Concepts of Thermodynamics
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Lecture – 53
Exergy (Availability)

Today, we will start with a new chapter which is titled Exergy or Availability.

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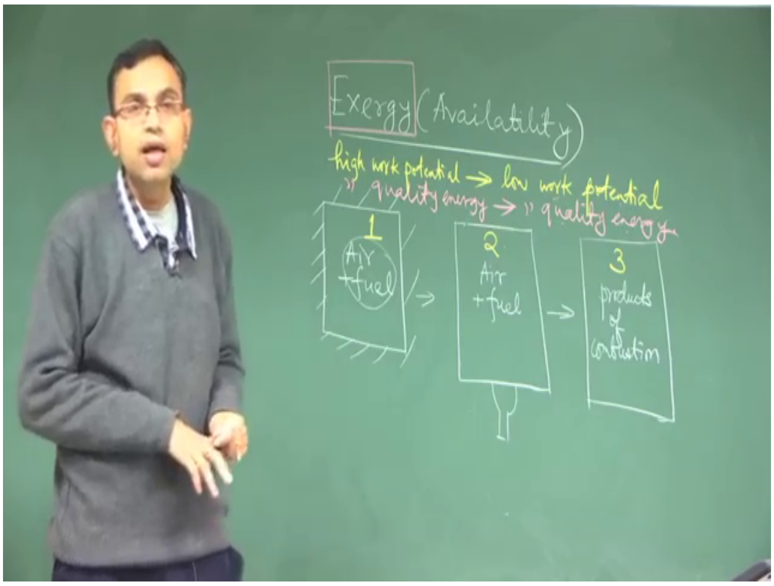

So, these are very synonyms terms; availability is a little bit old fashioned term exergy is little bit more modernized. So, before getting into what it is I will start with an example. Let us say that there is a chamber in which you have air and fuel. Let us say this is completely insulated from the surroundings. Then you transfer heat to this system. It was originally insulated.

Now, you transfer heat to the system so that there is burning of the fuel. So, maybe you do a sparking and all these things. So, you have still air and fuel and then finally, you have products of combustion. So, you had air-fuel mixture totally isolated from the surroundings, you remove the isolation and transfer some heat, so that there is combustion and then you have products of combustion. These three stages we are considered.

So, in all these processes if you include the heat transfer effect, then energy is conserved, right. Energy conservation is not violated. But, what happens is that here you had air and fuel with tremendous potential of doing work; why? Because you could have use this fuel to run a power plant, you could have use this fuel to drive a car, you could do this use this fuel to do many tasks.

In other words, the chemical energy associated with the fuel could be use for many purposes, but now when this is burned the products of combustion they get from, but you do not utilise any work out of that, it is just a closed volume chamber. No work is extracted from this, eventually if you leave it to interact with the surroundings, it will come to a state when it is in equilibrium with the surroundings and then the potential of utilising work from the system has degraded in this process.

So, we have two things one is energy another is the quality of energy. So, energy can be expressed in or energy can be sort of explain in two perspectives; one is the quantity of energy another is the quality of energy. Quality of energy gives the potential to do work. So, in terms of potential to do work out of these three cases which one is maximum? This has the greatest potential of doing work this is still less, but still you know the combustion is not complete so you could still extract some work out of this. These, in equilibrium with the surroundings is at a state where it has lost all potential of doing work and this is called as thermodynamically dead state when it is in equilibrium with the surrounding.

So, the quality of energy all though the quantity of energy remains conserved by taking into account heat transfer and all these, but the quality of energy has degraded as you go from state 1 to state 2 to state 3. High quality of energy means high quality of extract, a capability of extracting work out of the system low quality of energy means; low capability of extracting work out of the system. So, this is high work potential and this goes towards low work potential. So, in other words, it is a high quality energy degraded to low quality energy because work potential is associated with a high quality of energy.

Why work is always considered to be a high grade a form of energy or high quality energy? You must have noticed that in the second law analysis there is heat there is entropy transport associated with heat transfer, but there is no entropy transport associated with work transfer, right. So, entropy transfer or entropy transport which includes entropy generation effect, there when you are considering the net change in entropy heat transfer get reflected in that and there is also an obvious outcome of the second law that 100 percent heat in a cyclic process you cannot convert to 100 percent work. Therefore, a particular rate of heat transfer, an equivalent energy transferred in terms of heat does not have the full potential of getting converted into work. So, it is energy of a low grade.

Now, this quality of energy or work potential is expressed by a quantification which is called as exergy or availability. So, to understand this we have to consider a benchmark. Before establishing that benchmark I give you an analogous example which has nothing to do with thermodynamics, but thermodynamics is such a beautiful subject, it has analogy with society, economics or any branch of science and humanities.

