Energy Conservation and Waste Heat Recovery
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Lecture - 10
Reversible Cycles (Contd.)

Welcome back to the class of waste heat recovery. We were discussing regarding second law of thermodynamics. Second law of thermodynamics gives us many useful concepts; one of them is the concept of reversible cycles. Reversible cycles could be for heat engine reversible cycle could be for heat pumps and also we know how to calculate the efficiency of reversible heat engine cycles and the cop of reversible heat pump cycles or reversible refrigerator.

In some previous lecture, when I was explaining that; what are the attributes of waste heat and how we can understand that this source of waste heat has got good potential; we can get good amount of energy recovered from this source why the other source does not have enough amount of potential the recovery from that will be difficult. So, this happens though waste heat is present in some case we may find that the recovery is very lucrative in some other case, the recovery is not at all lucrative rather it is difficult and then I have told one thing that the sources that can be judged; obviously, depending upon how much of waste it is available from the source that is the quantity of waste heat; obviously, this is very important, but at the same time there is also quality of waste heat and now whatever knowledge we have gained from second law, we would like to see what is quality and quantity.

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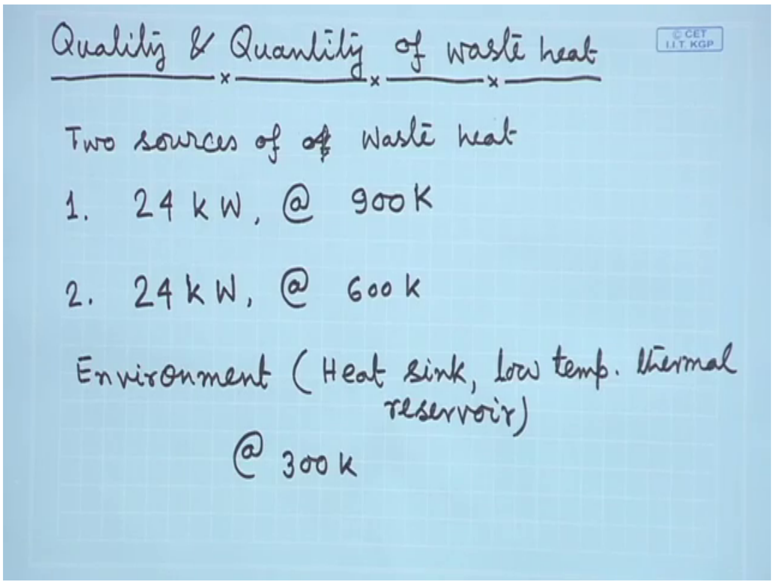

So, let us take an example. So, quality and quantity of waste heat; so, this is what we try to demonstrate. I have told verbally; what is quality and quantity, but now when we have learnt second law of thermodynamics, we want to demonstrate it with the help of numbers; let us say 2 sources of waste heat; one let us say the amount of waste heat, we are getting that is 24 kilowatt and we are getting it from at a temperature at let us say 900 k. So, we are getting 24 kilowatt at 900 K that is the first source second source we are getting same amount of thermal energy or waste heat 24 kilowatt, at 600 K; all right and then environment, we can call it as heat sink or we can call it as low temperature thermal reservoir that is at 300 K.

So, this is what is; this is; what are the available things. So, we have got 2 sources of waste heat both the sources are having 24 kilowatt by some estimation, we can estimate it and then first source is at 900 Kelvin, second source is at 600 Kelvin and let us say the environment or the surrounding which can act as the heat sink or the low temperature thermal reservoir that is at 300 Kelvin.

