can take a combination with a refrigerator. And you can show that if it is not equal, then it will violate. of the second law. So, I will not discuss it here, but you can understand how this concept can be proved.

Let's move on to the next one. So, the concept that we will consider further is on the thermodynamic temperature scale. As we discussed, if the reservoir uses two reversible heat engines, then both have ETA efficiency. What does this mean? It is not depending on the property. If both the reservoirs are the same, then the efficiency will be the same. The temperature of the reservoir is the same in both the reservoirs. We can consider it like this. If we discuss it further, we can try to understand whether we can get any temperature scale from it or not. So, this is a reservoir which is at temperature T1. From here we extracted Q1 energy which is using heat engine A. And this work is done by WA, and it rejects so much that it rejects at T2. And here Q2 is using heat engine B. WB is the net out work out and Q3 rejects at T3. And this is C, which is your heat engine C, which is doing Q1, starting from this reservoir. And WC is the workout, and this is your Q3 net. Please note that Q3 will be the same because finally the ETA thermal reservoir The efficiency of the heat engine depends on the temperature of the reservoir. As we said, no matter how many reversible heat engines you use, the efficiency of the same reservoir will be the same. This means that the heat engine inside the device is reversible. and what fluid you use does not mean anything it is only dependent on the temperature reservoir it means that eta is a function of TH TL and what is ETA? If you see it, it is Wnet Now if we balance it with the energy balance,

$$\eta_{th,rev} = g(T_H, T_L) = \frac{W_{Net,out}}{Q_H} = \frac{Q_H - Q_L}{Q_H}$$

$$\frac{Q_H}{Q_L} = f(T_H, T_L)$$

$$\eta_{th(A+B)} = \eta_e$$

Now if we pay attention to this, we can do it because this is you at this point So if we combine the efficiency of both, it should be the same. Now note that Q1 which you were here Q1 by Q2 We said that the ratio of two heat is TH-TL In this case, when the reversible Let's consider heat engine A. So Q1 Q2 will be your function T1 T2. And similarly, your Q2 by Q3 will be F T2 by T3. F T2 and T3 will be. And Q1 by Q3, which is connected to C, will be F T1 T3. Okay? Now if you consider that Q1 by Q3, then it will be Q1 by Q2 into Q2 by Q3. Note that finally, F2 should not come anywhere, whether you do it in this, 2 will be cancelled because your interest is in this only, finally, which is Q1 and Q2, Q3.

$$\frac{Q_1}{Q_3} = \frac{Q_1}{Q_2} * \frac{Q_2}{Q_3}$$

$$f(T_1, T_3) = f(T_1, T_2) * f(T_2, T_3)$$

$$= \frac{\emptyset(T_1)}{\emptyset(T_2)} * \frac{\emptyset(T_2)}{\emptyset(T_3)}$$

$$f(T_1, T_3) = \frac{\emptyset(T_1)}{\emptyset(T_3)}$$

$$\left(\frac{Q_H}{Q_L}\right) = \frac{T_1}{T_3} = \frac{T_H}{T_L}$$

So, We can see it like this and this is the function f t1 t2 f t2 t3 and this is f t1 t2 The left hand side does not depend on t2 The right hand side is t2 When multiplying, it should cancel And this is only possible when we can write it in this form Phi t2, Phi t2 by Phi t3 If we write it, then it will be cancelled And this is Phi t1 by Phi t3 So this condition is now at this point This expression Phi can be written in many ways And here Kelvin proposed that phi t is your T which is one form of solution but there can be other options like this and if you consider Kelvin then this will be if you consider T1 here then T1 and T3 will be T1 by T3 and if you consider T1 as high temperature then TH by TL will be and this will be your phi h by phi l reversible we are considering reversible in this case and this is what your Kelvin scale represents in this heat ratio and reversible simply your temperature ratio is there in this case we will call this scale Kelvin scale which is independent of physical property here the fluid does not come from anywhere it is only dependent on temperature so it is not dependent on any substance or physical property and its range T will be 0 to infinity and we still have to tell the magnitude so magnitude is that in this scale triple point is considered and the water magnitude of Kelvin 1, 273.16 of the difference T triple point of water minus zero. So, this is your 273.16 Kelvin. So, this has been fixed so that your scale is fixed, and delta T will be 1 Kelvin. Then you can also change it from the temperature. You can also remove the degree Celsius. So, you can use this relation in that.

