Energy Conservation and Waste Heat Recovery
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Lecture - 15
Second Law efficiency (Contd.)

Hello everyone if you recall we were discussing regarding second law efficiency of cycles or processes. We have seen the Exergy the analysis of close system and open system basically we have derived the derived the generalized equation of Exergy balance or Exergy T; transport taking an open system and from there one can easily derived the Exergy balance of a closed system. So, here we have introduced a very useful concept which is called Exergy, whenever there is energy transfer not that entire amount of energy we can convert into useful work, only part of this can be converted into useful work and again if we consider the interaction with environment the presence of environmental pressure, then only part of this useful work is available.

Because when a control volume or system expands, it will do certain work for the atmospheric pressure also which we cannot utilize which is not our goal. So, we have defined all these quantity that if there is any energy transfer what is the Exergy, if there is any heat transfer how much what quantity of heat can be converted into useful work; all this we have defined and based on that we have defined the second law efficiency, which is based on the concept of Exergy or concept of available energy.

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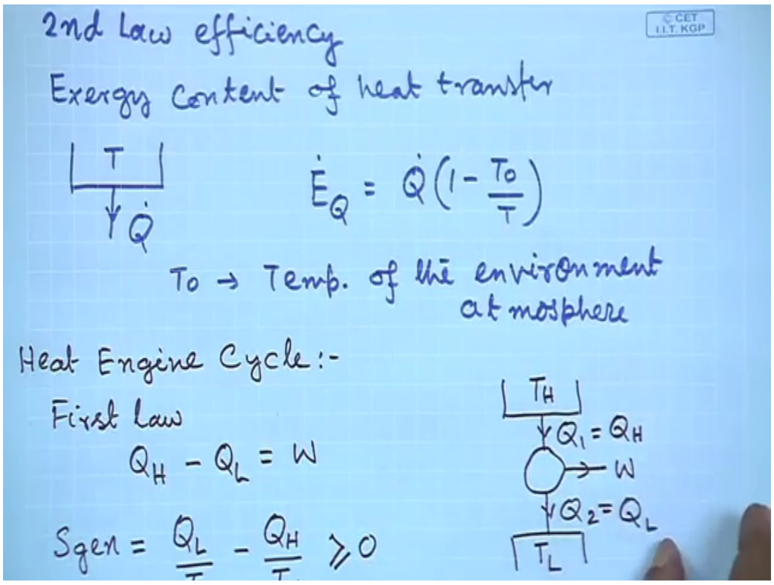

Now, if we proceed with the same concept. So, let us look into details the second law efficiency, first I like to define or recall what is Exergy content of heat transfer. So, whenever we are considering heat transfer, heat transfer is taking place from a body at a high temperature relatively higher temperature.

Let us say that body is at a temperature T and from there we are extracting heat, and let us say this heat flow rate is Q dot. Then Exergy content of heat transfer EQ dot that is equal to Q dot into 1 minus T 0 by T, where T 0 is the temperature of the environment or atmosphere because environment or atmosphere is the ultimate sink where the thermal energy is dumped.

Now, let us apply this to heat engine cycle let us apply the concept which we have learnt so far to heat engine cycle. So, heat engine cycle. So, for heat engine cycle first law we can write if side by side we are having one heat engine cycle. So, let us say this is the heat engine cycle we have got Q 1 over here Q 2 over here w over here, Q 1 can also be written as QH.

As it is taken from a high temperature source, Q 2 can also be written as QL as it is rejected to a low temperature sink and then this temperature we can denote as TH source temperature and the sink temperature we are denoting as TL. So, from first law what we can write is that QH minus QL that is equal to w. So, this is our first law of thermodynamics from energy balance we get this.

Now, we can easily calculate what is the entropy generation during this process s gen the formula which we have discussed in our earlier class. So, that will be equal to QL minus T QL by TL minus QH by TH and this is a quantity, which will be a nonnegative quantity. So, it is greater than equal to 0.

So, w lost, lost work if we want to calculate this also we have derived earlier. So, this will be e QH minus EW.

