Energy Conservation and Waste Heat Recovery
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Lecture – 09
Reversible Cycles

Hello everyone, we are continuing with our discussion of thermodynamic laws and principles, particularly we are interested to see how these laws and principles can be employed for waste heat recovery system for the design and analysis of waste heat recovery system. Now, so far what we have done, we have introduced first law of thermodynamics, first law of thermodynamics how it can be applied for cycles, for a process for closed system, for a process for open system these we have seen. We have seen second law of thermodynamics, what are the statement of second law of thermodynamics.

Second law of thermodynamics, when we discuss the classical statements, now we get two very important engineering devices that is heat engine and refrigerator. Refrigerator can also be used as a heat pump. So, these devices what is their working principle that we have seen from thermodynamic point of view not from mechanical point of view maker not from the mechanism point of view, but from thermodynamic point of view what is a heat engine, what is a refrigerator, and what is a heat pump this we have seen. Then we have learned a very important concept, which is within the purview of second law of thermodynamics that is Carnot principle.

And by Carnot principle we could learn that that if there are two thermal reservoirs thermal reservoirs are specified by their temperature. So, if there are two thermal reservoirs whose temperatures are known, and then if a reversible heat engine works between these thermal reservoirs then it will have a fixed efficiency. And then the fixed efficiency it follows from this particular statement then the efficiency of the reversible heat engine will be dependent only on the temperature of the reservoirs. Based on this principle one can derive a scale of temperature, which is known as thermodynamic scale of temperature or the absolute scale of temperature and temperature in this scale we denote by a capital T.

So, proceeding in this way we could derive the figure of merit for ideal devices like ideal heat engine or reversible heat engine reversible refrigerator and reversible heat pump in terms of the temperature of the reservoirs. In case of heat engine this figure of merit is called efficiency; in case of refrigerator and heat pump, we call it the COP or coefficient of performance. So, this we have got from our discussion whatever we have done for second law of thermodynamics. So, I like to continue little bit with the Carnot postulates and what Carnot said it has got far reaching consequences and we cannot discuss waste heat recovery unless we understand and appreciate Carnot principle.

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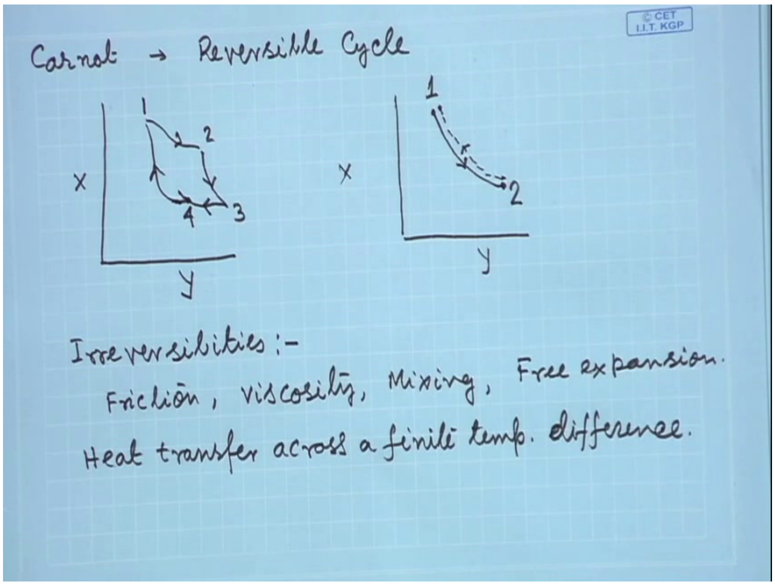

So, you see Carnot has talked about reversible cycle. I have already discussed that a reversible cycle is a cycle, which will constitute number of processes the cycle will have a series of processes taken in succession and so that one can come back to the initial point of the cycle itself. It can be represented something like this, lets say this is a thermodynamic plane there are two coordinate which a thermodynamic properties X and Y and in that we can have a cycle like this.

