Energy Conservation and Waste Heat Recovery
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Lecture - 06
Thermodynamic Principles of Waste Heat Recovery (Contd.)

Hello everyone. In the last lecture, I have mentioned that thermodynamic principles are essential for the design and planning of waste heat recovery system and as such we have started some recapitulation of thermodynamic principles. This is not looking into the thermodynamic principles and thermodynamic dynamics in details, but just to stress upon the important laws of thermodynamics, principles of thermodynamics and to relate them with the principle of waste heat recovery.

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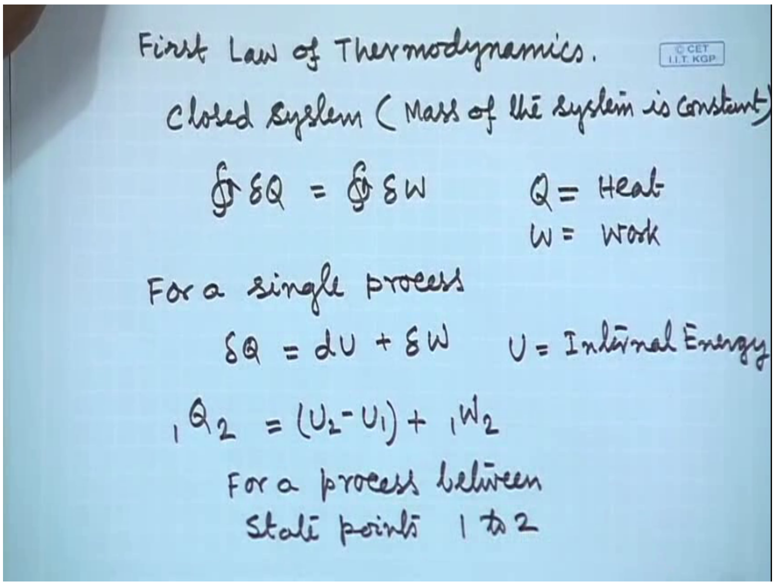

So, we have started with the first law of thermodynamics. So, if we quickly summarize, then first law of thermodynamics, first let us write first law of thermodynamics for closed system. For the closed system, the mass is constant, mass of the system is constant because no mass can enter the system or no mass can leave the system and then, for a cyclic process; we can write, cyclic integral of heat transfer is equal to cyclic integral of work transfer. Q is heat and W is work. If we take a single process and not a cyclic process, but for a single process in differential form, we can write dQ is equal to dU plus dW, where U, I have told; internal energy and this is in the differential form. If we consider a change of state from 1 to 2, one can write Q1 to 2 is equal to U2 minus U1 plus W1 to 2.

So, here you see the difference. Here we have written Q1 to 2 to indicate; what is the heat transfer during the change of state for the system from state 1 to state 2. Similarly W1 to 2 is the heat work transfer during the change of state for the system from 1 to 2 whereas, U2 is the internal energy of the system at state 2. U1 is the internal energy of the system at state 1. So, as U the internal energy is a property, we can write U2 minus U1 for a process which is undergoing between state 1 and 2, but as Q and W, they are path function, we have to write Q1 to 2 and W1 to 2.

So, this particular equation is for a process between state points 1 to 2. We can write this equation also in terms of mass as the mass of the system is remaining constant. So, we can write for per unit mass Q1, 2. 2 is equal to U2 minus U1 plus W1 to 2, where q and w are small letter. They denote the amount of heat transfer per unit mass and amount of work transfer per unit mass; whereas, u 2 is the energy at state 2 per unit mass and u 1 is the internal energy of this system per unit mass at state 1. So, this is for a closed system or a system with a fixed mass.

Now, also we have written this equation for open system.

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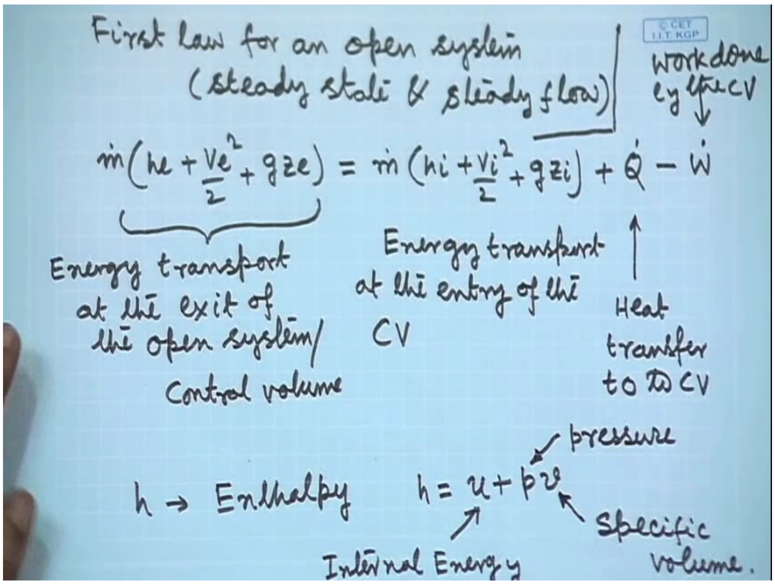