Let's move forward. The efficiency of Carnot cycle is shown by a limit of any device. In general, the efficiency is shown by definition. depends on the temperature of the liquid. So, you can write this ratio as TL by TH. L means low temperature reservoir, H means high temperature reservoir. So, eta, thermal efficiency, which is reversible, will be 1-TL by TH. So, this will be the highest efficiency. Any thermal energy reservoir operating on TL and TH will have the highest efficiency with eta thermal reversible. This means that if you have been given a limit, then you can get the maximum efficiency of a car engine. This is the Carnot engine. So, this is a kind of limit for you that how close we can achieve it.

Now in this, eta is like eta thermal efficiency of Reversible engine Eta thermal efficiency will always decrease on the normal side of the reversible engine So if there is a reversible engine, then it will decrease from the reversible engine If there is a reversible engine, then it will be equal This can never happen It means that Eta thermal will never be more than reversible Eta thermal will always decrease thermal efficiency of reversible engine.

Now, you can understand from the example that if you have a high temperature in any power plant, which is in boiler condition, if it is given 1000 Kelvin and the load temperature is 300 Kelvin, then its actual efficiency, which will be based on Carnot, on the basis of Carnot engine, will be 70%. Because it is 1 minus 300 by 1000, is eta reversible. So, this is 0.7. But the actual efficiency will be 40%. And as the temperature increases, the heat will increase. Similarly, as you reduce the TL, the heat will increase. So, it means that you can maximize thermal efficiency as much as you work at high temperatures. High temperature means it will depend on the strength of the material. So, there will be a limit to everything. Similarly, if you are rejecting the heat of the engine at a very low temperature, then also your efficiency will increase. But then it will depend on how you are bringing the medium to cool it down or maintain a low temperature. Let's ask a question. This is Carnot engine which has received 650 kg of heat from a source We don't know where it received from, what temperature it received from But we know that this is QH And this is rigid, so this is QL And this is sink So we don't know, this is QH This is Carnot heat engine and this is your QL this is your TL is equal to 24 degree Celsius of course this will do some work now we have to take out the temperature of the reservoir source we have to take out its TH so that of thermal is 1-QL by QH and we can write it as 1-TL by TH It means we can cancel it too. So here we have QL by QH is equal to TL by TH. And we have to remove TH. So, TH is removed. TL into QH by QL. So, this way you can remove the value. TL, we know 24 plus 273. In Kelvin, QH is 650. QL is 250, so you can remove TH from here.

Similarly, when this is removed, you can remove it with efficiency. In fact, you can remove it in this way also because you have 1-QL by QH, so 1-250 by 650. You can solve this, and you will get eta from here. Okay? As we said, the efficiency of the reversible heat engine increases as the temperature increases, the value of the heat increases, the quality of the heat increases, the efficiency of the heat increases. So, this is the efficiency of the heat engine. This is about the efficiency of the engine but there is a quality of every energy. Quality means that if there is energy at higher temperature then we can convert it more in work. After all, converting energy in work is my goal. So, we can increase the effect of higher temperatures. If we do it in 1000 kW, then we can't convert it to 300 kW. It will be wasted.