So, you see this is 1 to 2 one process, this is 2 to 3 another process, this is 3 to 4, and then 4 to 1 the fourth process. So, there are four processes and it is making a cycle. Now, if we are talking about a reversible cycle then what happens all the processes should be reversible processes. So, Carnot also gives us the concept of reversibility, and I like to take some time discussing what is reversibility.

See reversible process will be a process let say again on the same thermodynamic plane we are having a reversible process. So, reversible process initially the system is at state point 1, and then it has undergone a reversible process, and it has reached to state point 2. Due to this, there will be some property change of the system at the same time during the process the system may interact with the surrounding. So, there could be some changes in the surrounding all right.

Now, if it is a reversible process then I should be able to take it back in the opposite direction that means, in the forward direction it has gone from 1 to 2, now I will be able to take it back from 2 to 1. So, in the second case, my initial point is 2 and my final point is 1. And if I do so, obviously, initially whatever was the system property I have come back to 1, so system property will be the same, but what about the environment. Whether the changes I have made in the environment for the process 1 to 2, if those changes are reversed back, no effect of those changes are remaining after we complete the reverse process that means, process 2 to 1 then only we will call the process 1 to 2 is a reversible process.

So, this is what is meant by reversible process. And it may be stated probably you also know because most of you have gone through thermodynamics that no process in nature, no process in practical life day-to-day life is a reversible process. See all the processes are irreversible processes, but for the sake of our discussion to get some sort of an ideal condition to know what is the best possible outcome of any energy interaction process we can think of ideal process or a reversible process.

So, in that what we try to do, we try to eliminate at least theoretically, at least ideally, all the effect of irreversibilities from the process. So, now it becomes important to know what are the irreversibilities. So, during a process there are many irreversibilities, because there are many dissipative action. Like when there is a motion and one solid moves over another solid, so there will be friction. So, this friction is a dissipative effect or dissipative action due to which some amount of energy will be spent and that cannot be recovered back in useful form that will go to some other form which cannot be reused again or which cannot be reused again with simple means. So, this is some sort of irreversible process.

So, similarly there are effects which makes the process irreversible, friction is one, viscosity for fluid bodies that is another, then mixing of two fluids that is another, then free expansion that could be yet another process in which irreversibility generates. Free expansion, what is free expansion suppose there is a chamber which is under vacuum and then somehow a leak is created at the wall of the chamber. So, what will happen the atmospheric air that will rush into that the chamber which was initially under vacuum. So, then the atmospheric air that is expanding this expansion could have produced some amount of work, but now when it is going into the vacuum chamber without any resistance freely. So, this possibility of doing certain amount of work is lost, and at the same time it is an irreversible process.

Why it is irreversible process, see if we live leave this system as it is; that means, once atmospheric air has gone into this vacuum chamber, we leave it like this, the air will not spontaneously come out of this vacuum chamber and go to the atmosphere. So, this is a an example of irreversible process and pre expansion is a cause of irreversibility, but these are generally inside the system. See some irreversibilities are there when there is interaction between the system and the surrounding, so that is heat transfer and more correctly heat transfer across a finite temperature difference.

So, internally, what we get generally friction, viscosity, mixing, free expansion etcetera, these are the causes of your irreversibility. But at the system boundary when there is heat transfer, when there is heat transfer and that is that two across a finite temperature difference then we get another kind of irreversibility. And obviously, in these cases the process is irreversible. In these cases, if the process is a part of the cycle then the cycle is also irreversible. With these few words now let us go ahead to now let us go ahead to see how an ideal cycle can be constituted, which is known as Carnot cycle.