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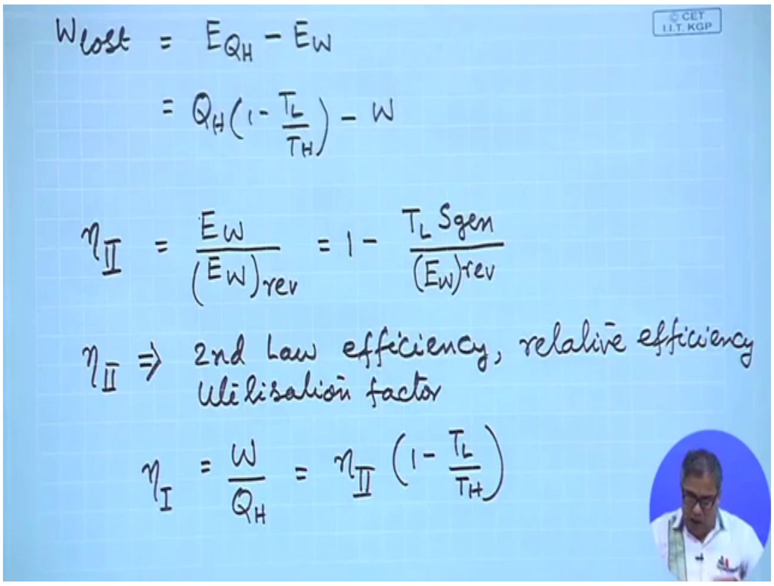

So, let us say in this heat engine cycle we have got some amount of work done and EW is the Exergetic content of Exergy content or exergetic content of work, we are taking some thermal energy QH from a high temperature source. So, EQH is the exergitic content of the thermal energy which is taken from the high temperature source, now the lost work will be the exergitic content of the high temperature source the exergitic content of work W. So, this can be written as the first term can be written as QH 1 minus TL by TH and this is simply W Exergy of work is the work itself, there is no change.

So, this is what we will get lost work. So, you see all the concept which we have learned in our earlier lecture the concept of entropy generation, concept of lost work everything we can do it for a cycle or even for a process also, we can do it. Now let us define the second law efficiency the second law efficiency can be defined as EW the Exergy content of work done, and then this divided by EW reversible.

Basically Exergy the content of the reversible work that is what we have written here, this can be written in another form also with some algebraic manipulation, this is 1 minus TL into S gen assuming TL is the lowest temperature available. So, that is y; TL multiplied by s gen divided by EW reversible.

So, you have to identify your appreciate one thing. So, EW what we have written at the numerator that is nothing, but n EW reversible minus the irreversibility that is your TL into S gen so that is how we have got this. So, either of these 2 or formally we can use and we can determine the second law efficiency. So, eta 2 that is second law efficiency some people call it also relative efficiency or utilization factor. Now eta 2 then what will be eta 2; eta 2 by this we can get a relationship between eta o1and eta 2, eta 1 is the first low efficiency that is equal to w by QH work done divided by thermal energy taken from the high temperature source and that is equal to u eta 2 multiplied by o1 minus TL by TH.

So, you see the term within the bracket within the parenthesis is the first law efficiency and that is multiplied by a factor. So, that is why sometimes it is called relative efficiency or it is utilization factor because whatever we have got that has to be multiplied with some utilization factor, to know the actual utilization what is possible of the thermal energy actual utilization of the thermal energy which is possible. So, this is your eta 2.

So, we can have the perspective of both first law and second law for a heat engine.

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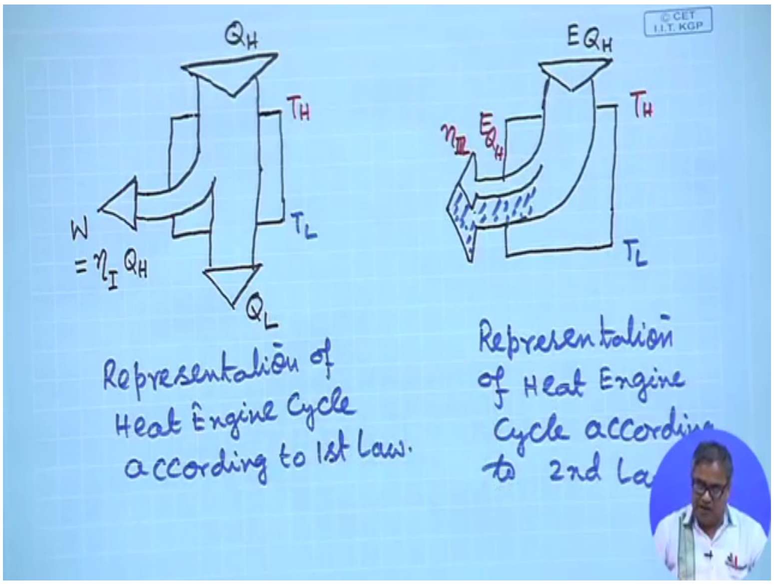

Let us see how we can express it. So, first I am trying to draw it for first law. So, first law we can represent the energy flow by this diagram; let us say the square which I have drawn that represents the; that represents the heat engine cycle. So, at the top of it we have got TH high temperature at the bottom of it we have got TL low temperature.