First law for an open system let me write it for steady state and steady flow. Again, I like to stress upon that steady state and steady flow that is the most common kind of incident in most of the industrial situation. There are situation where there will be change of flow with time, there will be change of state with time, but in general most of the industrial systems are operating under steady state. We want to do the analysis under steady state. So, we are writing the equation for steady state and we can write m dot he plus ve square by 2 plus gze, that is equal to m dot hi plus vi square by 2 plus gzi plus q dot minus w dot.

Let me explain each of the term. The left hand side; we have got energy transport at the exit of the open system which is also known as control volume. This is energy transport at the entry of the control volume short form CV heat transfer to DCV and this one work done by the CV.

So, you see we are getting some sort of a balance of energy. Basically we have to appreciate that this is a rate equation and we are getting some sort of a balance in the left hand side. We have got the rate of energy transport at the exit of the open system that is equal to rate of energy transport at the entry of the control volume or open system rate of heat transfer to the control volume and rate of work done by the control volume. So, this is how one can express first law of thermodynamics for an open system or for a control volume.

Now, here we are considering steady state operation and we are considering only one inlet and one outlet. Mass is entering to the control volume through one opening and mass is leaving the control volume through a single opening. I think terminologies are clear to you. H is called the enthalpy. Already I have mentioned that. So, this is a property of the system and h 1 can write as u plus pv where u is the internal energy, p is the pressure and v is the specific volume.

So, now at this point let us see what we have got from first law of thermodynamics. Basically it is giving some, it is energy conservation principle and it shows how energy can be converted into different forms and ultimately the conservation of energy that is established or that is maintained and it also introduces a new property of the system that is called enthalpy which is given by u plus pv. So, this is the thing which we come to know from first law of thermodynamics for energy analysis of any system. Particularly for wasted recovery, first law is of utmost importance because this is a principle of the nature. There will not be any violation of the law of energy conservation and from this kind of equation whatever we have derived or written. So, with this we will be able to analyze the wasted recovery system and we will take up certain examples to illustrate this.

Now, we have written the equation for single inlet and single exit, but there could be system with multiple inlet and multiple exit. In wasted recovery, there are examples where we will have system or control volume with multiple exit and multiple entry. So, let us take one example.

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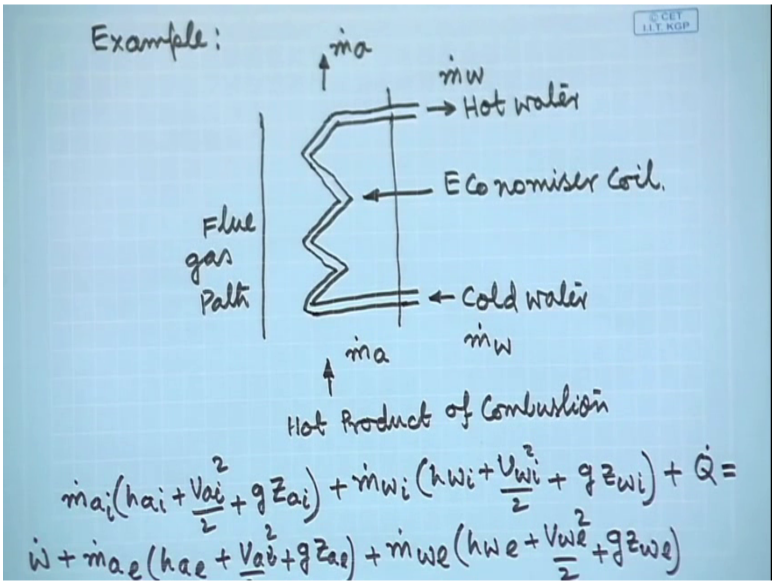

So, let us say we are considering one economizer. So, what is an economizer? It is the hot product of combustion that is the flue gas that passes through this duct. One can think of that this is part of the flue gas path, maybe before this deck we have got this portion of the flue gas path and as the hot gas passes through this, we can extract certain amount of thermal energy out of it. There are different ways of doing it. One way of extracting thermal energy is that we can introduce a coil structure something like this schematically which can be shown. So, here cold water is entering and when water will come out of this coil, this will be hot water. The temperature of the water will increase as it is transferring heat or as it is extracting heat from the hot product of combustion or the flue gas.