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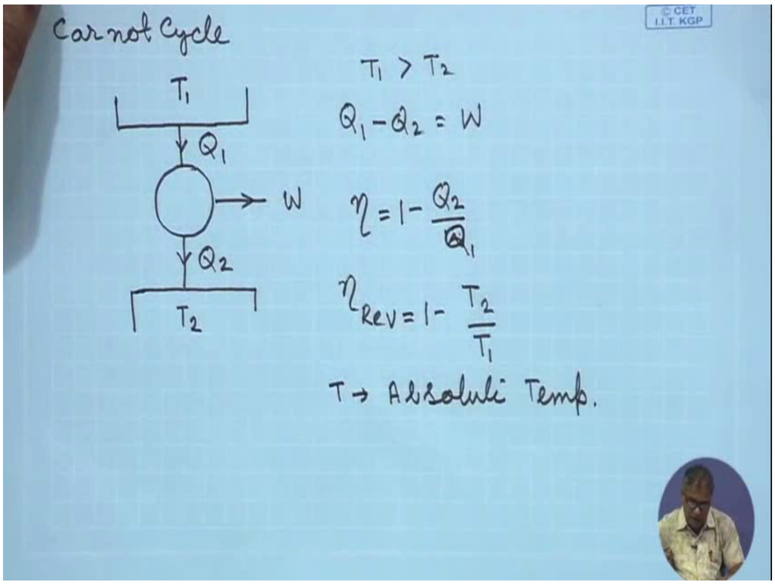

So, conventionally when we talk about Carnot cycle, we talk about an ideal or reversible cycle, and we talk about the heating in cycle though ideal and reversible refrigeration or heat pump cycle is also possible. So, symbolically if I draw a heat engine, it looks like this. As I have told it operates in a cycle, the circle represents that it takes Q 1 amount of heat from a temperature reservoir, which is at a high temperature that is T 1, and then rejects Q 2 amount of heat to a reservoir which is at a low temperature that is T 2 and then it does certain amount of work which is W. From first law, we know Q 1 minus Q 2 is equal to W and then obviously, T 1 is greater than T 2. Efficiency is equal to let me write it once again 1 minus Q 2 by W efficiency of ideal heat engine or reversible heat engine that is equal to 1 minus T 2 Q 2, sorry the efficiency will be 1 minus Q 2 by Q 1. And for reversible engine, efficiency will be 1 minus T 2 by T 1, T is the absolute temperature. So, with this, this of course we have done earlier, but with this background let us try to think that what could be the ideal cycle or Carnot cycle.

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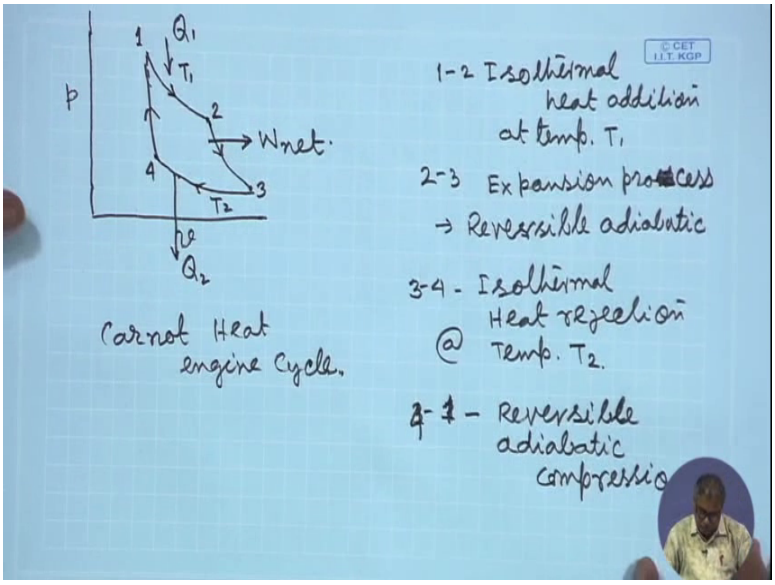

So, ideal cycle or Carnot cycle let say we have got some sort of thermodynamic some sort of thermodynamic plane on this we can represent this cycle. For the sake of convenience, we can take p and v, where p is the pressure and v is the specific volume. And we have taken a thermodynamic substance which is a compressible fluid. There could be different thermodynamic substance, but the substance which we have taken which is the working fluid of the cycle that is a compressible fluid. And then if we go back to our previous diagram, the first process is that we have to take certain amount of heat from a thermal reservoir which is at a high temperature, and then we have learned that he transferred across a finite temperature difference is irreversible.