So, this is the hot end of the heat engine cycle this is the cold end of the heat engine cycle. So, QH amount of heat that is entering the heat engine cycle, well w amount of work is being done and that is equal to we can write eta 1 into QH and then QL amount of heat that is rejected. So, you see thermal energy is entering, but part of it is getting converted into work, that is; what is the perspective of the first law of thermodynamics.

So, we can write representation of heat engine cycle according to first law according to first law then from second law if we try to represent this. So, from second law if we try to represent this then it will be something like this. So, it is representation of heat engine cycle according to second law. So, what we have got? Here some Exergy is entering the cycle which is again represented by these 2 temperatures TH is the hot end and TL is the cold end and then what is going out see this is going out eta 2 into eta 2 into EQ H. So, EQ H is the in a Exergy content of the heat which is taken from the high temperature source, this multiplied by your eta 2 that is what is getting converted into work and that is going out.

Then some other Exergy is also going out, but this Exergy; we are not able to equalize. So, this Exergy I am showing by some sort of a setting. So, in this case in the second case Exergy is coming in Exergy is flowing into the cycle and again exedy is going out of the cycle, but part of the Exergy it is the Exergy content of work which can be obtained by this relationship and part of this will be going to the low temperature source and that is shown by the setting. So, you see we are not differentiating between work and heat as we have done in the first case, in the second case; oh; all are Exergy, but a part of it is the Exergy content of the work done. So, that is what we are interested in now, let us see that we have seen for heat engine the 2 temperatures they are very important TH and TL.

Similarly, I can repeat whatever I have done or you can also do it yourself whatever I have done for a refrigerator or a heat pump now this will be some sort of repetitive exercise. So, that is why we are not going into it rather what we like to do let us see how the efficiency or the coefficient of performance of these devices that vary on what parameter they will vary they will vary only based on these 2 temperatures that is the high temperature and the low temperature here let us make some sort of a change or let us adopt a particular methodology.

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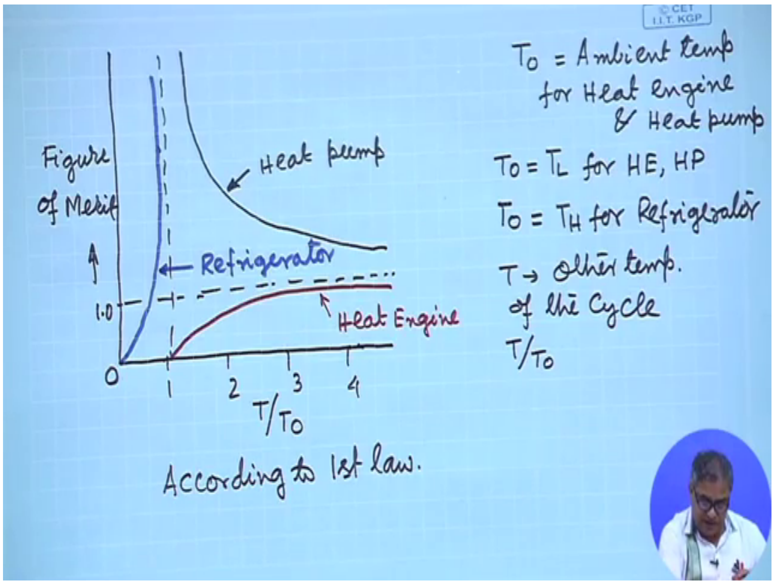

Let us say we are defining T 0, T 0 is the ambient temperature for heat engine and heat pump. See for all these devices for all these devices there will be 2 temperatures, one will be a high temperature and another will be a low temperature.

So, the low temperature in this case in almost in all the practical application the low temperature in case of heat engine and heat pump in almost all the practical application is the ambient temperature. So, I am defining or denoting it by P 0 T 0. So, T 0 is basically TL for heat engine or heat pump T 0, T 0 is TH for refrigerator the logic is very clear refrigerator has to maintain a space at a low temperature and the temperature should be lower than that of the ambient temperature. So, in case of a refrigerator ambient temperature is the highest temperature or maximum temperature and the temperature of the space where we are maintaining the where we are producing the cooling effect that will have a low temperature compared to the ambient that is why the ambient temperature T 0 here is equal to TH and the parameter which we want to take.

