Energy Conservation and Waste Heat Recovery
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Lecture - 05
Thermodynamic Principles of Waste Heat Recovery

Hello everyone. So, in the last few lectures, we have seen some background of waste heat recovery and its relationship with energy conservation. We have seen different ways by which waste heat recovery is possible, what are the options; what are the potential of waste heat recovery. Now, we will go to different designs of waste heat recovery systems, details of waste heat recovery systems. For doing this, we need certain background of thermodynamics and that is what we will learn in some lectures starting from this particular lecture. In the coming few lectures, we will learn some aspects of thermodynamics; particularly which are important for waste heat recovery.

Now, this is a recapitulation. This is important for waste heat recovery and it is also important because I assume that this waste heat recovery is important not only for mechanical engineers, it is also important in other branches of engineering where the details of thermodynamics has not been dealt. So, it will be good at the beginning to see a few principles and issues of thermodynamics which are important for waste heat recovery.

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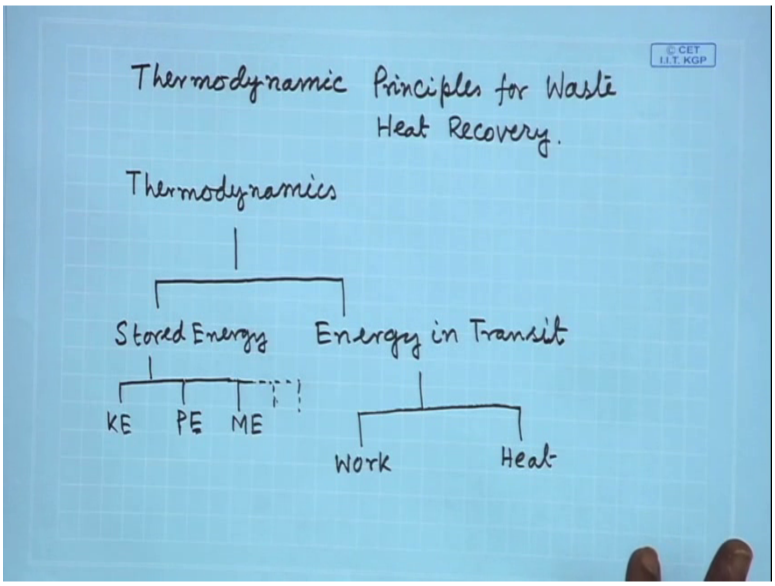

So, if we start with thermodynamic principles for waste heat recovery and it is good to start with the word thermodynamics. So, thermodynamics deals with different energy, energy conversion processes and it tells us how the energy conversion takes place, what are the different forms of energy and whenever we are having conversion of energy from one form to another form, what are the property changes, how one can estimate these processes of energy conversion and how one can design at least in principle how one can design the devices where energy conversion will take place.

So, it is basically the deals with energy and different forms of energy. Different forms of energy which is very important to understand if we like to discuss thermodynamics. Thermodynamics recognizes only 2 forms of energy; one is stored energy and another is energy in transit. Stored energy is generally associated with the mass of a substance and energy in transit; we come across energy in transit whenever there is an interaction; interaction between whom; interaction between the system and the surrounding. In thermodynamics, this concept of system and surroundings that is very important and I think everybody is having the basic idea of what is a system and what is a surrounding.

So, whenever there will be any energy interaction between the system and the surrounding without some sort of mass interaction, without some sort of mass exchange or flow of mass, we will come across with energy in transit. And energy in transit there are only two forms; one is work and another is heat. So, we have got energy in transit which is work and heat. Then, what is stored energy? Stored energy I have told it is associated with the mass of the substance. So, there could be many forms. There could be kinetic energy, there could be potential energy, for a magnetic substance there could be magnetic energy so on and so forth. I am not writing the other force.

In fact, a good way to define stored energy is that whatever is not energy in transit and it is very easy to define or identify energy in transit that is only work and heat. So, apart from what can heat, other forms of energy that is stored energy. So, there is a distinction between them and this distinction appreciate this distinction or to understand this distinction is very important. What is that distinction?

