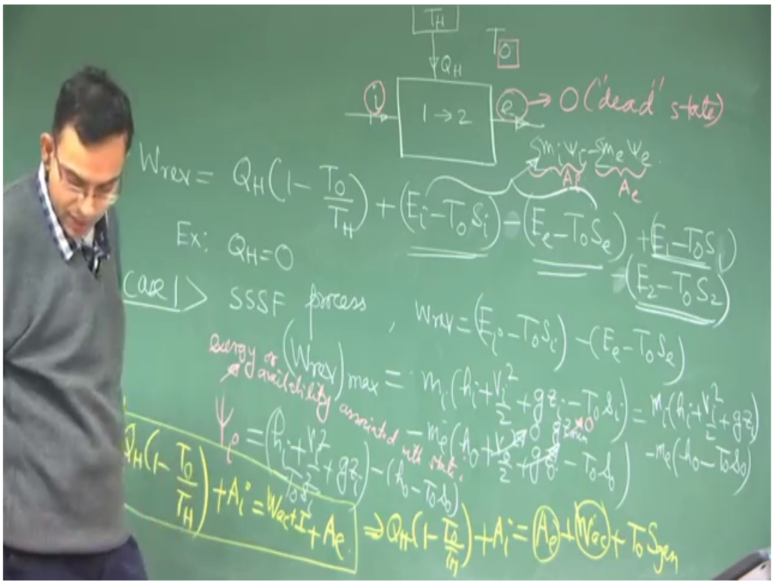
Concepts of Thermodynamics
Prof. Suman Chakraborty
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur

Lecture – 54
Exergy (Availability) (Contd.)

In the previous lecture, we were discussing about the concepts of reversible work, actual work and irreversibility.

(Refer Slide Time: 00:35)



So, to summarise the expression for reversible work let us consider this arrangement we have a heat source from which there is a heat transfer Q H there is a change of system from state 1 to state 2 and there is also inlet and exit and thus surrounding temperature is T naught. So, the reversible work associated with this is the reversible work associated with the heat transfer plus the reversible work associated with the change in state.

So, let us consider an example with Q H equal to 0. If Q H equal to 0, we are focusing on a reversible work solely exploited due to the change of state, ok. So, in this case you will have reversible work represented by this, these terms. So, to isolate now at this stage we will isolate the two perspectives; one is a control mass system, another is control volume. So, the case 1 that we will consider is steady state, steady flow process. So, if it is a steady state, the final energy of the control volume is same as the initial energy final entropy of the control volume is same as the initial entropy. So, these last two terms do not appear. So, then you will have W rev.

Now, let us pose another puzzle. Let us say that we have now states i and e given the state i, what is the state e for which the reversible work is maximum. So, I am posing the question again given the state i and assuming the state e to be variable: what is that state e for which the reversible work is maximum? Try to understand the concept you get work by virtue of the change in state from i to e. So, if there is a further potential of change in state beyond the state e, then that potential is not exploited by this control volume to do work.

So, you want the maximum change in state to take place before it reaches state e, then what is that state e beyond which you cannot expect a change of state? When the state e is in equilibrium with the surrounding if the fluid comes out in equilibrium with the surroundings, then it has no further possibility of having a change of state outside and then it has no lost what potential because of having a change of state outside the control volume or possible change of state outside the control volume. So, in that case this state e in equilibrium with surroundings the surrounding we give subscript this one this we call as dead state thermodynamically dead state in equilibrium with the surrounding.

So W reversible maximum is now let us write this full terms E i, E e all these; so, m this is m i and m e. So, if we have one inlet and one exit we can or let if you want to generalize let us write m i and m e this may be different if you have large number of inlet us and exit some total inlet will be some total exit mass, but individually they may be different. So, here we have considered one inlet one exit, but we could generalise it with a summation.

So, m i into h i plus V i square by 2 plus g z i minus T 0 s i minus m e into h e plus V e square by 2 plus g z e minus T 0 s e. Now, we will replace the state e with state 0, which is in equilibrium with the surroundings. So, where this is maximum when the right hand side the negative terms are minimum, right. So, negative terms are minimum; that means, this is equal to 0 right. The minimum kinetic energy can be 0, it cannot be negative potential energy is minimum. So, g z minimum you can choose z minimum to be 0 as your day term or reference this is as per your discretion. So, it becomes.

So, if you now express this per unit mass, this is for a flow process. No this is total. This is total reversible work. This is not the rate of reversible work you may put or may not put right if you put dots here you will be it will be dot here. So, now, if you express this as per unit mass then the term that is this maximum reversible work per unit mass that is called as availability associate or exergy associated with state i exergy or availability associated with state i.