So, let us say this is very common to our advanced education system in India. So, if you consider premier institutes when students enter the first year of undergraduate studies they are at this state. So, tremendous work potential because it is a highly competitive environment and students come after a whole lot of screening going through very rigorous entrance tests where I mean I can definitely say that I mean not many countries will have such a high level of competitive exam through which students have to go through to enter into you know very advanced institutes.

So, the students entering the first year of undergraduate study tremendous work potential they have. Now, as they go through different years of studies you know people are relaxed and they understand that it is more difficult to enter into these institutes, but much easier to pass through this institutes. So, they will go through a process where their entire potential as you know as a scholar as a scholarly individual in most of the cases is not exploited and they eventually when they graduate not all of them, but in many of the cases you find that the work potential has become much less than the state at which they have entered.

So, this is a law of nature I mean it is not a question that you know you can blame the system or you can blame the individual. What I am trying to impress upon you that it is a law of nature that you start with a high potential and then because you do not have if you do not have a conscious effort of exploiting the potential then your potential will automatically degrade and that is the law of nature. How much the potential will degrade you have to establish a benchmark. What is that benchmark? The benchmark is a reversible process. So, you have to see that given a set of inputs, what could be the reversible work that you could extract out of it and then what is the actual work. The difference between the reversible work and actual work is the irreversibility which is due to entropy generation during the process. So, with this broad understanding we will try to develop an expression for the reversible work.

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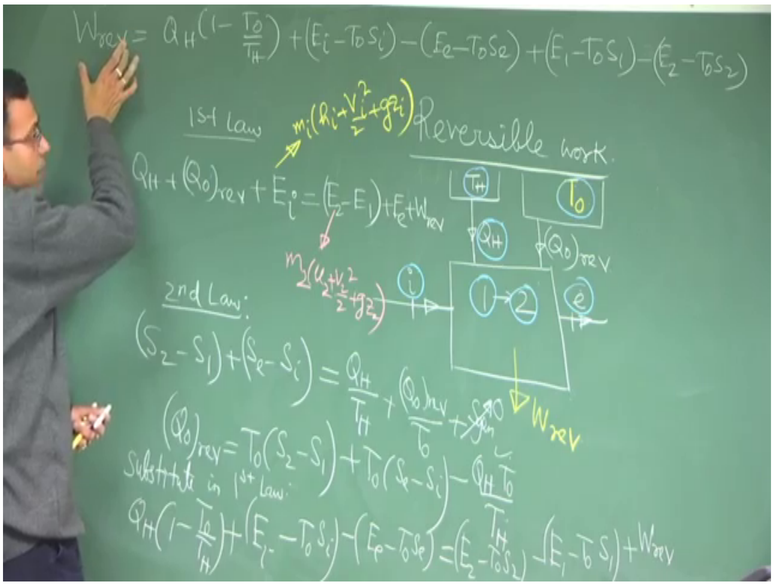

So, to generalise we will assume that there is a control volume, but you can consider the control mass system as a special case considering that there is some inlet, there is some exit and within the control volume there is state change of state from 1 to 2. If there is no mass flow across i and e, this control volume becomes a control mass system. So, control mass system is a special case of this if m i and m e are 0, ok. So, to have a general description which considers both flow and non flow process I have considered a generic arrangement like this.

What is specified? What is specified is that there is an ambient T 0 in addition to that there is a thermal reservoir at a temperature T H from which you are having a transfer of heat Q H to the system, ok. Again, what is specified? So, let us encircle what is specified this is very important T H, T naught, Q H, state i, state e, state 1, state 2. So, all the states are fixed. So, given all these states are fixed the puzzle that we have to solve is that given this arrangement what is the maximum work that we could derive out of this, that maximum work is the reversible work.

So, one missing link here is that given that you expose this system to a surrounding. So, there is a difference between two terminologies; one is called as immediate surrounding and another is surrounding. So, this one is an immediate surrounding because there is a arrangement by with this thermal reservoir directly interacts with the system, but you have a broader sounding which is the ambient. So, there is a potential of heat transfer by virtue of the temperature difference between the ambient and the system boundary. So, that is not given.

So, let us say that with this T 0, you have a Q 0. If it is a reversible process let us call this Q 0 reversible, ok. This is not something which is given, this is a spontaneous phenomenon because of the temperature difference between the system and the surrounding, ok. So, this is not given, but this will happen because of the temperature difference. So, now we will apply the; so, this will have a work output which is reversible work. So, how do we quantify this reversible work? We can quantify through first law and second law.