Let's understand it as an example. 100 kJ heat which you will reject from a high temperature Kelvin to a low temperature. So, if you reject 100 kJ from 1000 Kelvin to 300 Kelvin, then you have stored 100 kJ energy at 300 Kelvin. and this temperature will not have much value of this particular energy. But if you do this with a heat engine, then it will be exhaust and a sink. In this case, let's consider Carnot cycle as a 1-300 by 1000.7 It means that 100 kJ Kilojoules. You can convert 70 kJ of fuel to 30 kJ of fuel. You can transfer the fuel to 30 kJ of fuel. And the remaining 30 kJ of fuel will also be lost. So, you can understand that if you simply reject the fuel from 1000 kJ, then you will not have any use on 300 kJ. Because if you are working on 300 kJ, then there is no use. But if you are converting from 1000 kW to 300 kW, then you can use 70 kJ This means that the energy quality also increases at high temperature Because you can convert many portions of that energy into work in the assumption, the word quality is more associated with work. How you are converting energy into work. As you know, work can be converted into heat but there is no reverse. That is why the more you convert heat, the more quality you will get. It is important that high quality energy is more important for us than flow quality. As I said, if you have 100 kilo joules, it is not important for us. But if the same 100 kilo joules are at 1000 Kelvin, then it is more valuable for us. So sometimes it happens that when you throw 100 kJ, waste it, throw it in 300 kJ, it has no benefit. But if you convert it through the heat engine, then its value increases. So sometimes what happens is that the process to assess it Energy balance is not important. You have to see how much you can use the value. This is why the heat engine works; this is why second law works. First, law cannot tell you the quality of any energy. It can only tell you the energy balance. As I said before, the second law tells you whether the process will happen or not. Similarly, the second law can also tell us the quality of this energy. We will use that in the future through exergy. In the same process, we talked about the heat engine, in which the concept of reversible has been used. In the same way, you can use the refrigerator and heat pump. So, in this case, we will call it Carnot refrigerator and Carnot heat pump. So, the COP. You used eta for heat engine, you are using COP for efficiency, refrigerator. And this relation is derived from the previous one. Now this is the only thing that you can replace the heat ratio with temperature ratio. That's the only difference. In such a case, in your reversible case, this will happen. Refrigerator case and Heat pump case in this also you will use the same concept that the highest coefficient of performance will be in the case of reversible only. So, COP R will always be less than reversible. It can't be greater. This is very important We can talk about heat pump in this way We will close this lecture with an example Here you have Carnot Refrigeration Cycle Which is written in temperature and volume Here the temperature is shown on the volume plot. This is a closed system. And its working is such that it is using a saturated liquid vapor mixture.