So, I can write this is flue gas path, this is economizer coil direction of flow of the fluid that has been shown. So, I can do first law analysis for this economizer coil. So, let us assume that mass of flue gas that is m dot a, same mass of flue gas is going out m dot a mass of water, the mass flow rate of water that is m dot w and this is also m dot w same mass of water is coming out. So, how we can write? Just if we think of the previous equation, we can write m dot a i h a i plus v a i square by 2 plus gz a i plus m dot w i hw i plus v w i square by 2 plus g zw i plus q dot that is equal to w dot plus m dot a e h a e plus v a e square by 2 plus gz a e plus m dot w e h w e plus vwe whole square by 2 gz w e. That is all.

So, you see m dot ai that is the mass flow rate and these are the enthalpy, this is the velocity, this is the datum level. Already I have explained at the inlet of air enthalpy velocity determinable at the inlet of water stream. This is the enthalpy velocity determinable at the exit of air stream, enthalpy velocity and datum level at the exit of water stream and this is how we can write the equation. Considering the physics of the problem, we can simplify this equation slightly.

Let us now consider the flue gas paths or the duct is well insulated. If it is well insulated, then there will not be any heat transfer either from the system to the surrounding or from the surrounding to the system in practice. Of course, this is an idealization in practice. Of course, this is hot gas and the duct wall will be heated up. So, whatever may be the insulation, there will be certain amount of heat loss, but for the sake of analysis let us assume there is no heat transfer from the duct to the ambient atmosphere. So, if that is, then q dot that is equal to 0 and then, there is no work done neither the gas stream is doing any work nor the water which is flowing through the economizer coil, it is doing some work. So, work done that is also equal to 0.

So, basically we will have some sort of an energy balance between the two streams. So, from our common sense we know; what is the amount of energy released by the hot flue gas that will be picked up by the water and again we can do some further simplification. How we can do the further simplification? We can think of that the enthalpy of air and enthalpy of the water; they will be reasonably large compared to the other energy terms that is the kinetic energy term and the potential energy term. So, in the next phase of simplification or idealization what we can do is, we can delete this term from this equation.

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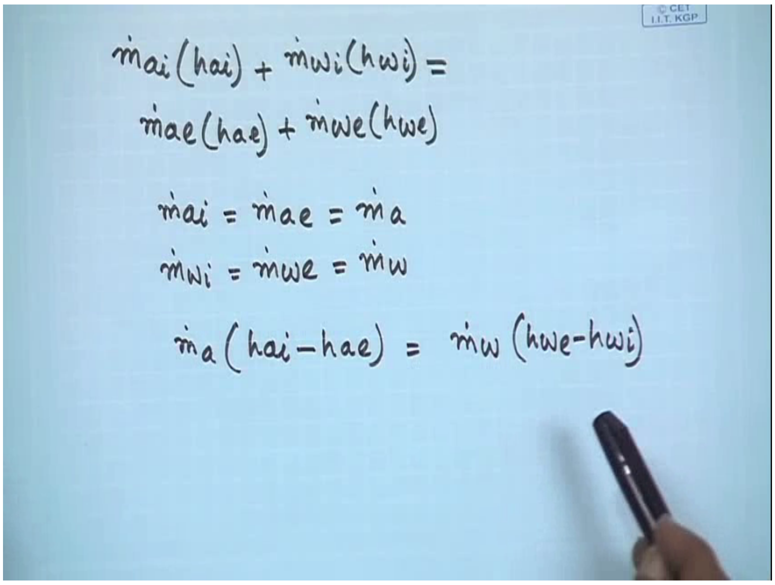

So, if we try that what we will write m dot a i hai plus m dot wi hwi that is equal to m dot ae hae plus m dot we hwe. Again we should appreciate at this point that m dot ai is equal to m dot ae that is equal to m dot a and m dot wy that is equal to m dot we that is equal to m dot w. So, with this if we further simplify, then we will get m dot a hai minus hae that is equal to m dot w hwe minus hwi.

So, you see starting from the general equation of first law, general expression of first law for an open system which has got two inlets and two exit, we have written this energy exchange equation and now, it is complying with our common sense that we know whatever is the heat released by the flue gas, hot flue gas that will be picked up by the water which is flowing through the economizer coil and the heat released by the flue gas that is equal to mass flow rate multiplied by the change in enthalpy. Enthalpy has reduced. So, that is why this will be a positive term and heat rejected by the stream or the flue gas stream that will be a positive term.

Similarly, this will be equal to the heat picked up, thermal energy picked up by the water stream. So, that is again given by the mass flow rate of the water stream multiplied by change in enthalpy. Now, how to determine the enthalpy? Most of you might have some idea. We will discuss it how to determine the enthalpy. So, in this case you see what we can do from the thermodynamics. Let us say we know the inlet condition of the flue gas and inlet property that is any enthalpy of the flue gas, we know outlet property of the flue gas. So, then we know the enthalpy change of the flue gas, mass flow rate of the flue gas that is also known. Mass flow rate of water stream that is known and inlet temperature of water is known. So, we can determine the outlet temperature of the water.

