Energy Conservation and Waste Heat Recovery

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Lecture - 14

Exergy, Second Law efficiency

Welcome back. So, we were discussing regarding Exergy in fact, we were deriving Exergy in a general way, taking a multi port control volume with a number of thermal interactions with a number of thermal interaction at different temperatures.

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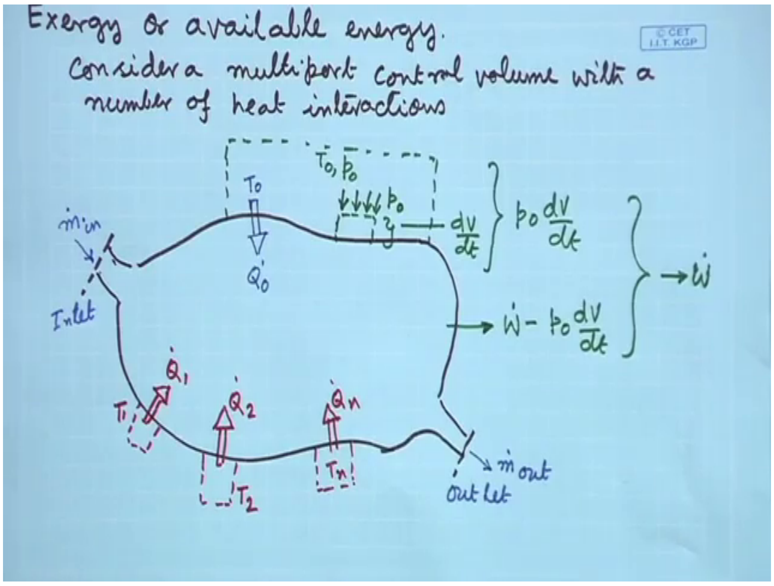

Exergy or available energy.

Consider a multiport control volume with a number of heat interactions

And let me quickly show this is the port configuration, which I have sorry, this is the multi-port control volume I have shown; this is the; a interaction with the control volume and the environment the different modes of heat transfer and mass exchange and work transfer that has been shown.

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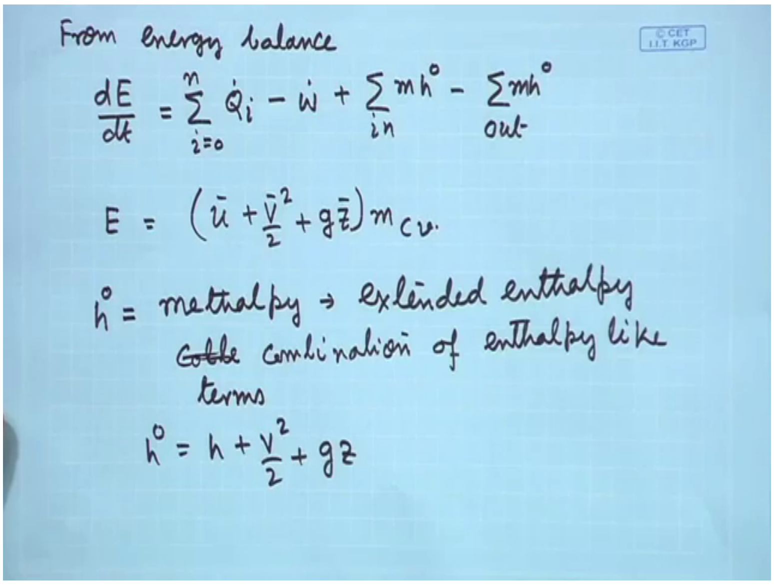

From energy balance

$$\frac{dE}{dt} = \sum_{i=0}^{n} \dot{Q}_i - \dot{W} + \sum_{in} m h^0 - \sum_{out} m h^0$$

$$E = \left(\bar{u} + \frac{\bar{V}^2}{2} + g\bar{z}\right) m_{c.v.}$$

h^0 = methalpy → extended enthalpy

~~Coble~~ combination of enthalpy like terms

$$h^0 = h + \frac{V^2}{2} + gz$$

And then we have also written the energy balance equation, this is the energy balance equation for the control volume we have written.