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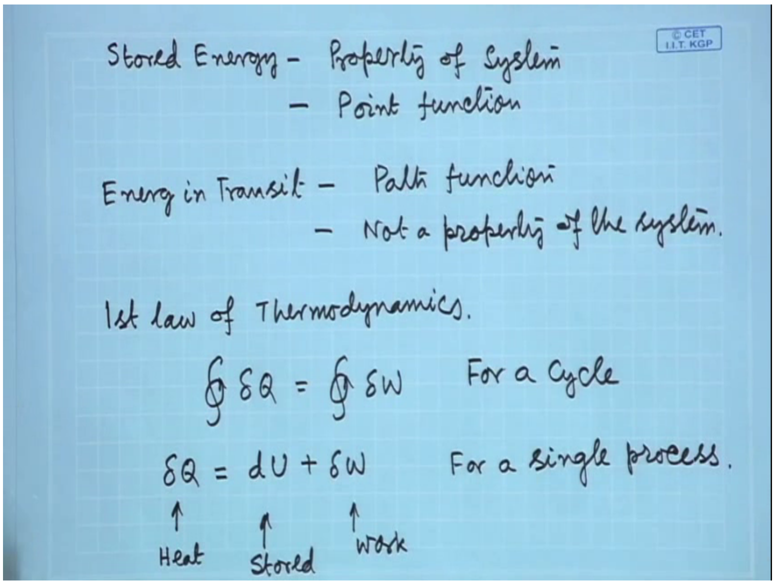

That stored energy is; it is a property of the system, it is a point function. So, property of the system, it gives the thermodynamic state and it is a point function. That means, if we know the thermodynamic state, then we know or we will be in a position to tell what the stored energy is. Whereas energy in transit, this is a path function and this is not a property of the system. So, it is not easy to understand or explain that as we are having the total existence of the energy in transit is only during the interaction. So, obviously it depends on the interaction and interaction is denoted by a path or a process. So, the amount of change in the energy in transit that will be a path function will depend on the path function and it will not be the property of the system.

So, that is why mathematically there is also little bit difference between stored energy and the energy in transit whereas, a infinitesimally small quantity of stored energy that is denoted by exact differential like many other quantities we are familiar with, the stored energy is not an exact differential. It is denoted by an exact differential. When we will learn the laws of thermodynamics, we will come across this particular aspect.

Now, stored energy of course is important because a substance that can store energy in different form, but energy in transit it has got a special place because we are interested in energy interaction. Energy interaction between two bodies or thermodynamically energy interaction between the system and the surrounding. So, obviously the energy in transit that is work and heat that is very important and obviously, that is important for our waste heat recovery and with the help of this in engineering thermodynamics or the laws of thermodynamics are stated. So, with this small introduction, let us go to the laws of thermodynamics.

So, let us first write the first law of thermodynamics. In engineering practice, we have got processes which are cyclic in nature or different kind of cycles. What are these cycles? These cycles they continuously produce work out of thermal energy. So, these kind of cycles are called power cycles or there are cycles which continuously produce low temperature taking some work or energy or electrical energy, mechanical energy or electrical energy. So, there are different kind of cycles and in engineering, thermodynamics is defined based on cycles. Referring to the cycle, the first law of thermodynamics is defined.

So, first law of thermodynamics it says, cyclic integral of heat transfer that is equal to cyclic integral of work transfer. Q denotes heat and W denotes work and you see I have not used exact differential. I have used in exact differential delta Q and delta W. So, cyclic integral means if we take all the process starting from a point and coming back to the same point, if we take all the process, then during all the processes, summation of that is equal to the work transfer during all the processes. So, this is our formal statement of first law of thermodynamics for engineering purpose.

Now, with this if we proceed we can write down the law of thermodynamics, first law of thermodynamics for a single process. So, this is for a cycle for a single process if we write the first law of thermodynamics, it can be written in this form EQ is equal to dU plus dw, where again this is heat, this is stored energy and this is work. So, for a single process, all the energy interaction can be written in this form. So, for a single process in general, there could be some form of energy, change in conversion in energy which are energy in transit and there could be some change or conversion of energy which is energy in stored form and we can write down the energy conservation in this particular manner. We know from our high school physics that first law is nothing, but the law of energy conservation and this is in engineering perspective in the terms of work and heat which are very important one can write the first law.