Now, this refrigerant cycle, as we have already told you, you have a condenser in it. which goes to the expansion valve then you have the evaporator which is extracting heat from the refrigeration space and then comes the compressor which Went. This is your condenser, and this is your evaporator. This operation is usually done in two phase regions. This is the region of vapor liquid mixture. In this case, you have 1 and 2. This is 1, this is 2, this is 3 and this is 4. So, this diagram shows that 1 and 2 are in 2 phase regions, 3 is in saturated vapor and 4 is in saturated liquid. 1 is again in 2 phase regions. So, let's read this question again. This Carnot Refrigerant Cycle is in a closed system, and it is in saturated liquid vapor mixture region. Where 0.8 kg refrigerant is 134 K, this is your working fluid. So, this is your working fluid. Now the maximum and minimum temperature is 20 degrees and minus 8 degrees. So where will be the maximum temperature? In the condenser. And where will be the minimum temperature? In the evaporator. So, this is your minimum temperature, and this is your maximum temperature. Now they are saying that the total work done in this cycle It is known that the refrigerators This saturation liquid The final state tells that the refrigeration fluid Comes in the saturated liquid at the end of the heat rejection So at the end of the heat rejection State 4 is the saturated liquid at the end of the condenser. Total work is 15 kJ. Now we have to find out the fraction of mass that is vaporized in the heat addition. Heat addition is here. It tells us how much amount is there. The question is how much the fraction of mass is vaporized in this process. 1 to 2. And what is the pressure? What is the pressure in the heat rejection process? What is the pressure on this? The pressure must be P sat. But let's do it systematically. First of all, notice that this is Carnot cycle. What does this mean? This means that your COPR QH by QL minus 1 which can be said to be QL Win this is 1 minus TH minus TL because this is Carnot, so this ratio QH by QL. TL by TH and TL are given 20 degree Celsius and minus 8 degree Celsius So we can get this value This value will be 9.46 So this is 9.464 is your COP Now we call this as the same value of QL by Win is 9.464 So you can extract QL. here QL is equal to 15 kJ multiplied by 9.464 and this is the value 142 Kilometer. This amount will be equal to the amount that you get to evaporate. So, if you see the QL, then this should be the mass that we are using. the mass that we are evaporating, multiply it by Hfg at minus 8 degree Celsius. So, we can extract the data of enthalpy from this Hfg. If this data is extracted, then we can extract the total value from this table. Because this is a refrigerant, it will come out here table A. So, from there your Hfg came out. So Hfg value is out. Now you can extract M evaporator from here. The amount we are evaporating. The same amount will evaporate. Already there is mass, but some amount will evaporate because your latent heat will evaporate the same amount from liquid to vapor. So, M evaporated. QL by Hfg Which comes out 0.694 So the mass fraction that we have been asked is m evaporate plus m total Because it will be in the vapor phase, that's why it is not evaporating. Only the latent heat, QL, can only do liquid. So, in this case, the mass fraction that evaporated, finally, is the ratio of both. Of course, it could also be that something is left. So, if you multiply this, it will be 0.6, divide this. And 0.8 is kg. 86.8% Rest is left in your state 1 combination You can also find out the quality of it, that will be a different question in the second part, it says what the pressure at the end of the heat rejection process is. So, the heat rejection process is 4. What is the pressure on this? P4. P4 is P sat. Saturation at 20 degrees Celsius. So, from here, you will see the table. And, on seeing the table, you will get A11 will be 572.1 kilopascal. So, the problem is that it is very complicated. But it is actually very simple. If you have a drawing like this or you have not been given this, then you can make it. The main thing is that you have to see where to put the arrow, from where, what is the rejection, heat rejection, what is the heat addition. If it is a current node, you can use that ratio. So, by using this basic concept, you can solve many questions easily. So, I hope that when we discussed the whole second law of thermodynamics, you must have understood that we started by saying that the direction is so important, and you cannot change the direction. That is why your second law of thermodynamics is connected. To understand that we have done a thermal energy reservoir. Because if you want to convert heat into work, you will have to use a heat engine. And for the heat engine, we discussed thermal efficiency. And how the second law of thermodynamics is violated, what are its conditions. In that, you understood the second law of the Kelvin Plank statement. Which is related to the heat engine. Then we understood refrigerator and heat pump, and how the coefficient of performance is related to its capacity. We understood that. Efficiency. Then we took this refrigerator and connected the violation of the second law with the Clausius treatment. And how they are connected, the kelvin plank and Clausius treatment. We studied that. We also talked about perpetual motion machines which do wallets, whether it is the first type or the second type. It depends on whether your first type will wallet the first log, second type will wallet the second log. Then we asked how we can maximize efficiency. For that we learned about reversible and irreversible processes. What is irreversibility and what is the reason for it. Then we understood internally and externally reversible processes. After understanding all these things, we said that Carnot cycle is such a cycle that is only reversible. And we introduced 4 reversible processes of heat engine. And that is Carnot cycle. When we can reverse it, it will be a reversed Carnot cycle. And through this, we understood the Carnot principle in 2 points. Its efficiency and efficiency will only depend on temperature. So, we got the Thermodynamic Temperature Scale and from there we discussed about Kelvin Scale and then we discussed about the quality of energy and how to solve the problem with Connard engines we tried to understand that with some examples, So I hope that This is the end of the lecture series of the second law of thermodynamics. We will continue to study this topic in the future. We will discuss the topic of entropy and try to give many examples in this series. See you in the next lecture with a new topic. Till then, Goodbye.