What we have done to make it make this expression little bit small, we have introduced a term called methalpy; methalpy is a collection of all the enthalpy like terms like enthalpy this is kinetic energy potential energy, which are associated with a stream of mass when it is coming in or going out of the control volume. So, this is our first law of thermodynamics or from the energy balance.

Similarly, we can write the second law of thermodynamics, particularly in the form of entropy balance equation and the entropy balance equation, we can write it like this.

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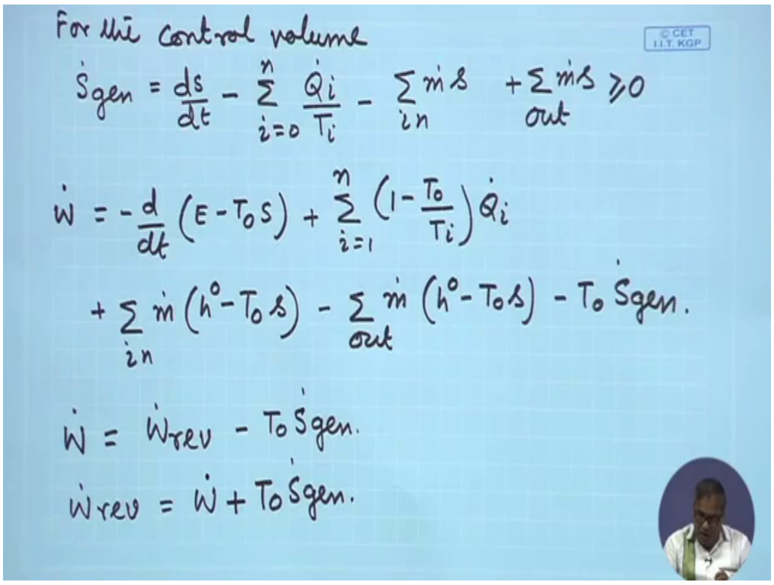

For the control volume

$$\dot{S}_{gen} = \frac{ds}{dt} - \sum_{i=0}^{n} \frac{\dot{Q}_i}{T_i} - \sum_{in} \dot{m} s + \sum_{out} \dot{m} s \geq 0$$

$$\dot{W} = -\frac{d}{dt}\left(E - T_0 S\right) + \sum_{i=1}^{n}\left(1 - \frac{T_0}{T_i}\right)\dot{Q}_i$$

$$+ \sum_{in} \dot{m}\left(h^0 - T_0 s\right) - \sum_{out} \dot{m}\left(h^0 - T_0 s\right) - T_0 \dot{S}_{gen}.$$

$$\dot{W} = \dot{W}_{rev} - T_0 \dot{S}_{gen}.$$

$$\dot{W}_{rev} = \dot{W} + T_0 \dot{S}_{gen}.$$

For the control volume we have got S dot gen that is equal to ds dt, change up entropy within the control volume minus sigma i is equal to 0 to n, Q dot i by Ti minus m dot S in plus m dot S out and this S dot gen that will be a nonnegative quantity, it could be 0 or it will have a finite positive value that is your entropy generation.

Now, you see I have written first law of thermodynamics for the control volume and also I have written the entropy balance equation for the control volume and we like to make a we like to combine these 2 and the a point is that, the entropy balance equation where all the terms are the having the unit of entropy. So, that is different from the unit of work or heat which is there in the first law. So, what we will do in the second equation that this the entropy balance equation we will multiply it with T 0. Both sides of the equation we will multiply by T 0, T 0 is the temperature of the environment already I have defined that.

If I do that and then if we combine the first law and second law; that means, entropy balance equations and the energy balance equation we will get this result that interesting result we will get. W dot that is equal to minus d dt of E minus T 0 s plus i is equal to 1 to n 1minus T 0 by Ti multiplied by Q dot i plus m dot minus. So, basically this is a rate equation. So, rate at which work will be done by the control volume is what we get from this equation. Left hand side the rate at which work is done by the control volume, right hand side what do we have.

The first term is the change of energy within the control volume minus T 0 into S, where S is the where s is the entropy total entropy of the control volume, here this is what we get due to heat interaction at a temperature Ti, this is the energy which is entering the control volume minus T 0 into s and this is the energy which is going out and last term that shows the entropy generation term. So, this gives a very useful consequence that if this is the work done and if the process is not reversible then probably we could have done some more work if the process would have been a reversible process; that means, from different kind of energy conversion if we have got this much of work.

