**Basic Thermodynamics**

**Prof. S. K. Som**

**Department of Mechanical Engineering**

**Indian Institute of Technology, Kharagpur**

**Lecture - 11**
**Second Law and Available Energy-II**

Good morning. Welcome you to this session. In the last session, we started the discussion on availability or <mark>exergy</mark> or available energy. We just recapitulate again, what we discussed in the last session with respect to heat, the energy in transit from a temperature $T_1$. Just a recapitulation,

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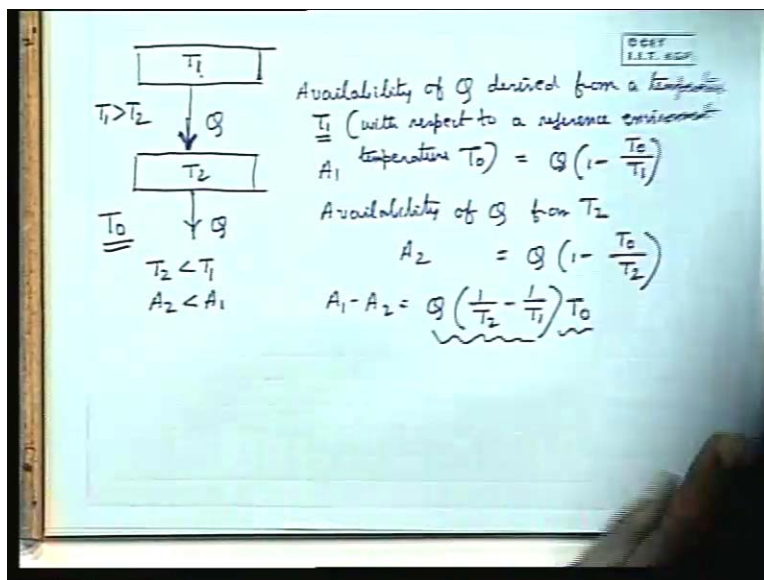


If heat Q is available from a temperature $T_1$ then the maximum work which is possible with reference to a fixed environment temperature $T_0$, was ascribed to its availability or available energy of Q. We can write the availability. These are the synonymous terminology, as we told in the last class, availability of Q derived from a temperature $T_1$ with respect to a reference environment temperature.

Why I am writing this thing? Because these are the specifications; that means, the availability or available energy of some heat quantity depends upon the temperature at which it is obtained and

the reference environment temperature. It is referred to as exergy or availability reference environment temperature. So, this becomes equal to the work by a Carnot cycle; that means, Q 1 minus $T_0$ by $T_1$. At the same time, we also appreciate that the same heat, instead of obtaining from $T_1$ could have been obtained from another temperature $T_2$ which is less than $T_1$ which means that if we first transfer this heat from a high temperature part or reservoir, to a relatively low temperature reservoir $T_2$.

Derive this Q from a low temperature. Then, this availability of Q with reference to the same availability reference temperature that is $T_0$, environment temperature, availability of Q from $T_2$ will be equal to Q 1 minus $T_0$ by $T_2$; since $T_2$ is less than $T_1$. Obviously, the availability from $T_2$ is less than this.

Let us consider this as $A_1$ and this as $A_2$. Since $T_2$ is less than $T_1$, $A_2$ is less than $A_1$ then calculate the difference if $A_2$ is less than $A_1$. So, what is $A_1$ minus $A_2$? It will be Q into 1 by $T_2$ minus 1 by $T_1$ $T_0$. So, this much is the loss, rather difference in the available energy; that means, the available energy or availability of Q is reduced when it is obtainable from a temperature $T_2$ rather than temperature $T_1$, where $T_2$ is less than $T_1$ by this amounts to.