So, suppose if I plan to have some sort of an economizer and like to utilize part of the energy which is taken away by the flue gas which will be otherwise released to the atmosphere, we want to utilize it. We can have this kind of a system and from the first law, we can analyze that how much energy we can extract. A deeper analysis can be done. When we include heat transfer knowing the velocity and geometry of the coil etcetera that what is the rate of heat transfer, then if we know the inlet condition of the flue gas and inlet condition of the water stream, if we know their mass flow rates, we will be able to find out what will be the rate of heat transfer and how much heating can be done to the water stream.

So, you see by applying first law of thermodynamics, we have proceeded one step towards analyzing or designing a waste heat recovery system and again if we apply the laws of heat transfer, we will be able to do a much better analysis, we will be able to size the economizer coil. So, as I have told in some previous lecture that thermodynamics and heat transfer that is very important, so we can understand from this example that how thermodynamic principles can be utilized for analyzing the waste heat recovery system. With this let us move to the second law of thermodynamics.

So, again I will not go into details of second law of thermodynamics as it is done in a course of thermodynamics. I will give the salient feature of second law of thermodynamics. Let us first see; what do we get from second law. First law gives us some idea regarding the quantity of energy exchange when there is a particular process of energy conversion. Second law gives something more actually. Second law gives many important information in addition to first law.

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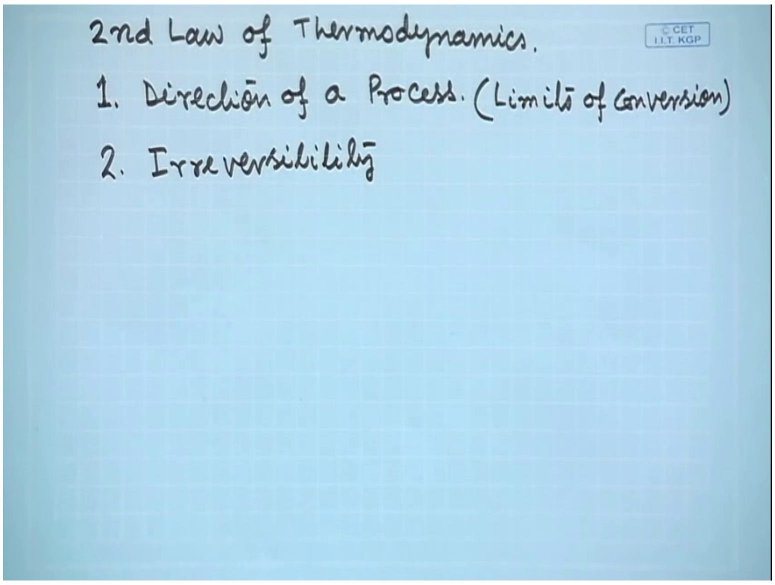

So, let us say we are discussing second law of thermodynamics and it will give us many important information and most of this information will be directly applicable for the design and analysis for the design and analysis of wasted recovery system.

So, first thing what we get is direction of a process. So, processes which occur in nature and which also occur in industry that will have a preferred direction and second law will give us this direction. So, this can also be told that it gives limits of conversion. This needs little bit of explanation that how it did gives the limits of conversion that let say we are converting one form of energy in transit to another form. So, we are converting let say from work to heat and then, we are trying again the conversion of heat to work.

So, how much of work can be converted into heat if a given amount of work is there or if a given amount of work transfer is there, how much of it can be converted into heat transfer that we can get from second law and if there is a given amount of heat transfer, how much of heat can be converted into useful work, that also we can get from second law. Then, second law gives another information which is irreversibility. So, the concept of irreversibility that is introduced by second law thermodynamics does not say first laws of thermodynamics quantify a process. It only says the energy conversion during the process whether the process can go in the forward direction and then, it can be made to proceed in the backward direction in the same way without creating any change elsewhere whether that is possible or not. It is not said by the first law of thermodynamics, but second law says whether a process that can be reverted back and the system can be taken back to its initial state without creating any change in the environment whether that is possible or not, that is told by second law.

So, if in any process, if irreversibility is involved, it cannot be reverted back without making any change elsewhere. If it is a reversible process, then only it can be diverted back. So, then it gives very useful concept of irreversibility which is very important for knowing how much we can expect from a process, how we can make the base, how we can take best out of a process by reducing the irreversibility. These are not possible from first law of thermodynamics, but from second law of thermodynamics these things are possible. I like to make an end over here.
So, I am in between describing what different aspects of second law of thermodynamics, what we get to know from second law of thermodynamics. I will continue over it in the second week in the next lecture.

Thank you.