Energy Conservation and Waste Heat Recovery
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Lecture – 08
Thermodynamic principles of waste heat recovery (Contd.)

Hello everybody, so if you recall we were discussing second law of thermodynamics. And I have told the two very important statements of second law of thermodynamics. One is Kelvin-Planck statement; and from that statement, we could get the concept of a heat engine. Then I have also giving this statement, which is given by Clausius that is Clausius statement of second law of thermodynamics. From there also we could get a very important engineering device, which operates in a cycle it can be called either a heat pump or a refrigerator

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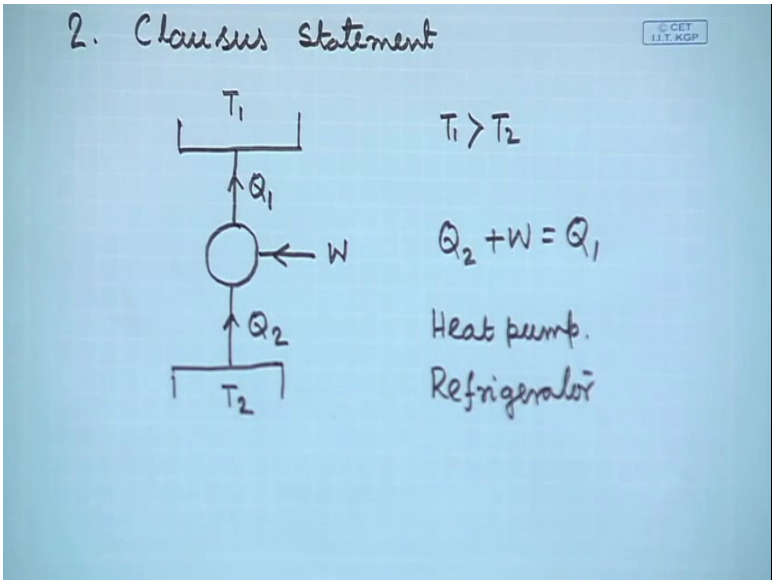

So, if we start with, so Clausius statement gives us a configuration like this, this is where we are taking some thermal energy Q 2 from a low temperature body. And with the help of mechanical work supplied from outside we are transferring or transporting this thermal energy to a high temperature body or high temperature reservoir which is at a temperature T 1. If we are interested in transferring heat to a high temperature body, we call this device a heat pump. If we are interested in extracting heat from a low temperature body, we call this device the same device as a refrigerator.

And I will draw your attention you will find that this device as far as the direction of energy transfer is concerned is just the opposites just the reverse of the device we called heat engine. So, it is some sort of a reversed heat engine. Now, for heat engine, we have defined efficiency. So, in this case also we can define some sort of a figure of merit, we do not call it efficiency, we call it coefficient of performance.

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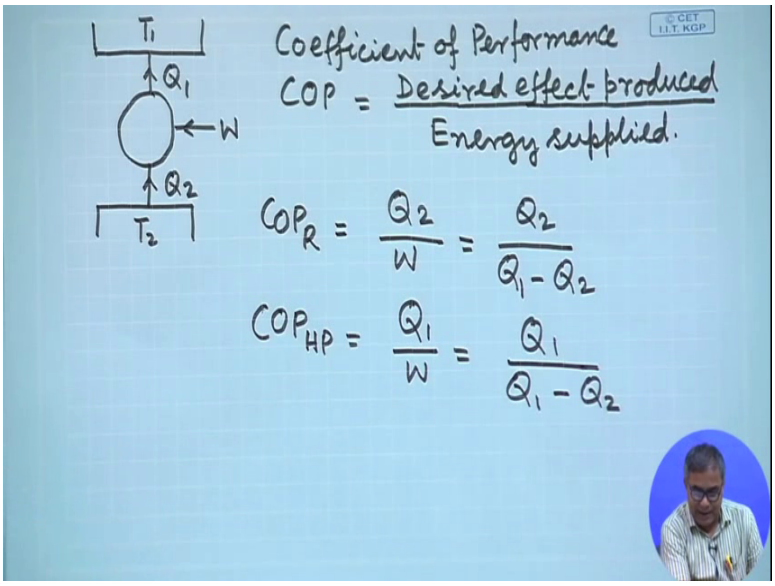