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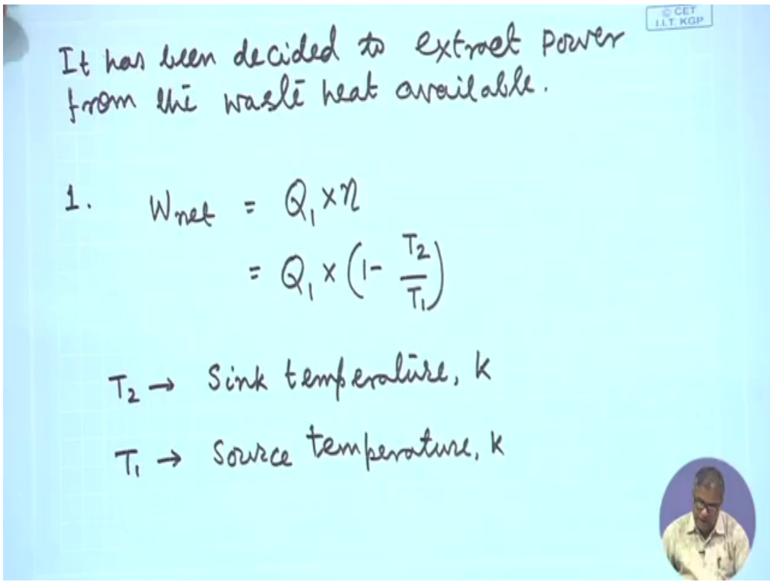

Let us now; it has been decided; it has been decided to extract power from the waste heat have available. So, it has been decided to extract power from the waste heat available as an engineer; it is your responsibility now to see the feasibility and we like to examine the feasibility of this one. So, how can we see the feasibility first let us see that if some ideal engine runs utilizing this waste heat then how much power we can get in actual case we can get less, but at least ideally how much we can get that we can decide or that we can determine and now we know second law of thermodynamics we know cannot principle we know ideal heat engine. So, it is possible.

So, the first case in the first case the work done that will be W net which we will get that will be equal to Q 1 into efficiency; what is the efficiency Q 1 into the efficiency will be 1 minus T 2 by T 1; T 2 is the sink temperature in Kelvin T 1 source temperature Kelvin and then Q 1 is the thermal energy available.

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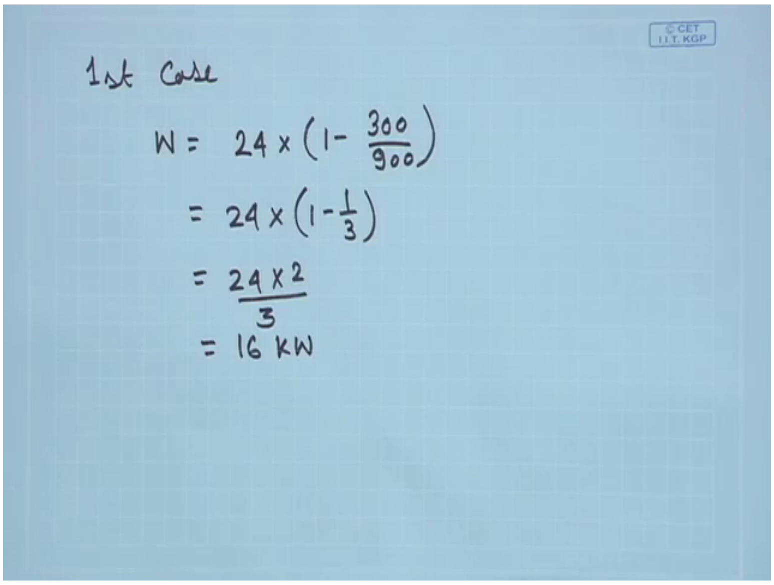

So, first case first case what we get is that W is equal to 24 kilowatt into the efficiency; that means, it will be 1 minus T 2, in both the cases; it is 300; 300 by 900; in the first case, the source temperature is 900. So, this will be 24 into 1 minus 1 by 3. So, this is 24 into 2 by 3. So, this is 16 kilowatt.

So, in the first case, if I try to generate power out of the available waste heat, I will be able to generate 16 kilowatt of power; whatever hard I may try, I will not be able to generate more than this because this is the limitation put by second law of thermodynamics in ideal case, I will get this mind that in actual case, we will get much lesser than this that will depend how much less we will get that will depend on my cycle design on the efficiency or the effectiveness or in a more-more correct sense on the irreversibilities of the processes, I select on the irreversibilities that will be generated by the equipment I select for the cycle, but ideally I should get 16 kilowatt.