We could have got more than this if our conversion process would have been a reversible one our conversion process would have been devoid of any irreversibility. So, easily we can do that we can write W dot is equal to W dot reversible minus T 0 S dot gen, and W dot reversible is equal to W dot plus. So, W reversible we can get by basically what we can we have to do by basically if from the left hand, sorry; right hand side expression, we removed T dot T 0 S dot gen, then we can get the expression for W reversal another thing. We can get very useful information that is W dot reversible is greater than equal to W dot.

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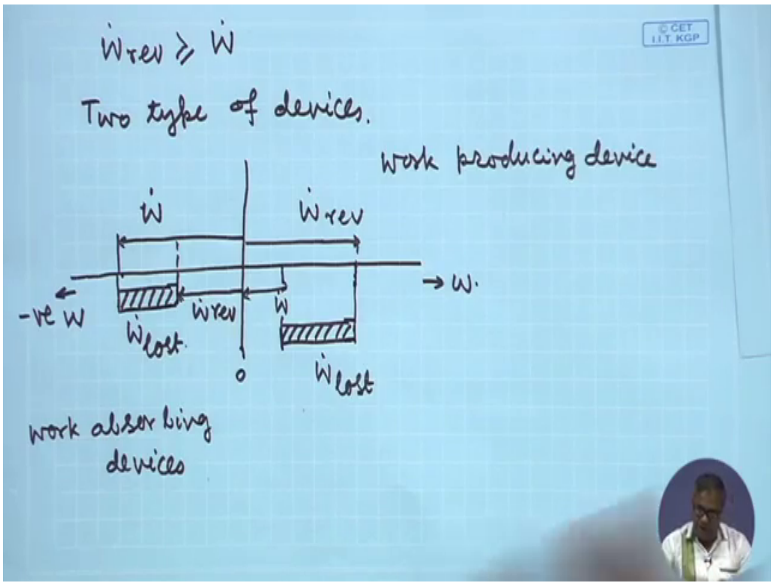

So, what I have told that I wanted to introduce the concept of energy; sorry Exergy or available energy. So, this is how we get the concept. Now whatever energy conversion is there we can get some sort of a maximum work or reversible work, and this reversible work can be also called the available work and then that can be obtained by the combination of first and second law; the way I have explained the way we have derived it. So, this W reversible is greater than W; what does it mean? There are 2 types of devices 2 type of devices; let us say some of the devices are producing energy and some of the devices are absorbing energy. So, these are energy or work producing devices work producing devices this side.

This is 0 and work is positive in this direction and this is work absorbing devices work absorbing devices. So, what do we get this side work that is negative? So, what we get is like this reversible work will be. So, during a process this is the reversible work W dot W dot reversible and actual work will be somewhere over here this is the W dot, and this particular portion due to irreversibility we will not able to we will not be able to realize and this is called W dot lost, this is unavailable work or lost work . So, work producing devices which produces the work like turbine. So, let us say there is a process in a turbine and then we could have produced some work which is W dot reversible.

Due to the in efficiency of the process due to the lack or shortage in the] design inefficiency in the design, we will not be able to produce W dot reversible we will be able to produce only W dot and certain amount of work will be lost work . So, there is a reversed or there are many reverse devices, let us say we have got the compressor.

So, for a compressor what we need to do is that we need to supply work; if everything is ideal then we would have supplied W dot reversible, but things are not ideal there will be some amount of losses irreversibilities, etcetera. So, we have to supply more work and this much amount is W dot lost or W dot unavailable work.

So, this is what we get in actual practice for a process, if we do this analysis we can calculate what is the reversible work, but in the actual practice we will have certain part of it as unavailable work or lost work and that is due to the irreversibility. So, you see how irreversibility unavailable work and entropy generation. They are closely related to each other there is another point which I like to stress upon which will bring us to the end of our discussion regarding Exergy, it is like this what is the effect of atmosphere or ambient or the surrounding. So, one thing is that the surrounding temperature T 0 that has already been entered that has already entered in our expression of the combination of first and second law.