So, what is psi i? Psi i is h i plus V i square by 2 plus g z i minus h 0 minus T 0 s 0. This is specific exergy or specific availability. This is essentially per unit mass what is the what potential associated with state i, ok. So, similarly you can calculate the work potential associated with state E and clearly E i minus E e. So, I have me forgotten to write this minus T 0 s i, very important.

So psi i minus psi e when you write this term get cancelled h 0 minus T 0 s 0; so, and if it is a single inlet and single exit, so, m i and m e at the same. So, you can as well write this as this part of the term as m i psi i minus m e psi e assuming m i is equal to m e this s 0 minus this T 0 s 0 gets cancelled out. Even if m i is not equal to m e summation of m i is summation of m e. So, when summed overall, the inlet us and exits this term get cancelled out. So, this equally works if you have a summation. I hope you follow this, right. So, individually m I may not be same as m e, but totally m i is same as total m e.

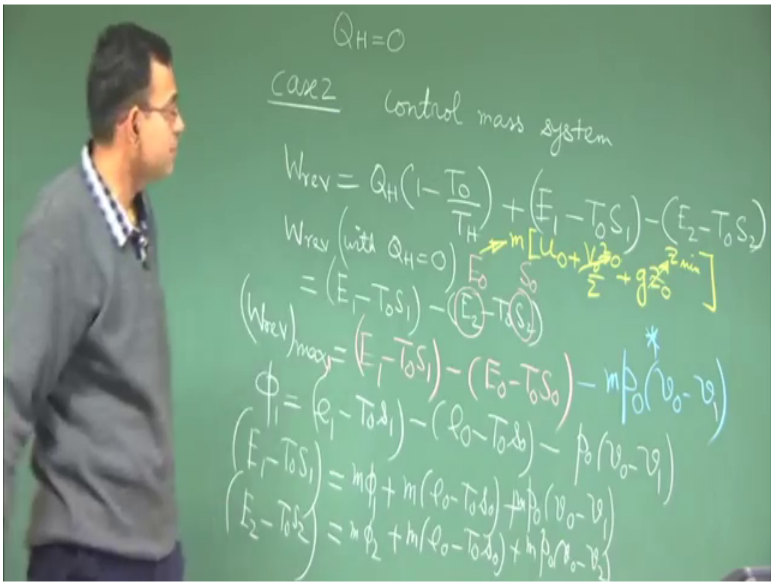
So, when you total these over m i and m e this is subtracted from the same thing; h 0 minus T 0 s 0 is fixed for all states inlet exit whatever. So, for summed over all states these get cancelled, ok. So, you are left with this one. So, this is called as A i this is called as A e. So, this is exergy or availability associated which state I per unit mass into per unit mass into total mass this is per unit mass into total per unit mass into total mass. So, this equation this equation we can write or we cast in a very interesting way. We can write Q H into 1 minus T 0 by T H right plus A i is equal to W reversible plus A e, right. This is called as exergy balance equation.

So, what does it physically tell? You have an exergy or work potential associated with Q H. So, this is the exergy supplied to the control volume the work potential that is supplied is by two ways one is by heat transfer another is by providing with a inlet state i. So, the work potential is a sum of the work potential due to heat transfer plus sum of the work potential due to this one. So, then is it is a reversible then all the work potential is utilised and whatever is not utilised is attributed to the exit state, but if it is not reversible then the reversible work can be replaced as W actual plus irreversibility, right.

So, the exergy balance can be written as Q H into 1 minus T 0 by T H plus A i is equal to A e plus W actual plus i is T 0 S gen that we derived in the previous lecture. So, the total exergy supplied is the exergy utilised by work the exergy that comes out and the remaining exergy is destroyed through entropy generation. So, to summarise this is what is exergy balance. Exergy supplied is equal to exergy utilised plus exergy living plus exergy destroyed due to irreversibility, that is the physics that is conveyed by this equation. So, we have considered this case 1 as the steady state steady flow process.

We will consider another very interesting case where there is no flow across the boundary. So, it is a control mass system. So, that is case 2.

(Refer Slide Time: 15:43)



Control mass system we will start with the expression for the reversible work. So, we have already assume the Q H equal to 0 so that we are going to formulate the reversible work due to the change of state only. So, the reversible work one component is due to the change of state another component is due to heat transfer. So, with by setting the heat transfer equal to 0, we can write an expression for reversible work. So, we will write the full expression first this is due to heat transfer.