Into $T_0$. So, what exactly this amounts to be? We should know what exactly this means. The difference in available energy which is lost; the available energy is lost when we transfer the heat from high temperature to low temperature. To understand these things, let us go through the concept of irreversibility.
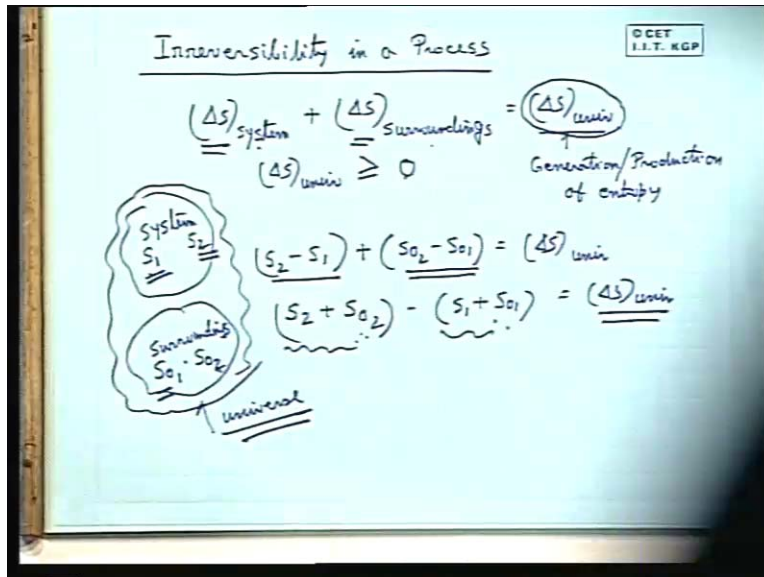
What is meant by irreversibility? Irreversibility is a process in which all natural process is an irreversible process. So, what is the criterion of irreversibility? We know from the entropy principle that, when a system interacts with its surroundings and performs a process which may be ideal or natural, the basic principle from second law, as far as the change of entropy of the system and the surrounding is concerned, is that the algebraic sum of the entropy change of the system and surrounding which is known as entropy change of the universe which is entropy change of the system plus entropy change of the surrounding, will be greater than equal to zero.

When the process is reversible for both the system and the surrounding, this means the entire process. If we consider the system and the surrounding as an equivalent isolated system which is termed in a limited sense, as the universe is totally reversible then the entropy change of the system plus the entropy change of the surrounding becomes zero; that is, they become exactly equal but opposite in magnitude. Otherwise, this algebraic sum of entropy change is which entropy change of the universe is greater than zero. Therefore, entropy change of the universe is definitely a criterion for the reversibility of a process. If a process is both externally and internally reversible then this entropy change becomes zero.

So, if the entropy change of the universe is approaching zero, as the process performed by a system approaches a reversible process. Therefore, delta S $_{system}$ plus delta S $_{surroundings}$ is equal to

delta $S_{universe}$. Delta $S_{universe}$, according to second law of thermodynamics is greater than and equal to zero; for a natural process greater than zero and for an ideal process equals to zero.

Now, this equation can be interpreted in various forms. Delta $S_{universe}$ sometimes can be written as generation of entropy or production, generation or production of entropy. If we consider a surrounding and we designate the system entropy, initial $S_1$ and final $S_2$ and the surrounding entropy initially $S_{01}$ and final $S_{02}$, then delta $S_{system}$ is $S_2$ minus $S_1$ and delta $S_{universe}$ is $S_{02}$ minus $S_{01}$. That becomes surrounding is equal to delta $S_{universe}$ which becomes equal to, that means that delta $S_2$ plus $S_{02}$ minus $S_1$ plus $S_{01}$. Therefore, this delta $S_{universe}$ represents the sum of the entropy after the process minus the sum of the entropy before the process. If you designate some entropy, some absolute entropy of the system $S_1$ at the beginning of the process and that of the surrounding when the process takes place only, we equate the entropy change. Therefore, we designate final entropy $S_2$ so that the change is $S_2$ minus $S_1$.