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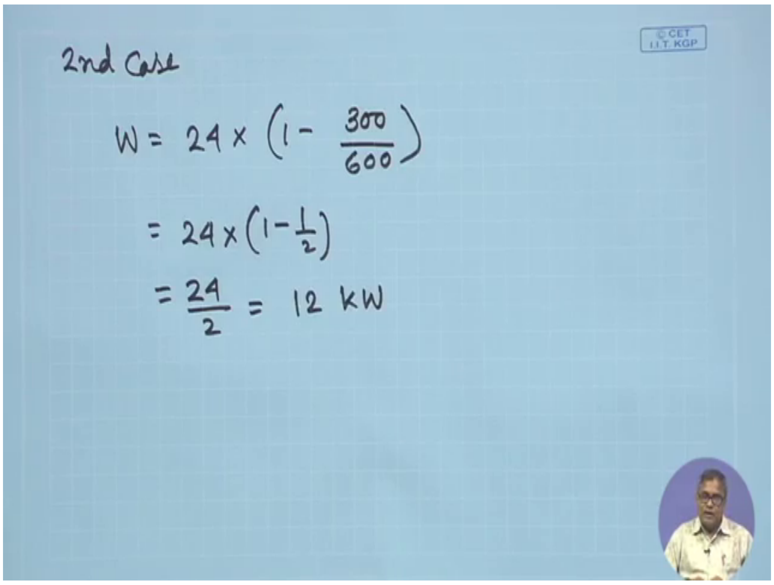

Let us go to the second case second case in the second case W is equal to again 24 into 1 minus 300 is the sink temperature, but the source temperature is 600. So, this will be 24 into 1 minus half. So, this will be 24 by 2 that is equal to 12; 2 kilowatt. So, in the first case, I am developing 16 kilowatt of power and in the second case, I am getting 12 kilowatt why is the difference because in both the cases we had the same amount of waste heat that is 24 kilowatt.

So, here comes the concept of I think here I can demonstrate the concept of quality and quantity the quantity of waste heat in these 2 examples were same; but the qualities were different in the first case, when we had the waste heat or the thermal energy at a higher temperature we had the higher quality and when we had higher quality from the same amount of waste heat, we could recover more power and in the second case though, we had the same amount of waste heat we had a lower quality and we could recover we could extract less amount of power in the second case. So, this example gives you I think I mean it, it makes it clear by this example; we can make it clear; what is quality and quantity of waste heat.

I can extend it little bit generation of power from waste heat is only one option there are other options another option could be this thermal energy, I could have utilized to heat another stream of fluid and then that hot stream of fluid would have been utilized for some process application. So, heating is one of the major application for waste heat recovery in that case how can we understand the quality quantity in both the cases are the same quality is like this in the second case; that means, when we take heating as the option the rate of heat transfer again will depend on the temperature difference.

Let us say in both the cases we take a stream of fluid which is at ambient temperature and that is for the present case it is 300 K; 300 Kelvin. So, in one case I will have to start with a temperature difference of 600 K in the second case I will give a temperature difference to start with that is 300 K so; obviously, the rate of heat transfer or the process of heat transfer will be much easier in the first case compared to the second case. So, if we consider even if we consider that the waste heat we are using for heating another stream we can think we can see that it has got a quality and in most of the cases quality is denoted by its temperature.

There is another kind of quality I have already mentioned that is the chemical quality; that means, whether it is having some sort of hazardous gas or not hazardous component or not whether it is having particulate or not whether it is having some sort of a component when it is condensed it produces some corrosion. So, those are other kind of quality, but mainly quality is denoted by the temperature at which the waste heat is available.

So, with this example let us go to another very important concept in second law of thermodynamics that is the concept of that is the concept of entropy and from Carnot cycle, we have seen that the processes could be reversible and irreversible similarly as the processes could be reversible and irreversible the cycles could be reversible and irreversible. So, considering both reversible and irreversible cycle Clausius gave a very important postulate or principle Clausius principle.