So, if you are now solely interested about the change of the maximum work utilised due to the change of state. So, W rev with Q H equal to 0 will be equal to E 1 minus T 0 S 1 minus E 2 minus T 0 S 2. So, what is W rev maximum? Given that you have state 1 as fixed if you have state one as fixed as I have already discussed for the control volume analysis the final state if it is in equilibrium with the surroundings it comes to a dead state and then the maximum potential of doing work of the initial state is utilised.

So, in that perspective the maximum reversible work will be obtained if these states are in equilibrium with the surroundings; within this E 0 you have 0 kinetic energy and minimum potential energy. So, these let me write it explicitly what is E 0 this is m into u 0 plus V 0 square by 2 which is 0, plus g Z 0 which we set as Z minimum which is 0.

So, the maximum reversible work from this expression will be associated with the state 1. So, I am writing 1 because the maximum reversible work we are assuming that state 1 is fixed and state 2 we can vary to a limits that maximum work is obtained. So, this is E 1 minus T 0 S 1 minus E 0 minus T 0 S 0. This expression is elusive because it is not complete and that is where there is a distinction between a control volume process and a closed system.

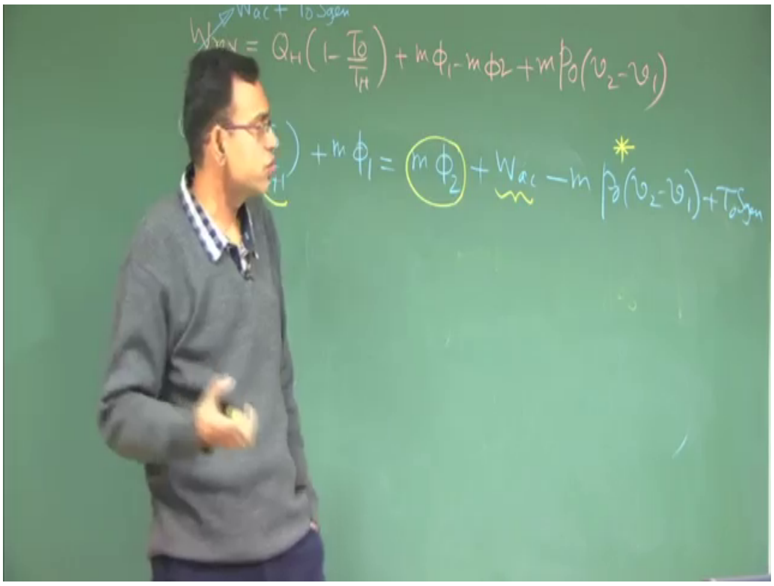
So, if you have a closed system or a control mass system you have a provision of doing work because of the moving system boundary and that potential is because you always have the ambient pressure acting on the system as a resistance pressure. So, the work done to against that resistance pressure is simply this one. So, this extra component of work which is spontaneously done because of the moving system boundary is not exploitable as a part of the work that you can extract out of the system because this work is already done spontaneously to allow a moving system boundary from volume v to the final volume v 0 corresponding to the dead state.

So, this per unit mass represents the maximum reversible work for a close system and that we call as the exergy associated with a given state. So, exergy associated with any state we just drop the subscript one. So, we can write E 1 minus T 0 small s 1 minus, ok. Let us write pi 1 just to make it clear that it corresponds co to state 1 E 1 minus T 0 S 1 minus E 0 minus T 0 S 0 these are all per unit mass minus p 0 into v 0 minus v 1. So, this v is v 1, ok.

Now, from here we can write that E 1 minus T 0 S 1 this is m phi 1 plus m into E 0 minus T 0 S 0 plus p 0 m p 0 into v 0 minus v 1 right, this is what we can write as. So, we can bring this on the other side this minus becomes plus, this becomes plus and we are expressing these in terms of phi 1. Similarly you will have E 2 minus T 0 S 2 just replace 1 by 2. So, m phi 2 plus m E 0 minus T 0 S 0 plus m p 0 into v 0 minus v 2; just replace 1 with 2, that is all, ok.

Now, come to the expression for the reversible work where both heat transfer and change of state is allowed so, this general expression.

(Refer Slide Time: 23:37)



So, we will write W reversible is equal to Q H into 1 minus T 0 by T H then this E 1 minus T 0 S 1 minus E 0 minus T 0 S 2 this that is why actually we evaluated these two expressions. So, when you subtract this two this will be plus m phi 1 minus m phi 2, this gets cancelled then plus m p 0 into v 2 minus v 1, right. And, we know that the reversible work is the actual work plus irreversibility which is as per our earlier derivation T 0 into entropy generation.