Similarly, the surrounding suffers a change in entropy so that its final entropy becomes $S_{02}$. So, this is the change of entropy of the surrounding; that means the change of entropy of the system plus surrounding is, the change of entropy of the universe is nothing but the change of the entropy of the total equivalent isolated system or universe. That means final entropy of the system minus initial entropy of the system. That is always greater than zero means in all natural process, entropy is generated, because <mark>this is more than this.</mark>

If the process is an ideal one that is the reversible interactions then the entropy before and after remains the same. Otherwise, always entropy is generated; that means, entropy of the universe is always generated. Universe that means entropy of the universe is monotonically increasing for all natural interactions within the universe. So, that is why it is sometimes written as entropy generation.
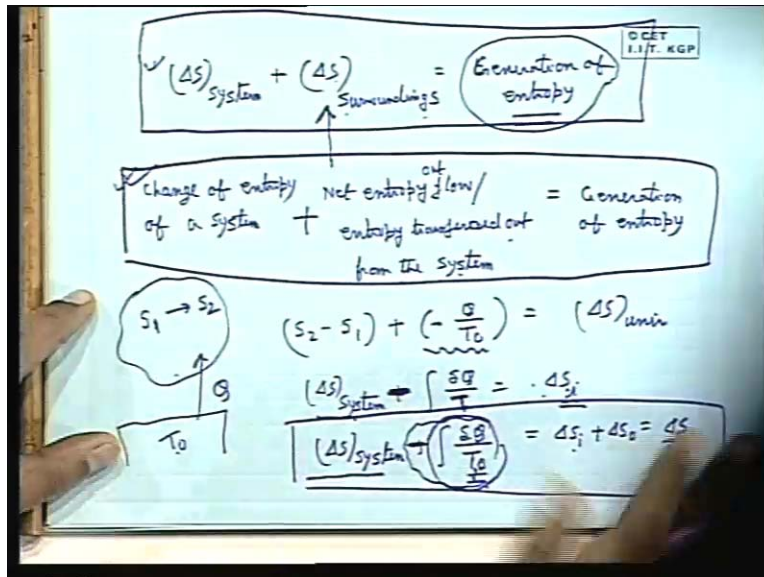
If we write in this way then we write, delta S $_{system}$ plus delta S $_{surroundings}$ we must know the various forms, so that we should not have any confusion, can be written as entropy generation. Delta S $_{universe}$ I write now, the generation of entropy or entropy generated or generation of entropy.

Now, in irreversible thermodynamics, sometimes this delta S $_{surrounding}$ is written as delta S $_{system}$. What is delta S $_{system}$? Now, I write in language change of entropy of a system. This delta S $_{surrounding}$ is sometimes written as net entropy flow or entropy transferred out, flowing out, net entropy transferred out from the system. In case of a close system, we usually use this terminology entropy transferred out or entropy out flow. Therefore, this plus this is equal to generation of entropy in irreversible thermodynamics. Now, how we equate delta S$_{surroundings}$? There is a system and there is a surrounding at $T_0$.

let the system is heated by an amount Q. The entropy changes from $S_1$ to $S_2$. So, according to our classical reversible thermodynamics, this statement is that delta S $_{system}$ $S_2$ minus $S_1$ plus delta S $_{surrounding}$. What is delta S$_{surrounding}$? It is a reservoir at constant temperature. Heat is being rejected that means this will be minus Q by $T_0$ and this part is the same, entropy generation delta S $_{universe}$ which is nothing but entropy generation or production.

So, minus Q by $T_0$ can be looked as the net entropy transferred out or entropy flow out of the system with a minus sign, because it is coming in. So, minus of that is going out. If the system could have rejected the heat Q to the surrounding then surrounding entropy could have increased. So, it could have been plus Q by $T_0$; that means, this is entropy out flow or entropy transferred out. So, this is nothing but entropy out flow or entropy transferred from the system. This is synonymous to the delta S $_{surrounding}$ that means, whether I write in this version or write in this version, change of entropy of the system plus change of entropy of the surrounding is the same thing. Whether I write, delta S $_{universe}$ or entropy generation rate is the same thing.

Again, in another equation which we already appreciated that delta S of a system ==you please be careful I can tell you, not in a single book this is shown elaborately explained these three equations for the entropy change and the relationship between these three==. They are the same equations, synonymous equations, but explained or interpreted in a different way. Now, we know that delta Q divided by T is equal to internal irreversibility; that means, it is the entropy change due to internal irreversibility. We appreciated that delta Q divided by T delta S system.