Now, let us start again from this point.

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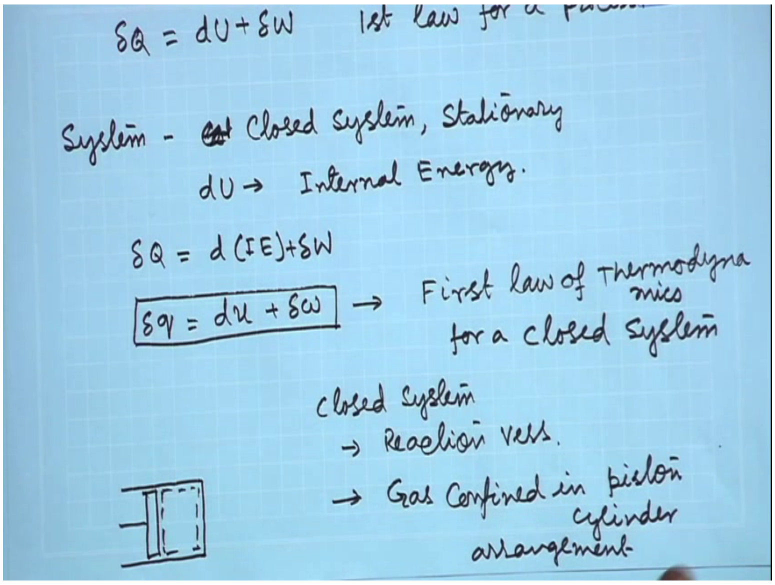

So, delta Q is equal to du plus dw first law for a process. Now, this delta u is this stored energy. If we consider a system which is a closed system and stationary, then there is no change in kinetic energy, no change in potential energy. Let us say the electrical energy, magnetic energy surface energy etcetera are not important and as a system, we are having a compressible substance only which is the working substance of many engineering systems like air, water, vapor, steam etcetera.

So, in that case dU that becomes internal energy, so we can write the equation in this particular form and actually more common term is u, assuming u to be the internal energy and what we can do that as the system is a closed system, it has got a fixed mass and we can divide both the sides with the mass and then, we can write it in this form dq is equal to du plus dw. So, what we have done is, first I have told that u is nothing, but the internal energy and denoted it by ie, but conventionally u is used. U itself is used and one understands that there is no kinetic energy, potential energy change and then, we are writing the equation per unit mass that is dq is equal to du plus dw. So, this becomes the first law of thermodynamics for a closed system.

So, closed systems are there. Definitely there are many closed system in our engineering practice, let us say a reaction vessel in which some sort of a chemical reaction is taking place is a closed system, some sort of internal combustion engine if we idealize it. So, closed system we can have a reaction vessel, then we can have that gas confined in piston cylinder arrangement which is nothing, but the idealization of one internal combustion engine or some sort of air compressor. So, this is also a closed system.

So, for this kind of system, I have written the first law of thermodynamics and I hope most of you know this particular form and it is only a recapitulation which will be important, but you see many of the engineering system will not be a closed system. As I have demonstrated, many of the engineering system will be such that it will have some mass flow into it and it will have some mass flow out of it.

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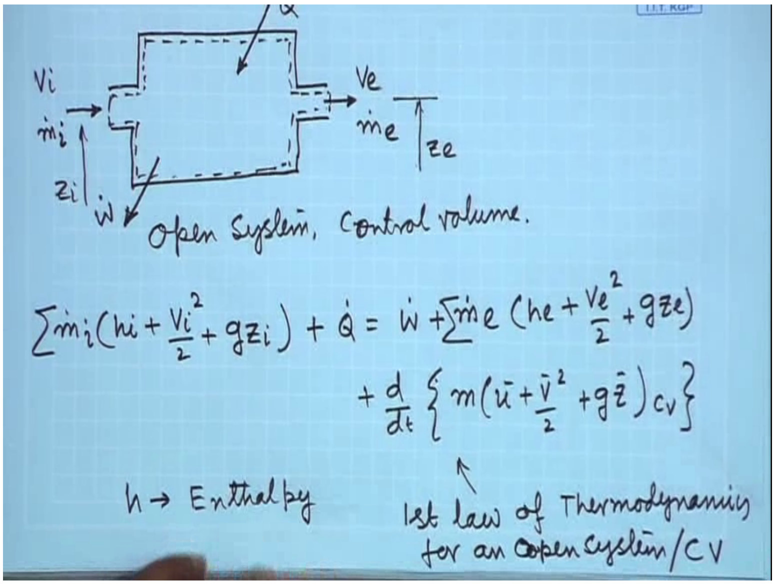