So, first law you have Q H plus Q 0 reversible which is not known plus energy associated with state i. So, what is energy associated with state i m i into h i plus V i square by 2 plus g Z i. So, in short form we are writing this in this way. So, just for the first time I am writing this next time onwards I will not write this. So, this is m i into h i plus V i square by 2 plus g Z i. This is equal to E 2 minus E 1 within the control volume.

Now, what is this E? This is for example, is I have not completed the equation here, but I am writing the expression this is m 2, this is energy of the control volume. So, it is internal energy and not enthalpy, ok. Similarly, E 1 plus E i sorry plus E e plus W rev ok. But, how do you guarantee that this work is reversible work? You can guarantee that this work is reversible work if there is internal and external reverse reversibility associated with it. So, that is guaranteed by 0 entropy generation in the entropy transport.

So, second law so S 2 minus S 1 plus S e minus S i these are all capital S; that means, specific entropy into mass, this is the change in entropy is equal to Q H by T H plus Q 0 reversible by T 0 plus there is no entropy generation because it is reversible. So, if you just want me to write entropy generation I can write, but you straightaway have to set it as 0.

So, what you can do is see it is a very straight forward exercise. This Q 0 reversible is not known. So, we eliminate that from these two equations. So, Q 0 reversible is equal to T 0 into S 2 minus S 1 plus T 0 into S e minus S i minus Q H into T 0 by T H you substitute that in first law. So, Q H plus Q 0 reversible is this expression. So, you have another term with Q H. So, you will have Q H into 1 minus T 0 by T H plus E i minus T 0 S i minus E e minus T 0 S e is equal to E 2 minus T 0 S 2 minus E 1 minus T 0 S 1 plus W rev, right.

So, I will try to explain this equation physically. So, you will get an expression for reversible work. So, if you are interested for that expression we will isolate all the terms. So, Q H into 1 minus T 0 by T H plus E i minus T 0 S i minus E e minus T 0 S e plus E 1 minus T 0 S 1 plus E 2 sorry minus E 2 minus T 0 S 2, right.

So, see a couple of interesting things. First of all this is the maximum work potential of the system which you can exploit because it is reversible, there is no loss. So, a part of the work potential is a is associated with this heat transfer Q H. And what is the maximum work that you can get? If you feet a Carnot cycle engine that connects the thermal reservoir one with T H and another with the surrounding then this is actually the work done by the Carnot cycle in a cyclic process. So, with this Q H so, this is like Q H into one minus T l by T H T l is T 0 here.

So, this is a reversible utilisation of this Q H for work and this is the maximum potential governed by the initial and the final state and inlet and exit state and you can see that it is just like the first law expression, but energy is replaced by energy minus T 0 S. So, this E minus T S is considered to be a sort of a term called as free energy which we will discuss later on. But the concept starts from here that you have an energy that is freely available which is not the difference in E, but the difference in E minus T S, where the T is the reference temperature of the surroundings. So, this tells you so, these are the this totality is the work potential due to the change in state and this is the work potential due to heat transfer. So, the total maximum work that you can extract is this one. Now, consider the reality so the real process; real process is not reversible, right. So, I will keep the same box, but for your notes please draw a fresh diagram.

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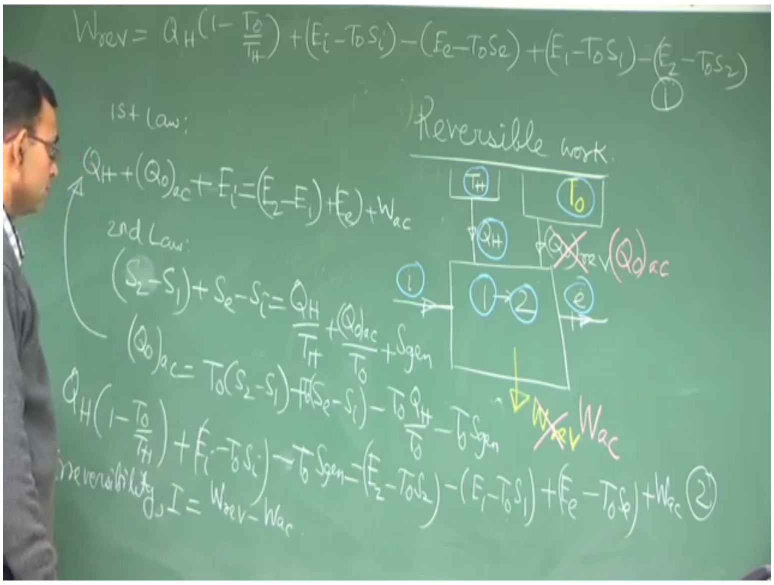