What is this delta Q divided by T? This is an integral evaluated with this system temperature, but if I just substitute these, or write this in delta S $_{system}$, plus delta Q divided by $T_0$, while $T_0$ is the surrounding temperature, this is little changed as delta $S_i$ plus delta $S_0$. The delta S is the entropy change due to both internal and external irreversibility, where I consider these are the surrounding temperature.

Therefore, this is delta S system and this is an integral delta Q divided by $T_0$, where $T_0$ is the surrounding temperature. If we think T as the system temperature then it is the entropy change due to internal irreversibility. This is the entropy change due to externally irreversibility plus internal irreversibility. This is the entropy change because of the heat transferred to the system. If we evaluate these at surrounding temperature then this is equivalent to this net entropy out flow transferred out and this is the delta S $_{surrounding}$ therefore, the delta S $_{system}$. ==This will be minus.==

So, this will be nothing but the entropy change of the surrounding. This will be, this side delta S $_{system}$ is delta Q divided by T plus delta $S_i$. So, there will be a minus sign. Therefore, we see now that these three equations are synonymous. Now, I write these three equations.

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I write first, delta S $_{\text{system}}$, and change of entropy. Delta S $_{\text{system}}$ plus delta S $_{\text{surroundings}}$ is delta S $_{\text{universe}}$. Delta S $_{\text{system}}$ is nothing but net entropy out flow or transferred out. I am not writing both the statements from the system. When I write this, usually I write generation of entropy. Sometimes, I write, delta S $_{\text{system}}$ minus integral Del Q by $T_0$ is equal to which is the entropy change due to heat transfer. Therefore, this will be delta S which is the entropy change due to irreversibility. When the process is both externally and internally irreversible then delta S is 0, delta S $_{\text{system}}$ is del Q divided by T.

Therefore, these three equations which are very important are synonymous which means that delta; we should rather follow this one for our calculation. This will be simpler one and we will always recognize delta S, delta S $_{\text{universe}}$ is nothing but the generation of entropy. That means this delta S $_{\text{universe}}$, this generation of entropy is same. that means delta S $_{\text{universe}}$ of the first equation is nothing but delta S of third equation and these two equal to generation of entropy. That means because of irreversibility there is always a generation of entropy in an equivalent isolated system. That means, whenever there is an interaction between system and surroundings, between different systems, it causes the entropy of the equivalent isolated system on the universe to increase. That is the generation of the entropy.

Now, irreversibility - I. When the process is more and more irreversible the generation of entropy will be more. Its value will be more and more positive. It is always positive for a natural process. When the entire interactions between the system and the surroundings or interacting systems tend to reversible process, then this generation of entropy tends to zero. So, irreversibility in the process is gauged or characterized by this entropy generation. It is quantified as some reference temperature environment reference temperature into entropy generation or delta S $_{universe}$ or $T_0$ delta S $_{universe}$.

Sometimes, the entropy generation is symbolized as sigma $T_0$ delta S; that means, sigma is entropy generation which is nothing but delta S $_{universe}$. It is always better. This would be simpler to calculate system and surroundings entropy change separately, sum it up algebraically, get delta S $_{universe}$ multiply it with $T_0$, and get the value of irreversibility. So, this gives a quantified equation of irreversibility which comes in terms of the energy. Because irreversibility is something due to which the energy is being converted from the higher to lower grid. So, its unit is always expressed in terms of energy. Delta S is energy per temperature del Q by T. Therefore, you multiply with a reference temperature which is usually this standard environment temperature and this gives the irreversibility.

So, we define irreversibility quantitatively for any interacting system and surrounding equivalent isolated system, where a process is being taken place. We have to define the reference environment temperature based on which we define the irreversibility.