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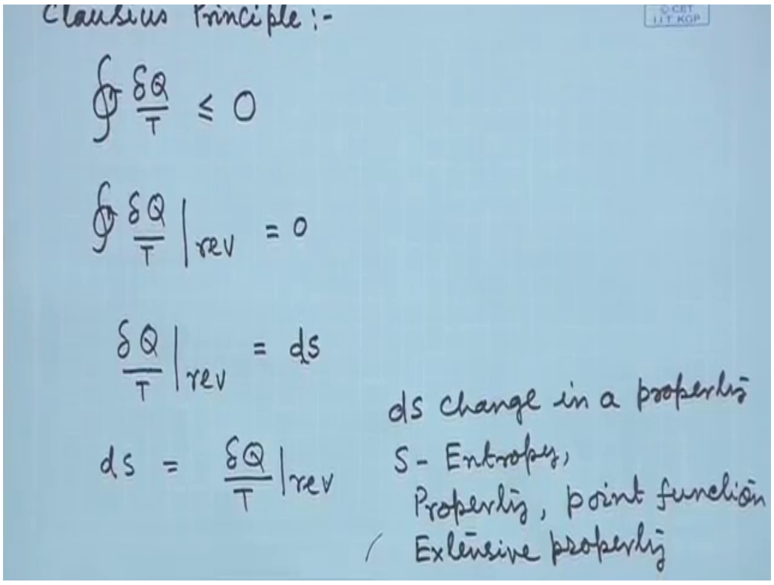

So, what is Clausius principal? Clausius principal cyclic integral of dQ by T that is less than equal to 0. So, it is inequality sign is there. So, sometimes it is also called Clausius inequality principal shore cyclic process and we are not qualifying the cycle, whether it is reversible or irreversible when we are not qualifying the cycle whether it is reversible or irreversible, then it is a general cycle it could be reversible, it could be irreversible shore general cycle cyclic integral of dQ by T that is less than equal to 0.

Now again, it can be shown in any standard book of thermodynamics if we find it that cyclic integral of dQ by T for a reversible cycle that is equal to 0. So, this is again a very profound information profound derivation profound conclusion that can be obtained in the discussion of second law. So, what does it mean it means like this that dQ, you see I have written in the form of in exact differential dQ has been written in the form of in exact differential, but when it is dQ by T and the process is reversible this is becoming dQ by T and the process is reversible. So, this is becoming some change of a point function because if I take this quantity dQ by T along a cycle the summation is equal to 0. So, then for a process dQ by T reversible will be change of some sort of a point function and I am denoting it by s. So, this is equal to dS or I can write dS is equal to dQ by T reversible.

Let me write dS change in a property. So, let me introduce S we call it a new property is being introduced we call it entropy. So, this is a proper property this is a point function and more correctly this is extensive property. So, I think from the discussion of thermodynamics one knows that; what is extensive property? Extensive property is the property which depends on the expanse of the system or the control volume. So, it depends most of the cases it depends on the mass more mass means more entropy of course, one can define entropy per unit mass. So, then you see we are coming across a very important property called entropy from the Clausius principle or Clausius inequality relationship.

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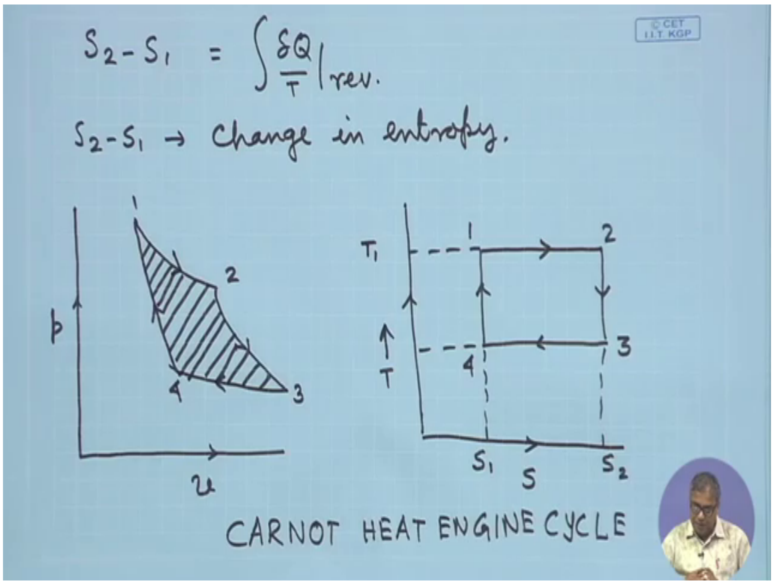

So, we can write S 2 minus S 1 integration is possible. So, it should be dQ by T reversible and S 2 minus S 1 is change in entropy. So, entropy change is related to the process of heat transfer and you see it again heat transfer has got a sign convention. So, accordingly the sign of entropy whether there is a positive change of or increase in entropy or decrease in entropy; entropy being a property that will depend on the sign or direction of heat transfer all right.