So, there must be heat transfer, but this heat transfer should learned be across a finite temperature difference. So, then only possibility is that this heat transfer has to take place isothermally; that means, this heat transfer has to take place at a constant temperature. So, the first process what we have we have an isothermal heating 1 to 2, 1 to 2 isothermal heat addition at temperature T 1. Then once we have received the thermal energy, so we can do certain amount of work. So, we will do certain amount of work that is W amount of work I will do. If I do W amount of work then what will happen then in this process we should not create any kind of irreversibilities. During this process, what will happen if I try to get the work out of expansion then there will be change in temperature. If there is change in temperature, so during this process to avoid irreversibility I cannot have any heat transfer.

So, then I should have some sort of an expansion process 2 to 3, 2 to 3 - expansion process, but this expansion process has to be reversible again. So, it should be reversible adiabatic; that means, there will be change of temperature obviously, but there will not be any heat transfer. So, there is no heat transfer though there is a finite change in temperature. So, this is again a reversible process. So, third thing I have done the work now I have to reject certain amount of heat, and I have to reject this heat to a low temperature reservoir.

So, if I do that again I have to select one isothermal process, because we know that heat transfer across a finite temperature difference is irreversible. So, 3 to 4, we have reached 4 now that will be isothermal heat rejection at temperature T 2. So, this is at temperature T 1, and this is a temperature T 2. Here we are getting Q 1 amount of heat transfer to the cycle here the cycle is rejecting Q 2 amount of heat to the surrounding. So, then we are in midway, if we have to complete the cycle, we have to go back to point 1. So, there is a change in temperature T 2 to T 1, there is a change in temperature, so obviously, I have to select the process which will allow me this change of temperature. At the same time, we have to select the process which will allow me reversible action that means, if there is temperature difference I cannot go for any heat transfer.

So, 4 to 1 that will be reversible adiabatic compression, it is a compression process, because by this process we are having some sort of elevation in temperature. So, 4 to 1 will be the reversible adiabatic compression. So, by this we will complete the cycle which will be a reversible cycle and is known as Carnot cycle, Carnot heat engine cycle. So, this is a very important concept and it will be utilized I mean it will be very helpful while we will analyze different cycles and not only that while we will try to take some decision or some sort of design we want to do for waste heat recovery system. So, this concept will be very useful. And here you see the cycle is operating between temperature T 1 and T 2, and then there will be heat transfer from T 1 to T 2 while there is certain amount of work W. So, this we can call W net out of this cycle.

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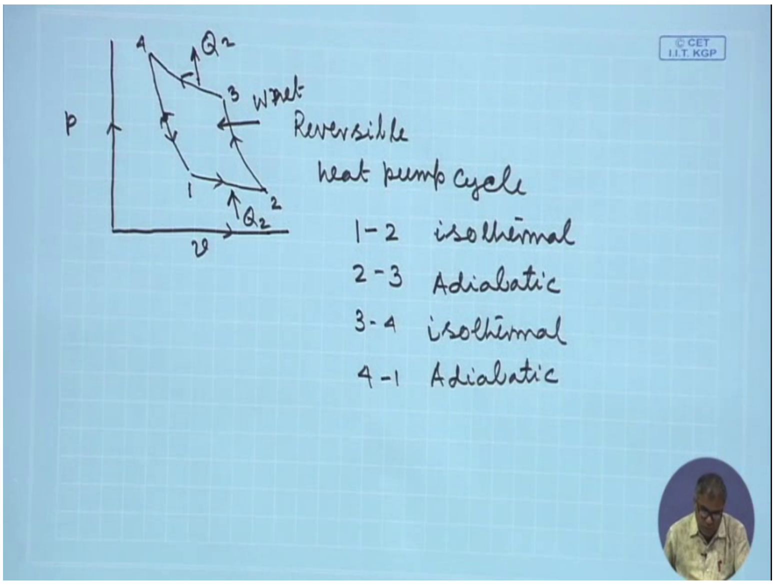