So, you see let me draw it quickly. So, this is T 1, and this is another reservoir at T 2. In between there is a cyclic device which is being operated with the help of work supplied from outside, and by this supply we are able to take Q 2 amount of heat from the reservoir at T 2 and supply Q 1 amount of heat to the reservoir at T 1. So, we are defining coefficient of performance, we call it COP; it is defined as desired effect produced by energy supplied. This energy supplied, it has to be understood that the energy, which we supply by paying something. The energy for which we are paying that is your that is meant by the energy supplied over here. And in this device we pay for the external work which we supply to run this device. So, W is the energy supplied.

Now, if we are thinking of a refrigerator COP refrigerator then our focus is the amount of heat we are extracting from the low temperature body. So, this will be Q 2 that is the desired effect and W this is what is the energy which we pay for and which we are supplying to run this device. So, it is Q 2 by W and from first law of what we can write this is Q 2 and this is Q 1 minus Q 2. So, this will be the COP of a refrigerator. In similar fashion, we can get COP of heat pump, so that will be Q 1 by W that is equal to Q 1 by Q 1 minus Q 2. So, COP of heat pump will be Q 1 minus sorry Q 1 divided by Q 1 minus Q 2.

Here again I like to draw your attention to one fact that as the efficiency of a heat engine will always be less than 1; the COP of heat pump will always be more than 1. Why, because it is Q 1 divided by Q 1 minus Q 2; Q 2 is some sort of a finite quantity nonnegative finite quantity, so that is why this part will be less than Q 1, and COP a heat pump will be more than 1. So, by this we have got the we have understood hopefully the two statements of second law of thermodynamics. There could be many statement, but these two are the most important statement, these two are the most relevant statement for engineering application. And obviously, you will find these statements are also very important for waste heat recovery. And then how to define the figure of merit for these two devices, which comes from these two statement, one is heat engine and another is heat pump, so that also has been learned.

Now, once we have done this, we have come to the engineering domain that we have got devices where energy conversion is possible continuously. All the devices, which we are talking about the operating cycle that means, they produce or they have the energy conversion continuously. Obviously as an engineer, one will be interested to know or to have this devices operating at the best possible condition. For example, we will like to have the highest efficiency of a heating when we are converting thermal energy into work we would like to have the maximum amount of thermal energy to be converted into work and when we are having heat pump or refrigerator.

We would like to have the highest COP of the refrigerator or the heat pump now is it possible to have some sort of principle then which guides us to know what is the highest possible performance of these devices. And is it possible to have when the conditions the input conditions are given, is it possible to evaluate what is the highest possible conversion. So, these are the question which we like to which we seek for which we seek answer and fortunately answer is already available in second law probably we have to learn a little bit more.

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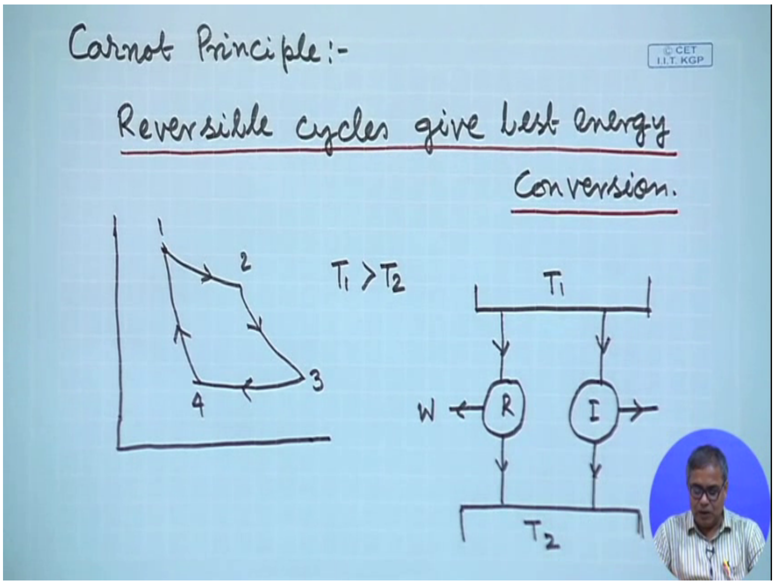