But there is something else the pressure of the surrounding that has also got some effect we can understand it with a simple example.

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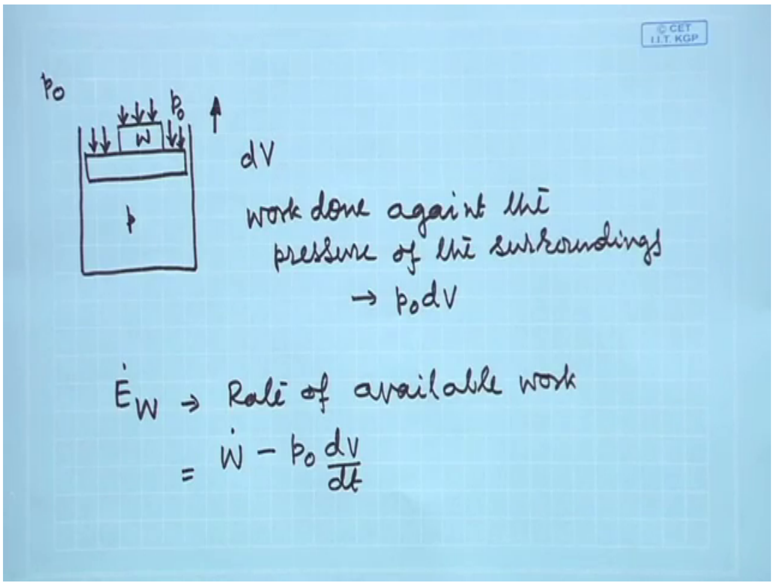

dV

work done against the pressure of the surroundings

$\rightarrow p_0 dV$

$\dot{E}_W \rightarrow$ Rate of available work

$$= \dot{W} - p_0 \frac{dV}{dt}$$

The example is like this suppose we have got a piston cylinder kind of arrangement inside the piston cylinder kind of arrangement we have got a gas at a pressure p, outside if this there is a pressure of the surrounding that is p 0 and let say there is a weight which we want to raise by the upward movement of the piston. This W we want to raise with the upward movement of the piston, but if we want to do this what we have to do we have to move the piston in the upward direction whereas, the piston on the top surface of the piston ambient atmosphere.

Sorry ambient pressure that is also acting. So, if there is a change of volume of the gas confined in the piston that is dV. So, it is not only raising the weight, but it is also doing certain amount of work which is equal to work done against the pressure of the surroundings that is equal to p 0 into dV, but really I do not need this work, but as the surrounding is having some sort of a pressure. So, if I have to do another work like raising of a weight or raising this weight in the vertical direction, then we have to do certain work due to the pressure of surroundings. So, this is inevitable.

So, total work done by my process will be in summation of these 2 work; raising of the width and the work done against the pressure of the atmosphere. So, if that is the total work, then my useful work is only raising of the width. So, from the total work, then I should deduct the work done against atmospheric pressure to get what is the available work we have got for the particular from the particular control volume or during a particular process. So, with this consideration what we can write we can write the following; E dot W that is the rate of available work that is equal to W dot minus p 0 dV dt; now our combined first and second law whatever we have written that can be changed little bit to incorporate this concept that we want to calculate the available work and with that.

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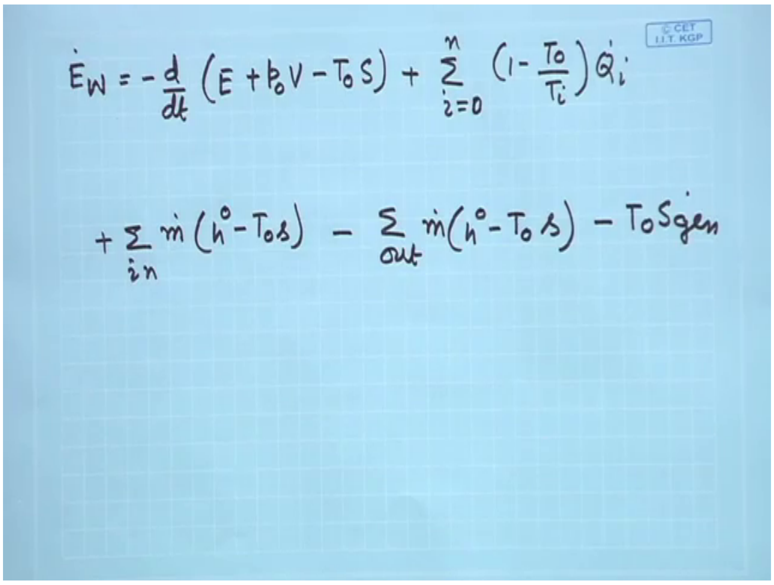