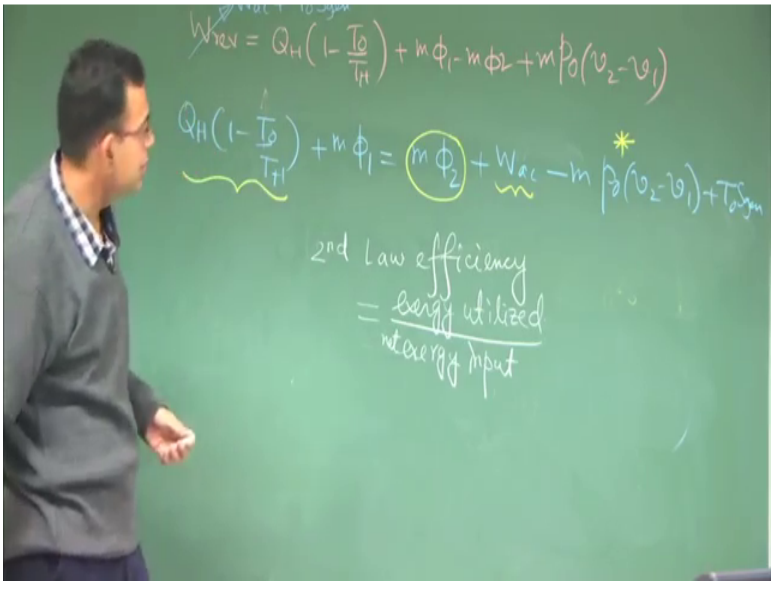
So, we come up with an expression for exergy balance which is similar to that for a control volume process with a correction term due to the possible p d v work due to moving system boundary. So, you have Q H into 1 minus T 0 by T h plus m phi 1 is equal to m phi 2 plus W actual minus m p 0 into v 2 minus v 1 plus T 0 into entropy generation, right.

So, physically what does it represent? It represents this represents the exergy input due to heat transfer. This represents the exergy input due to the initial state the initial state has a work potential. So, this is the total exergy that is input to the system; one due to the initial state, another due to heat transfer. The net result is that there is some exergy that remains within the system; some work is done. This is utilisation of the work potential. There is some lost opportunity of doing work because of the moving system from a volume v 1 to a volume v 2.

And, there is so, the so, the net work will be this one which is utilised and this will be the entropy generation due to irreversibility. So, this sums up the a exergy balance for a control mass system very similar to exergy balance for a control volume system control volume except for this term, but there are certain systems which are rigid which do not change any volume like even solids and so on. So, for that this correction term is not important.

So, there are many cases when this correction term is not important, but if you have moving system boundary in a problem this correction term will be important. So, we have discussed so far about what is reversible work, what is irreversibility, what is exergy for control volume and control mass system and how we can write exergy balance for these two cases.

(Refer Slide Time: 27:03)



So, the final thing that we need to discuss is the like when we have discussed about exergy it gives a different perspective altogether that some exergy is supplied and the part of that exergy is utilised in whatever way. The utilisation maybe to do thermodynamics work it may also be utilised for example, for heat exchange, exchange of heat from one fluid to the other. So, the exergy utilisation need not always be through work done, it may also be through some other purpose like heat exchange and so on. But, philosophically you supply an exergy a part of that exergy is utilised and the remaining part of the exergy is destroyed due to irreversibility.

So, considering exergy balance we define a term called as second law efficiency. So, second law efficiency is nothing, but the exergy utilised divided by exergy input net exergy input. Net exergy input is nothing, but that in case you have a heat transfer and a change of state the net exergy input is the exergy due to heat transfer input due to heat transfer plus the net exergy input due to the difference in the state properties that is due to the difference in phi 1 and phi 2 that is the net exergy that is input. So, what is the exercise utilised and what is the net exergy input.

So, net exergy input if you look at the expression the net exergy input will lead to a reversible work, right. So, this is essentially the expression for reversible work. The net exergy input in this case is what? The net exergy input in this case is this plus this minus this. So, that is nothing, but the reversible work; that is the actual work plus the reversibility, ok. So, net exergy input is a reversible work exergy utilised maybe actual work in case it is a work producing device or it may be the net exergy change of a stream across which heat transfer is taking place, be it for a heat exchanger.

So, this depends on purpose it need not always be work, but denominator is necessarily the expression for reversible work, that is the net exergy input. We will discuss more about second law efficiency and why it is more meaningful than first law efficiency, where the first law efficiency talks about energy balance. And, we will show later on through examples why the second law efficiency becomes more meaningful in many cases as compared to the first law efficiency which is obtained on the basis of energy conservation of a system.

Thank you very much. We will continue with problem solving in the next lecture.