So, one temperature I have defined another temperature I am defining as T, T is the other temperature of this cycle and the parameter which I like to define that is T by T 0. So, T by T 0 for heat engine and heat pump it will be something and it will be slightly different for your refrigeration. Now based on T by T 0 if I have this figure of merit. So, this side let us say figure of merit this is figure of merit and this side the coordinate starts from 0 in this direction it increases, and this side we have got T by T 0 and we have got values like 1, 2, 3, 4, etcetera, then we can have 2 envelopes, this is also one heat engines will have figure of merit within this envelope.

So, this is your heat engine refrigerators will have their figure of merit within this envelope, this is your refrigerator and heat pumps they will have the figure of merit like this. So, this is your heat pump and it is according to first law. So, you see this will be the figure already I have told when I have introduced heat pump, that heat pump always will have its figure of merit more than one and that is what we are seeing and how it is changing with T by T 0 that also we can find out from this figure, and then heat engine will have its um efficiency always below one that is also we are getting and refrigerator of course, it can have.

Even below one and above one that is also you are getting. But the thing is that all of them are cycles only the direction of energy transfer is different and we are getting such a different figures in such different figures for different components. So, second law gives us an opportunity to unify them. So, by second law what we will get by second law we will get a figure like this.

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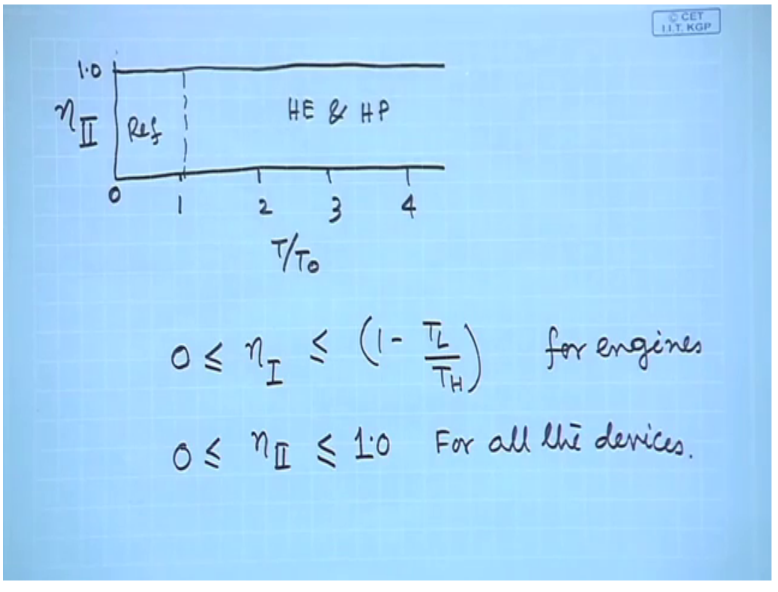

So, this is your second law efficiency or relative efficiency, this is 1 and this is one this is 0 of course, 2 thre3 4and this quantity is T by T 0 as before. So, what we will get we will get all the figure of merits or all eta 2 within this envelop and refrigerator we will get in this zone, heat engine and heat pump we will get in the other zone. So, you see this gives some sort of an unification and all right different cycles can be compared better.

Because the limit of a figure of merit that is now from 0 to 1. So, this is one of the advantage of second law efficiency. So, second law efficiency of course, can be defined for other cases also, but this is readily one can show one advantage of this. So, what we can write from this exercise, first law efficiency that is 1 minus TL by TH for heat engine of course, for engines and second law efficiency what one can write eta 2 this is 1.0 for all the devices. What I mean to say as for heat engine we I have written this one can write similar figures for heat pump and refrigerator, but when we adopt second law then all the devices their figure of merit or the relative efficiency second law efficiency all will fall within this range 0 to 1.

So, this gives a better comparison and this also gives us knowing the absolute value of the figure of merit, whether there is any scope of improvement how difficult will be the improvement if the eta 2 value is let us say close to point 8, we know that further improvement will be difficult if it is point 2 point 3 then one can try of course, that one can prime of as you say that there is an opportunity or there is a possibility of improving this efficiency. So, this also holds good this also holds good for waste heat recovery devices, waste heat recovery principles what we are going to adopt and there also if we do this kind of an analysis it will easily or it will readily give us whether there is a possibility or not.

So, with this I like to conclude or end our discussion on thermodynamic principles now we will go for the application of thermodynamic principle. What we are going to do in the next series of lectures next couple of lectures, we are going to look into different cycles particularly power cycles heat engine cycles and see how the thermodynamic principles can be applied and also we like to see where we have got a opportunity for waste heat recovery. How these cycles can be utilized for waste heat recovery or how these cycles can be modified for waste heat recovery.

Thank you.