So, this gives us the concept of reversible Carnot cycle. I have shown one heat engine cycle. Similarly, one can think of a reversible heat pump cycle. So, a reversible heat pump cycle will look like this let say I start 1 from here, 1 to 2, 3 and 4. So, what are the processes 1 to 2 we get isothermal process; and then 2 to 3, it is a compression process, so 2 to 3 is adiabatic compression process. Then again 3 to 4, there you will be another isothermal process sorry this arrow mark will be in the opposite direction. So, 3 to 4, there will be another isothermal process and finally, the cycle will be closed with the final process that is 4 to 1 which is again an adiabatic process.

So, by this we are getting a reversible heat pump cycle. How, again let me write 1 to 2 - isothermal, 2 to 3 - adiabatic, 3 to 4 - isothermal, and 4 to 1 - again adiabatic. And we will have like this Q 2 heat is entering, Q 1 heat is going out of the cycle, and some sort of W net that is supplied to the cycle, to run the cycle we have to supply certain W net. So, with this we can understand how the reversible cycle both for a heat engine application and heat pump application can be constituted following Carnot principle. So, this is a very good concept and we like to proceed further with our discussion. So, let me take a small addition or rather small extension of this principle, which was developed by Carnot.

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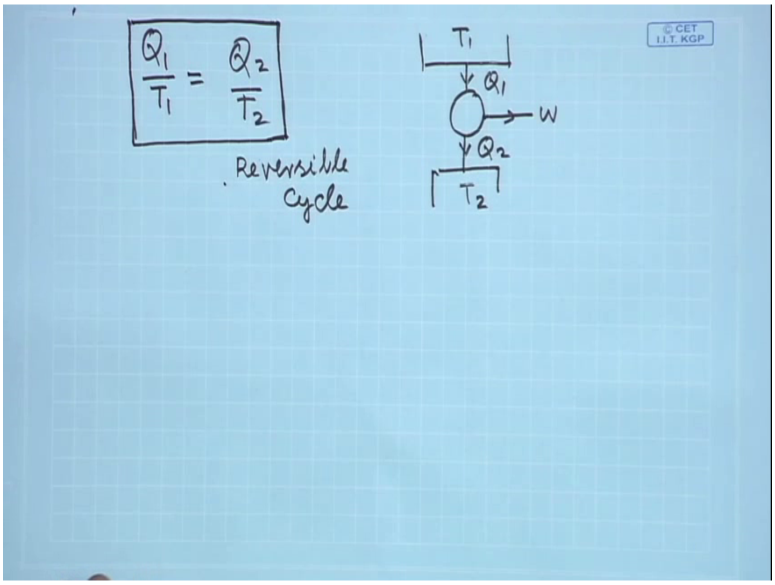

So, according to Carnot principle what we have got that Q 1 by T 1 that is equal to Q 2 by T 2, where Q 1 is the heat supplied to the cycle Q 2 is the heat rejected to the cycle and T 1, T 2 are the temperatures. Now, only thing is that we have to qualify this because this is for if reversible cycle. So, this is also another principle which has been given by Carnot, which is utilized for deriving the efficiency or the COP of Carnot cycle is very useful when we try to see how the energy transfer is taking place. It is also very important to know whether there is any irreversibility in the system, because if there is irreversibility, we cannot apply this particular relationship.

If there is reversibility if the cycle is reversible then we can apply this and from the application of this principle that is Q 1 by T 1 is equal to Q 2 by T 2 we can derive consequences which will be very useful in our practice, in our engineering practice. So, with this, I like to close this lecture. In the next lecture, we would try to take some example from the domain of heat engine and then we will see how it can be related to our waste heat recovery devices, and how it can be, how Carnot principle helps us to know what we can extract from the waste heat recovery devices.

Thank you.