Now, here comes the epoch making findings of Carnot. So, now, we go from heat engine and a pump. We move to Carnot principle. So, Carnot he was bothered regarding the low performance of heat engine in those days of course, steam engines were there low performance of steam engine. And he tried to find out some means why the engines are not performing as they should perform what could be the best performance out of a heat engine. So, that is what he was wondering about he was searching. And then he came with some sort of simple, but very far reaching conclusion out of his research and that is that these devices are operating in cycles and best performance can be obtained from a reversible cycle.

So, what is a cycle, and what is a reversible cycle. So, let me write this, this is very important. Reversible cycles give best energy conversion, this is very important. So, though Carnot did it for in the context of heat engine, but heat engine in general one can say that reversible cycle gives the best performance for energy conversion. Now, what does it what is meant by this. So, a cycle suppose this is a thermodynamic plane, there are two coordinates of thermodynamic properties. And in this thermodynamic plane, we have got a cycle. So, cycle could be represented like this. So, there are at number of processes 1, 2, 3, 4 like this there are four processes and let say the processes are like this 1 to 2 there is one process; 2 to 3 another process; 3 to 4 another process, and 4 to 1. So, if we have started from point one we are coming back to point one. So, this is a cyclic process or a cycling.

A reversible cycle means that all the processes are reversible. And if all the processes are reversible then the direction of the cycle can be reversed. And if we reverse the direction of the cycle, then there will not be any change elsewhere neither in the system nor in the surroundings. So, here the concept of reversibility is coming. At the beginning probably in the last lecture I have told that second law gives us the concept of irreversibility; basically it gives us the concept of reversibility and irreversibility. So, this is your concept of reversibility. So, if the all the processes are made reversible then the cycle is a reversible cycle. And Carnot postulated that a reversible cycle will have the best performance as far as energy conversion is concerned.

Now if we are having a reversible cycle then what is happening, if we are having reversible cycles then Carnot has given two statements these are again postulates of Carnot. First postulate is that between two given temperature only a reversible heat engine cycle will have the highest efficiency. So, let say the temperature limits are given let say this is T 1 this is the source temperature; and let say this is the temperature T 2 that is the sink temperature and T 1 is greater than T 2. So, in between this we can have heat engine cycles. So, let say this is one heat engine cycle, and we are having some sort of work out of it. So, this is reversible and then we are having one irreversible cycle. So, this is also taking heat and converting heat into work, rejecting the rest of heat into the reservoir.

So, in no case whatever may be the design whatever may be the working principle in no case the irreversible engine will have higher efficiency than a reversible engine. If we have number of irreversible engines, all the reversible engines will have lesser efficiency compared to a reversible engine. So, this is the first postulate of Carnot. The second postulate says that within this temperature limits if we have got number of reversible cycles, number of devices which are operating on reversible cycles, then all the heating engines or all the cycles will have the same efficiency. So, it will not depend on the working fluid we are using, it will not depend on the size of the cycle we are using, it will not depend on how many processes are there in the cycle. But if these cycles are reversible all of them will have the same efficiency.

Then you see that in this thing two points are very important or two attributes are very important that that is T 1 that the source temperature and T 2 is the sink temperature. If T 1 and T 2 are given then we will get best performance of a cycle working between these two temperatures, when it is operating reversibly. And when it is operating reversibly, its efficiency is constant because all the reversible cycle will be have will have the same efficiency. Its efficiency is constant means its efficiency now it will depend only on T 1 and T 2 because these two things only we have specified.