Not the system temperature. It is $T_0$, because $T_0$ is the reference fixed constant temperature. Not by the system temp then irreversibility will change. So, this is just a formula. We take a reference value. It means irreversibility is directly proportional to delta S $_{universe}$, or entropy generation rate. $T_0$ acts as a constant scale factor to express it in terms of the energy. It is not any varying temperature of the system or any varying temperature of the surrounding to which it is interactive. It is a fixed environment different temperature.

Sometimes, we call it as fixed in temperature. They are fixed reference quantity, because it acts as the scale factor with the entropy change of the universe, which is exactly the criterion. It

should be even quantitative criterion for irreversibility, but to express it in terms of the energy unit; we just multiply it with $T_0$, a fixed reference environment temperature.

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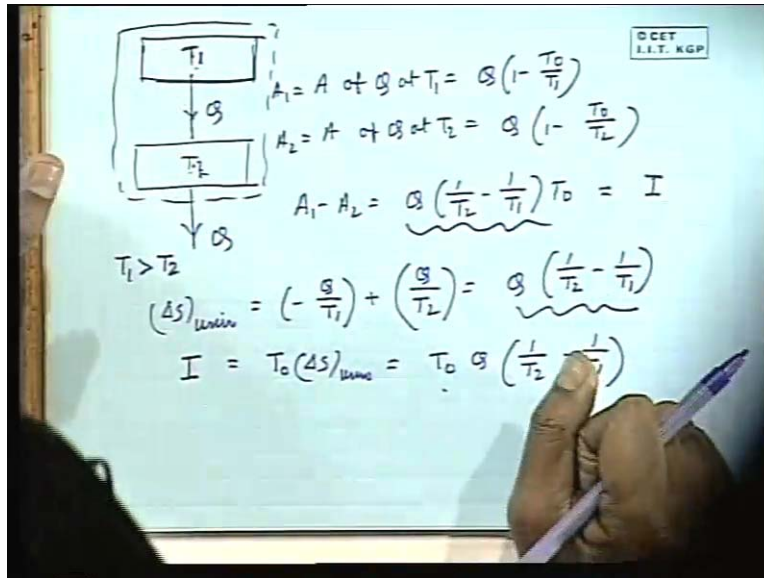


When heat is available at $T_1$ temperature and instead of that if we transfer this to $T_2$ temperature and the same heat is taken, the availability A of Q at $T_1$ is Q into 1 minus $T_0$ by $T_1$ and availability of Q at $T_2$ is Q into 1 minus $T_0$ by $T_2$ and <mark>let this is A1 and let this is A2</mark>. $A_2$ is less than $A_1$ and the difference is Q into 1 by $T_2$ minus 1 by $T_1$ into $T_0$.

Now, if we consider this heat transfer process, this is an irreversible heat transfer process. Heat transfer due to a finite temperature difference. Whenever I transfer heat from a high temperature to a low temperature, this is a natural process and irreversible heat transfer process. So, what is the entropy change of the universe? It will be greater than 0. To find this entropy change of the universe in this heat transfer process, how to find out entropy change of the universe? <mark>The entropy change of this system plus the entropy change of this system; this rejects it.</mark> So, entropy change of this system at a constant temperature gets the same heat Q by T2.

Therefore, Q into 1 by $T_2$ minus 1 by $T_1$ is the generation of entropy or the entropy change of the universe, because of finite temperature difference heat transfer, there is irreversibility. So, irreversibility due to this finite temperature difference heat transfer will be equal to $T_0$ into delta

S $_{universe}$; that means, $T_0$ into Q into 1 by $T_2$ minus 1 by $T_1$. Therefore, this quantity is nothing but the irreversibility I, because of the heat transfer due to finite temperature gradients.

Now, what is the philosophy? When exergy or the available energy is the work potential, we must receive the energy, low grade energy for example, heat. We are discussing heat now. For converting into work, at that state, why this work potential is much more? For an example, in a cricket team, we won such a cricketer in our squad whose work potential is much more. We do not want somebody whose work potential is less. Therefore, state is very important that what his potential is so that this is most likelihood that he will deliver the good. Therefore, similar way, the heat which has to be converted into work should be derived at certain state so that its work potential or availability should be maximum.