$$\dot{E}_W = -\frac{d}{dt}\left(E + p_0 V - T_0 S\right) + \sum_{i=0}^{n}\left(1-\frac{T_0}{T_i}\right)\dot{Q}_i$$

$$+ \sum_{in}\dot{m}\left(h^0 - T_0 s\right) - \sum_{out}\dot{m}\left(h^0 - T_0 s\right) - T_0\dot{S}_{gen}$$

It will be E W; E dot W that is equal to minus d dt of E plus p 0 V this is the only change minus T 0 S plus i is equal to 1 I is equal to 0 to n 1 minus T 0 by Ti Q dot i plus in m dot T 0 s minus out m dot all right. So, you see now we can call it an Exergy balance equation this is within the control volume. So, here there is no flow at least nothing is entering the control volume and going out of the control volume those part; we have taken care separately. So, this is the rate of change of Exergy within the control volume.

This is the Exergy transfer due to heat transfer this is the Exergy in due to inflow of due to inflow of mass this is the Exergy out due to outflow of mass from the control volume and this is the extraction destruction of Exergy . So, this is a very important equation and it basically gives us how the available work or available energy is getting converted and getting changed and also is getting destroyed. So, this equation its solves sorry it serves as some sort of in standard, if we want to calculate during a particular process how much we can expect how much available work we can expect out of the process. So, this particular equation we can use and of course, if we want to modify the process we want to make it better then also this equation is very helpful.

Again the Exergy which is the available energy which is the energy in the usable form we can get from some energy transfer energy conversion. So, that you see that varies and the way first law tells us regarding energy, this particular when we are taking care of both first law and second law it does not say the same thing and here we get a better or a realistic picture for example.

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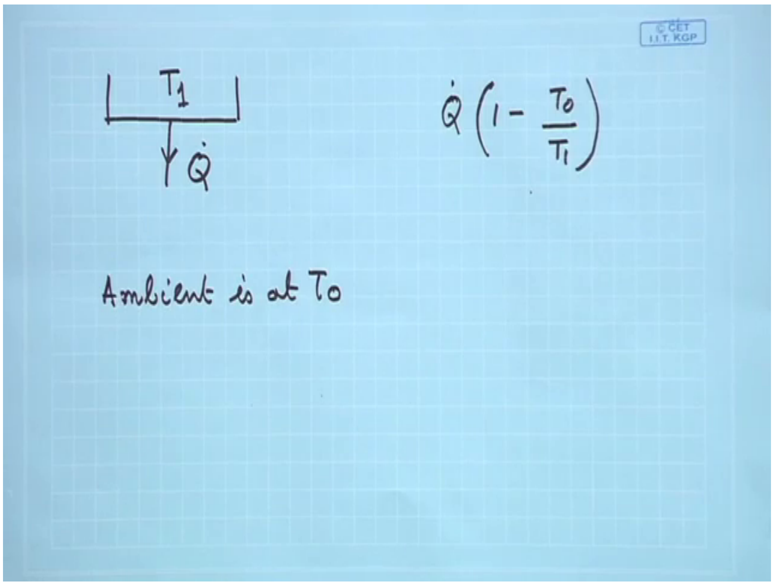

Let say there is a source which is a source of thermal energy and we are taking some Q dot amount of energy thermal energy out of it the source is at temperature T 1 and the ambient that is at temperature T 0 ambient is at T 0, all right.