$W_{rev} = Q_H\left(1-\frac{T_0}{T_H}\right) + (E_i - T_0 S_i) - (E_e - T_0 S_e) + (E_1 - T_0 S_1) - (E_2 - T_0 S_2)$ ①

1st Law:

$Q_H + (Q_0)_{ac} + E_i = (E_2 - E_1) + E_e + W_{ac}$

2nd Law:

$(S_2 - S_1) + S_e - S_i = \frac{Q_H}{T_H} + \frac{(Q_0)_{ac}}{T_0} + S_{gen}$

$(Q_0)_{ac} = T_0(S_2 - S_1) + T_0(S_e - S_i) - T_0\frac{Q_H}{T_0} - T_0 S_{gen}$

$Q_H\left(1-\frac{T_0}{T_H}\right) + (E_i - T_0 S_i) - T_0 S_{gen} - (E_2 - T_0 S_2) - (E_1 - T_0 S_1) + (E_e - T_0 S_e) + W_{ac}$ ②

Irreversibility, $I = W_{rev} - W_{ac}$

So, the same box which is the control volume you have state i let me encircle same inputs that is you have heat transfer Q H to the box, it changes from 1 to 2 and the exit is E, T 0 is there, but the process is not reversible because the process is not reversible instead of this W reversible we will have W actual, ok. Instead of W reversible we will have W actual, instead of Q 0 reversible we will have Q 0 which is Q 0 actual.

So, then let us write the first law and the second law Q H plus Q 0 actual is equal to plus E i, now I will not write what it is we have already written is equal to E 2 minus E 1 plus E e plus W actual. Again Q 0 actual you do not know. So, you have the second law from which you get an expression for this and you eliminate in the process. So, second law Q H by sorry S 2 minus S 1 plus S e minus S i is equal to Q H by T H plus Q 0 actual by T 0, now there will be entropy generation because of irreversibility right.

So, you can eliminate Q 0 actual as T 0 into S 2 minus S 1 plus S T 0 into S e minus S i minus T 0 into Q H by T H minus T 0 into entropy generation, you substitute that here. So, Q H into 1 minus T 0 by T H plus E i minus T 0 S i is equal to E 2, sorry then we will have minus T 0 S gen right is equal to E 2 minus T 0 S 2 minus E 1 minus T 0 S 1, plus E e sorry S, so plus E e minus T 0 S e plus W actual, right.

So, this is one expression where you have W reversible this is one expression you have from which you can get W actual. The irreversibility is defined as the difference between reversible work and actual work. So, if you subtract these two expression for W actual from W reversible all the terms will cancel, you can see except T 0 into entropy generation.

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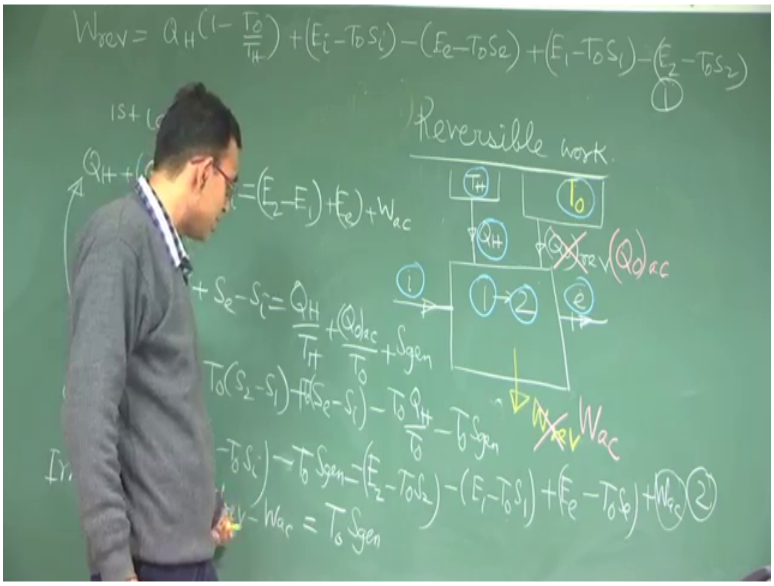

So, this is equal to T 0 into entropy generation and this sounds meaningful. This makes sense because the irreversibility is associated with entropy generation. So, irreversibility which is a difference between reversible and actual work is nothing, but the T 0 into the entropy generation. We will stop here in this lecture we will continue with this in the next lecture.

Thank you very much.