Then, next question is that when you transfer it to $T_2$, this work potential is reduced. This is because of the irreversibility in the natural process through which heat is transferred to $T_2$. Then why do you transfer? This concept is the underlined concept that sometimes we cannot use this low grade energy at this state, where its work potential is high or maximum, because of some practical reasons. So, there we have to transfer the heat at the lower temperature, where its work potential is reduced because of this natural process of transferring this energy.

Sometimes in fuel, for example, fuel has got some energy inherent in it; chemical energy. To obtain this chemical energy in to power, when this energy reaches the work producing device, we will make a combustion process. We liberate heat through burning of the fuel. Then ultimately the products of combustion at high temperature and pressure come to the working device which contains a high thermal energy, internal energy.

So, while doing so, if we evaluate the available energy or work potential of the fuel at the beginning, that will be taught afterwards in chemical availability in the chapter chemical thermodynamics or thermodynamics of reactive system, is lost because of this natural processes of combustion and heat transfer. All these things combine together creates a loss in the work potential availability, but we cannot use like that. Closer example of this is a solar energy. We obtain heat from sun we cannot obtain that heat from sun's temperature or the temperature of the sun, to develop work.

So, what we have to do? We have to use the collector where we collect the heat even if we consider the entire amount of heat is coming to this collector without any absorption in this surround medium. But the temperature of the collector from where we utilize the heat, or a medium which absorbs the heat from the collector and ultimately goes to the engine is much less than the temperature of the sun. So, if somebody equates the available energy of the amount of heat radiated from the sun at sun temperature, it is huge. But when we calculate the same amount of heat neglecting the absorption in the medium at the temperature where it is collected or absorbed by a system, available or obtainable at what available I will not use here obtainable for utilizing it in developing work through a heat engine is a much less and its available energy is less.

So, each and every natural process this way grades the quality. This is known as quality of energy that work potential of energy or available energy. I will explain this again, more in detail, but at this moment, we go to another form of available energy.

So far, we have discussed the available energy with respect to some heat coming out at some temperature. Now you consider, there is a closed system. There is a system which is at an elevated condition; that means, its state is different from the surroundings. Now, there is a possibility that if this system interacts with the surrounding and comes to the dead state, we cannot extract some work; that means, the system has a work potential similar to that heat flow, similar to that of the heat energy coming from $T_1$. That is ascribed to as the available energy or availability of a system. Let us consider a closed system.
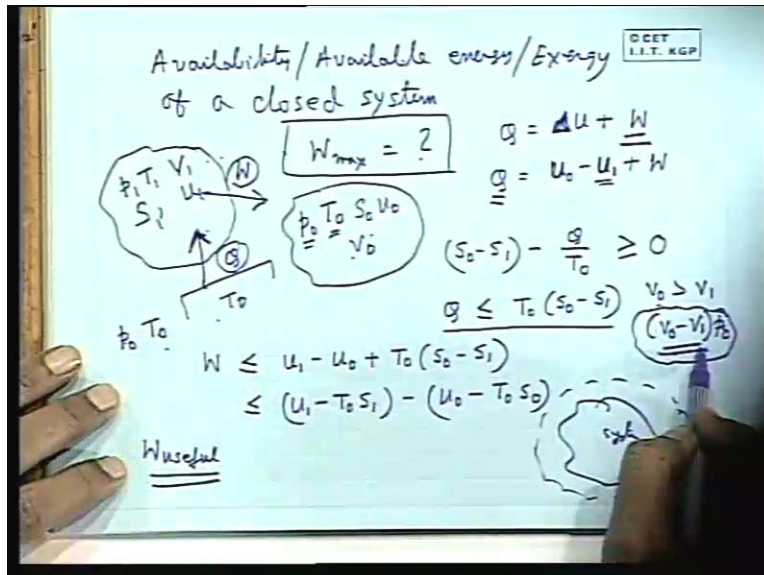
Now, I will discuss the availability energy. Again, the synonymous term, available energy or exergy of a closed system. From where does the concept originate? Concept originates from here. Let us consider a closed system which is having a pressure p, temperature T, volume V, entropy S, and internal energy u. Let the environment be at a fixed pressure and temperature $p_0$, $T_0$. Let $p_0$, $T_0$ be the pressure and temperature of the environment.