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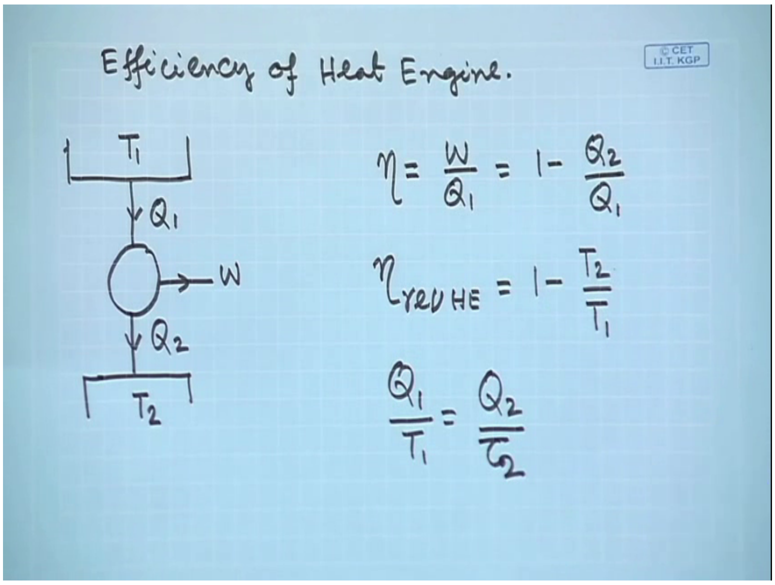

So, let us make a broad step we have defined the efficiency of heat engine. So, let say efficiency of heat engine, let me draw it once again Q 1 heat is taken, W work is produced and Q 2 heat is rejected. Q 1 heat is taken from reservoir at T 1, Q 2 heat is rejected to the reservoir at T 2, W work is produced. So, efficiency from the first law, we have got as W by Q 1, so that is 1 minus Q 2 by Q 1. So, now we know that efficiency is dependent only on the temperatures T 1 and T 2, if this engine is a reversible engine and this is of course, beyond the course because it is not a course of thermodynamics. It can be shown with some sort of a logic that efficiency of a reversible heat engine can be expressed as 1 minus T 2 by T 1, where T 2 is the sink temperature, and T 1 is the source temperature, but these are the absolute temperature or temperature according to thermodynamic scale. So, this is very, very important consequence of second law of thermodynamics that for reversible heat engine we are getting 1 minus T 2 by T 1 that is the efficiency of the reversible engine.

Basically for reversible heat transfer what we get if the engine is operating reversibly then we get the heat transfer processes are also reversibly are also taking place reversibly. Then for reversible heat transfer process, what we get is this Q 1 by T 1 is equal to Q 2 by T 2 sorry Q 2 by T 2. So, if we get this and this can be seen how it has been obtained in any book of thermodynamics then from that it logically followed that the efficiency of a reversible engine will become 1 minus T 2 by T 1.

So, now, you see that higher the T 1, the more will be the efficiency of the reversible engine. So, when we were having this introductory lectures of waste heat recovery, I have told that waste heat recovery for waste heat recovery we have to look into two aspect; one is quantity of waste heat we are getting, and another is the quality of waste heat we are getting. So, here we get some sort of equality concept of quality of energy which is also given by second law that equality of energy quality of thermal energy is associated with the temperature from which the thermal energy is extracted. So, you see quality of waste heat that is also related to the temperature from which or at which the waste heat is available.

So, now probably we can relate what we have studied or what we have discussed in some previous lecture that quality of waste heat that will be relate I mean that will be dependent on the temperature at which the waste heat is available. So, then for converting waste heat very usefully profitably not only the amount of waste heat which is available that is important. It is also important at what temperature that waste heat is available. The higher the temperature suppose the waste heat we are utilizing in a heat engine to produce some sort of work more work can be produced if the waste heat is available at a higher temperature. Same amount of waste heat is available at a higher temperature we can extract more work; the waste heat same amount again is available at a lower temperature, we will not be able to extract the same amount of work out of it the equal amount of work out of it. When it is available at low temperature, we will have lower amount of lesser amount of work out of it. So, this is very important. And we are getting also the concept of quality of energy from this.