Let us say schematically I am denoting the physical entity like this n show this dotted line which I am drawing. This is known as system boundary and what I have drawn is known as open system or sometimes it is also called control volume.

So, what it is? In this some mass is entering let say we denote it m dot i mass flow rate at the inlet. Some mass is going out of it m dot e and there is some sort of heat interaction which is Q dot and there is some sort of work interaction which is w dot. So, this is a general representation of an engineering system or open system, where there is mass flow in, mass flow out, some amount of heat interaction between the system and the surrounding and some amount of work interaction between the system and the surrounding.

So, we have already written the form of first law of thermodynamics for closed system expanding that particular form which I have written earlier. One can write the form of first law for this open system. What is the change here? When the mass is coming inside, it will have some kinetic energy, it will have some potential energy plus as the mass has two flow inside the control volume or open system, the gas, the fluid molecule, they have to do certain amount of work that flow energy will also be there and obviously, the same similar quantities will be associated with mass which is going out and then, with some sort of a simplification one can write the first law of thermodynamics for this open system or control volume in this form; m dot i hi plus vi square by 2 plus gzi plus Q dot that is equal to w dot plus m dot e he plus Ve square by 2 plus gze plus ddt of. Let me explain each of the term. So, some mass is entering the control volume. So, it will carry certain amount of energy.

What it will carry? It will carry the potential energy plus the kinetic energy plus some amount of internal energy. So, we can write that Vi is the velocity at the inlet, Ve is the velocity at the exit. It has got some sort of a datum which is given by zi. On the other side, the datum is given by ze and the internal energy plus the energy which is needed for the fluid molecule to enter into the control volume that can be combined together to give h. H is called Enthalpy.

I hope most of you are aware of this kind of formulation and this kind of terminologies, but it is good to have some sort of recapitulation that is why you are having this class. So, this side then the mass which is entering, it will enter with certain amount of energy which constitute of enthalpy, the kinetic energy and the potential energy. So, that is going inside the control volume, then certain amount of heat that is also coming to the control volume; what is going out of the control volume that work and then, the mass which is going out of the control volume, it will carry certain amount of energy in the form of enthalpy, in the form of kinetic energy and in the form of potential energy.

Now, the energy which is coming in and which is going out, they may not be equal. If they are not equal, then within the control volume, there will be certain storage of energy. What will be that storage of energy is, u bar that gives the internal energy per unit mass, v bar is that gives the average velocity of the fluid inside the control volume and z bar gives the average datum height for the control volume. So, this gives the stored energy per unit mass u bar plus v bar square by 2 plus g z bar that gives the energy per unit mass within the control volume this multiplied by mass of the control volume. That gives the energy within the control volume and ddt of this quantity is the change with time.

So, basically you see this equation you should see very carefully. This is kind of a rate equation, the rate at which energy is coming, is equal to the rate at which energy is going out plus the rate of change of energy within the control volume. So, this is simply some sort of a balance equation. Only one thing I like to remind you which probably you know already that there is some sort of a sign convention for work and heat. It is assumed that work done by a system is positive and heat transfer to a system or control volume that is positive. So, this sign convention we have used, one can use some other sign convention also. There is no harm, but most commonly this sign convention is used and using this sign convention, we have written the energy balance equation for a control volume or for an open system that is we have written the first law of thermodynamics for an open system.