Now, the system is at an elevated state that means the state point of the system is different from that of the environment. Therefore, there exists an opportunity of obtaining work from this system if it is allowed to interact with the surrounding and comes to the dead state. That means the property will be such that it will be in thermodynamic equilibrium to the surrounding.

In that case, our objective is to find out what is the maximum work obtainable. That will be defined as the availability of the closed system. Let us do that now. To do it, let us consider, some heat Q is given from this environment at $T_0$; that means, I cannot bring out some other system, that environment; we have to think in terms of Q going from the environment.

So, it may come out from the system in that process. Does not matter, whether it is coming out or going in, just by a reference, by convention, I just do it. There some heat is added and all over that is in general analysis, we do like that and some work is coming out of this system.

In the process where it has taken heat from the surrounding and developing work W, it has come to the dead state; that means, these are the finite amount of energy interactions after which the system comes to the dead state; which means, system pressure will be $p_0$ temperature will be $T_0$, and system has to be a thermodynamic equilibrium, both mechanical and the thermal equilibrium.

Here, we are not considering the chemical equilibrium no must transfer chemical reaction is considered; that means, the mechanical and thermal equilibrium will be the only criteria for the thermodynamic equilibrium. Let the corresponding properties are $s_0$, $u_0$, $v_0$ like that and let us consider these with a suffix 1. That is the initial state and that is the final state.

Now, I can write the first law of thermodynamics; Q is equal to delta u plus W. Delta u is simply $u_0$ minus $u_1$ plus W. Now, here I neglect any form of kinetic energy within the system, closed system, will consider a stationary closed system. That is why the initial internal energy is inter molecular energy and finally, when it will be coming to equilibrium dead state, internal energy will be only the inter molecular energy $u_0$. So, if we consider these, then we can write this according to first law of thermodynamics.

Now, what is Q? I can write from the entropy principle that this change of entropy of the system that is $S_0$ minus $S_1$ change of entropy of the surrounding minus Q by $T_0$ has to be greater than equal to 0. Then we can write, Q is less than equal to $T_0$ into $S_0$ minus $S_1$. Then, if I substitute this in equality relation, we can write W becomes equal to less than $u_1$ will go this side $u_1$ minus $u_0$ plus $T_0$ into $S_0$ minus $S_1$.

Then we can write, is less than $u_1$ minus $T_0 S_1$ minus $u_0$ minus $T_0 S_0$. I can write, W becomes less than equals to this. Now there is a little concept. If we are interested only with the useful work, what is useful work?

Now, when a system delivers work, then a different form of work interactions I have told here, generally I have written W. Now, when we deliver the displacement or a part of it is been spent by displacing its surrounding. What is that? That means there is a system and when the system expands, for example, this is the final shape of the system; that means, difference in this volume

that means $v_0$ is greater than $v_1$ that means this $v_0$ minus$v_1$ into $p_0$ is required to push the system. That means this amount of work is utilized in displacing the system by an amount of $v_0$ minus $v_1$.

So, that much work is not available as useful work that is being spent to the surrounding. Because surrounding does not mean this entire environment; that means, it is another system. If two systems are in close contact and if one is expanded. Consider a cylinder divided by a piston. If one side is a system and another side of the gas is the surrounding; that means, when it delivers to another side of the gas, if it is allowed to maintain its pressure constant, it is being pushed. So, $v_0$ minus $v_1$ into $p_0$ is the work that is being spent by displacing the surrounding.

This work is not the useful work. Therefore, useful work, we write, W $_{useful}$ is equal to W minus this $p_0$ into $v_0$ minus $v_1$. Therefore, I can write, W useful is less than equal to... Now, if I subtract this, I can write, $u_1$ plus $p_0 v_1$ minus $T_0 S_1$ minus $u_0$ plus $p_0 v_0$ minus $T_0 S_0$.