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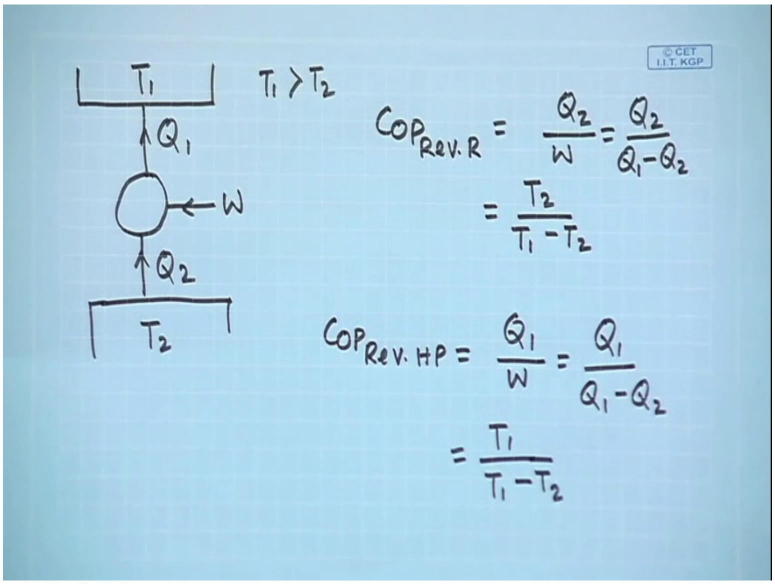

Let us now see with this principle what could be the COP. So, again this is the temperature T 1 and we are having a cyclic device which is operating in the reverse direction. Work is supplied from outside, it is taking Q 2 amount of heat from a reservoir which is at T 2, where T 1 is greater than T 2. And supplying Q 1 amount of heat to a reservoir which is at a higher temperature at T 1. So, this can be seen either as a refrigerator or as a heat pump. So, COP reversible refrigerator that will be Q 2 by W that is equal to Q 2 by Q 1 minus Q 2; and as it is reversible we can write it will be T 2 by T 1 minus T 2. COP reversible heat pump that will be Q 1 by W and that is equal to Q 1 by Q 1 minus Q 2 and in terms of absolute temperature, we can write T 1 minus T 1 divided by T 1 minus T 2, T 1 upon T 1 minus T 2. And as T 1 is higher compared to T 2, we will had COP of heat pump more than one same thing what I have told earlier.

So, you see now the ideal performance of these two devices, heat engine and heat pump that is available or that is known to us. So, obviously, I had told in previous lecture, the best strategy of waste heat recovery is to produce no waste heat or produce the least amount of waste heat. Waste strategy of energy conversion will be produced to convert it in the most efficient way. So, now from second law, we know that if we have adopted the most efficient way of energy conversion what could be the figure of merit of these new important devices one is heat engine and another is heat pump. So, as far as this discussion is concerned, this is very useful for both energy conversion and waste heat recovery. And then we have also got the idea regarding the quality of energy. So, quality of energy particularly, when it is thermal energy, so that is directly dependent on the temperature at which it is available, so that holds good for waste heat also.

So, quality of energy again let me tell you one thing we have got energy in transit there are two forms; one is work and another is heat. For work there is no division, but heat or thermal energy, there is something associated with it that is temperature. So, what is the highest quality of work is having the highest quality of energy, then or it is the highest grade of energy, then heat or thermal energy is a lower grade of energy. Again in heat or thermal energy, there could be division, there could be again different quality of the thermal energy and that quality depends on the temperature at which that thermal energy is available.

So, now I think with the second law of thermodynamics this picture is clear. And with this information at our hand, we can proceed for planning, for designing, for selecting different waste heat recovery techniques or principles and again for equipment selection also this helps us. With this, I like to end today’s lecture. In the next lecture, we will come to another important concept that is entropy. And from there, we will go to exactly again these concepts again these concepts may be known to many of you, but for the sake of completeness we will do this and then with that we will come to an end to our discussion on thermodynamics which is relevant for waste heat recovery

Thank you.