Now, from the first law the energy which I have got that is equal to Q dot the rate at which I have got this energy. From the second law the energy which can be you used the energy which I have got whole of it cannot be used only a part of it can be used and the part which can be used that is equal to Q dot into 1 minus T 0 by T 1. So, you see now the energy is no longer only a function of the source or no longer is what we have got from the source, it has got some sort of dependence on the sink or the environment also . So, basically Exergy that is a composite function, Exergy is a composite function and it is a function of source and the environment similarly thermal energy we can see that.

Whatever essential energy we can get available energy we can get from a source of thermal energy that depends not only on the amount of energy we get, but it also depends on the source temperature, it also depend on the temperature of the environment and this is what is ideally what we can exploit as work this is also very important. Suppose some amount of thermal energy Q dot is available from a reservoir at temperature T 1. So, ideally; we can use only Q dot multiplied by 1 minus T 0 by T 1 when T 0 is the temperature of the environment, in actual process we will not be able to use even this much there will be other losses which will reduce our usage of energy for some useful work for or for some useful purpose.

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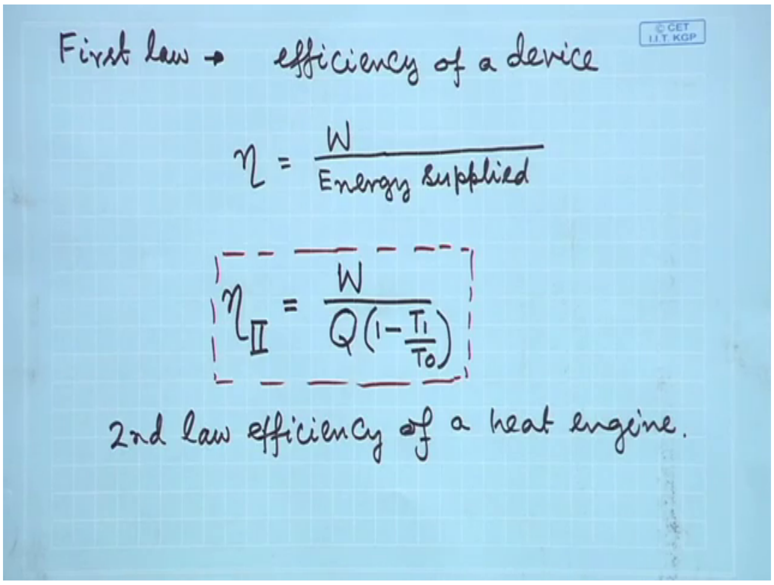

First law → efficiency of a device

$$\eta = \frac{W}{\text{Energy supplied}}$$

$$\boxed{\eta_{II} = \frac{W}{Q\left(1-\frac{T_1}{T_0}\right)}}$$

2nd law efficiency of a heat engine.

So, this brings us to another concept, from the first law we have defined from the first law we have defined efficiency of a device like efficiency of a heat engine we have defined as whatever work we have done divided by energy supplied that is the efficiency of heat engine we have divide and we have defined, but whatever discussion we had. So, far it is now clear the efficiency will depend if this way we defined efficiency, it will have dependence on some hidden parameters, those hidden parameters are the temperature of the source and temperature of the ambient or environment or sink . So, basically you see the essence of the energy transfer process again by first law, we will not be able to communicate. The first law efficiency will give us some picture which is not a complete picture.

So, we can define now a second law efficiency, there are different way at different conventions of um denoting second law efficiency, but we can take this kind of a notation which denotes the second law efficiency and in this case what we can do we can for heat engine we can put the work done, but here instead of heat Q 1 that is the heat supplied, we can write down the potential of that thermal energy supplied what was that potential? This potential of the thermal energy supplied is this multiplied by 1 minus T 1 by T 0 and this will give us the second law efficiency for heat engine. So, let me write it this is your second law efficiency of a heat engine.

Similarly, incorporating Exergy, again one can see this is the Exergy of heat transfer or Exergy associated with the heat transfer. So, one may call it exergetic efficiency also. So, using this concept we can define second law efficiency for different processes devices and cycles and that will give us a different outlook regarding the energy conversion process and with the help of first law and second law; that means, first law efficiency and second law efficiency a more complete picture of the process will be available to us. So, we will take up certain examples in our next class and with that we will try to complete our discussion. We will take up example to show how for waste heat recovery process these kind of efficiencies are useful.