This is the most generalized form of first law. Of course, considering that there is only one inlet and one outlet, in general there could be number of inlets and number of outlets. So, this equation itself I can change that let us say there are number of inlet and their up number, there are number of outlet for some sort of a control volume and this is the generalized equation of first law for a control volume or for an enthalpy system. So, here we can write this is first law of thermodynamics for an open system or control volume.

Now, in most of the cases, we will come across situation where things are not changing with time.

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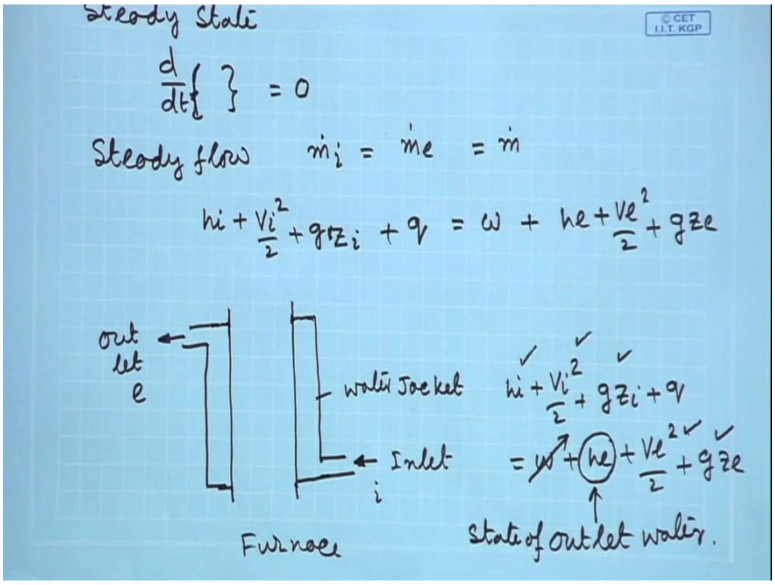

So, steady state means d dt of this energy terms whatever I have written or the change within the control volume that is equal to 0 and then, we will also have steady flow in many situation. If there is steady flow, then we will have m dot i that is equal to m dot e that is equal to m dot. So, this we can write.

So, first law of thermodynamics for a control volume you will find that in many cases we will apply it for steady state, steady flow situation. If there is single inlet and single outlet. So, our equation will become hi plus vi square by 2 plus gzi plus q that is equal to w plus he plus ve square by 2 plus gze. Please have a closer look, I have written here a small q without any dot. So, that means this is heat transfer per unit rate of mass flow. I have written w which is denoting work and small w without a dot. So, this denotes transfer per unit of mass flow. So, this is a very common form of first law of thermodynamics when there is single unit, sorry single inlet and single outlet and the control volume or the system is operating under steady state.

Let us take an example from waste heat recovery domain. Let us say this is the body of the furnace and the body of the furnace that is generating, that is radiating heat and we want to extract some amount of heat from the hot body of the furnace. So, what I will do? I will have some sort of a jacket to the body and through this jacket I will circulate water. I will circulate water through this jacket. This will have dual purpose. So, this is a furnace and this is water jacket. So, this is your inlet and this is the outlet. Cold water will come in and cold water will go out. So, I can write the equation which I have written earlier that this is i and this is e. So, hi plus Vi square by 2 plus gzi that will be plus q that is equal to w plus he plus Ve square by 2 plus gze.

Here probably there will not be any work done. Let say inlet conditions are known flow rate of the water that is known. So, velocity will be known and heat loss from the wall that will be known. So, what I will get ultimately these are known quantities. So, ultimately at what condition? So, state of outlet water I will know at what condition the water will go out. The thermodynamic state will be known. That means, the temperature will be known and then, with that hot water what activities I can have that I can of course decide. So, this is an example which I have taken from waste heat recovery itself and how first law of thermodynamics can be applied to this.

With this I like to end today's lecture, thermodynamics or the principles of thermal dynamics we have to go to some more. There are some more aspects which we need to discuss, particularly second law is very important. So, in our next class, we are going to take second law and we will also take some small examples and then, we will demonstrate how for waste heat recovery, the principles of thermodynamics can be utilized for small calculation, for some estimation, for some planning.

Thank you.