Now, most of you already know that entropy is a very important property, it has got different significance both in the industry and in other sphere also this is not the place to discuss all these things, but let us take that entropy is one property which we have derived from second law and which is given by this particular relationship. Once we get entropy, then many things can be derived from the concept of entropy and; obviously, for energy conversion processes entropy is very useful and for waste heat recovery also it is very useful.

Let us see the first use of entropy. So, entropy is a thermodynamic property and it can be very conveniently used as a thermodynamic coordinate see I have already drawn Carnot cycle on pv plane. So, this is how I have drawn Carnot cycle 1, 2, 3, 4. So, 4 processes and this is Carnot heat engine cycle; now using entropy, we can draw a Carnot cycle like this; 1 2 that is the isothermal heat addition at a temperature T 1 this side is T coordinate and this side is your S coordinate. So, this is S 1 this is S 2. So, 1 to 2 is the isothermal heat addition 2 to 3 is the adiabatic expansion process 3 to 4 is the isothermal heat rejection and 4 to 1 is the adiabatic compression process.

So, you see, we have got an alternate representation of Carnot cycle in an alternate thermodynamic plane, but is it just a simple variation of the representation of Carnot cycle or does it give something more than that; obviously, it gives something more than that. So, you see in pv diagram from thermodynamics we know the curve the sorry the area under the curve of pv diagram that gives the work done during a process. So, basically the work done during a process, if it is given by the area under the curve then for a cycle the area enclosed by the cycle will give us the work done by the Carnot heat engine cycle. So, that is what we get from pv diagram.

In TS diagram, let me explain what we can get from TS diagram and for that.

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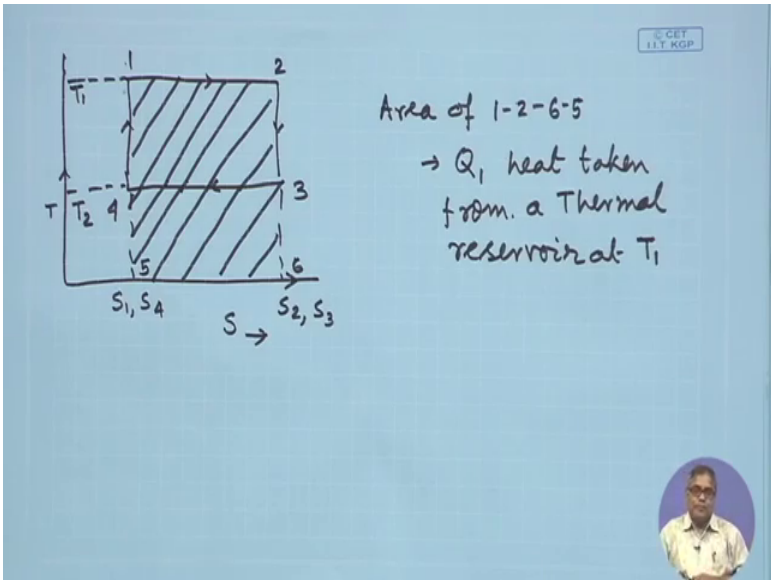

Let us draw the Carnot cycle once again on TS plane. So, T this is S and this is the Carnot cycle 1, 2, 3, 4 and let us say this is your T 2, this is T 1, this is S 1 and S 4, let me denote this point as 5 and this point as 6 and this will be S 2, S 3. So, from here, if we consider the area of 1, 2, 6 and 5; this area; so, this gives Q 1 that is heat taken from a thermal reservoir from thermal reservoir at temperature T 1. So, you see that the area under the curve which is a straight line of course, 1 2 up to the entropy coordinate that gives whatever thermal energy, I have taken from reservoir at temperature T 1. Similarly, we can get; what heat has been rejected, but let us end our discussion at this at this point we are halfway in between we will start from this particular slide and we will see what implication; we can draw from here and how we can use this concept again for energy conversion or for waste heat recovery.

Thank you.