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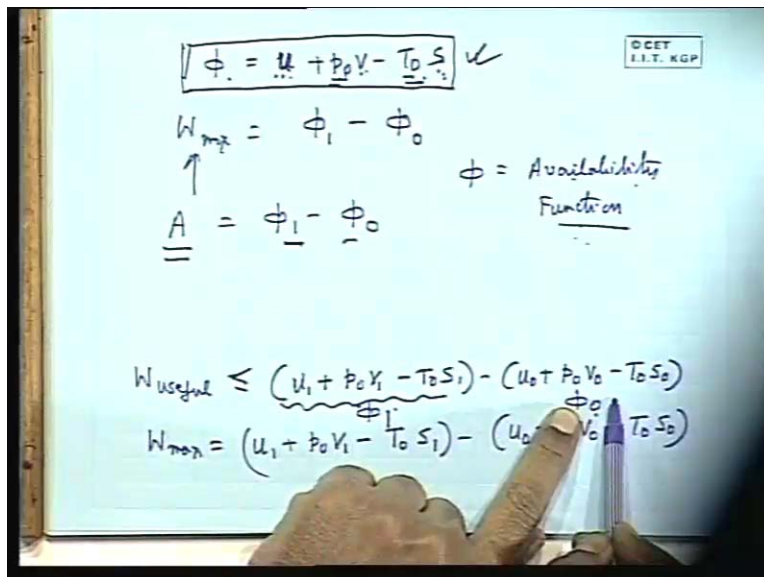


Now, with this expression, I can write that maximum work will be equal to $u_1$ plus $p_0 v_1$ minus $T_0 S_1$ minus $u_0$ plus $p_0 v_0$ minus $T_0 S_0$. If I define a function phi like this, at any state given by the p, v, T, S like this u plus $p_0 v$ minus $T_0 S$. If I define a function like this then I can write, this is the function at state 1 and this is the function at state 0; that means, I can write the W $_{maximum}$ is this function corresponding to state 1 corresponding to state 0, 0 is the dead state.

Now, you see how I choose this function. This is not a property of the system. This does not contain only the system properties or the state variables of the system, it contains the surrounding property; that means this is a composite function of both system and surrounding. Variable u is the system variable and the internal energy of the system. v is the volume of the system, S is the entropy of the system while $p_0$ and $T_0$ are those of the surrounding.

So, this function is a composite function. If you want to describe these are the property then you will have to tell that this is a binary property or a composite property of both, system and surrounding in this fashion, u plus $p_0$ v minus $T_0$ s.

Then this composite property is evaluated at state 1 and evaluated at state 0. The difference of this is the maximum one. So, this by definition is the availability of a closed system $phi_1$ minus $phi_0$. $phi_1$ and $phi_0$, the phi rather it is known as availability function.

Therefore, the maximum useful work obtained from a closed system which is elevated from that of the surrounding is known as availability, available energy or exergy of that closed system to that specified state, with reference to a prescribed environment at $p_0 T_0$. We know that this available energy that is the maximum work, we will get if the system is allowed to interact reversibly with this prescribed surrounding or environment, and comes to the dead state so that naturally, no other process is possible. That means, in that way you will get the maximum amount of work available. That equals to the availability or available energy or exergy of that closed system which equals to the difference of the same functions availability function evaluated at state 1 and evaluated at the dead state.

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I will tell you what is the maximum work from state 1 to state 2 for a closed system; not the dead state that means the closed system at state 1 and we forcefully stop it at state 2. We make the boundary in such a way that again it comes to equilibrium state which may not be the dead state. That means the boundary is made such that no further process or interactions with the surrounding is allowed.

In that case, the maximum work will be $phi_1$ minus $phi_2$, because phi 0 will be cancelled from both the cases. So, that is the reason for which the phi itself is sometimes defined as availability; it is the index of availability. Sometimes, phi is u plus $p_0v$ minus $T_{0S}$. This itself is sometimes called as availability function. This is known as availability because corresponding values with $u_0$, $v_0$ and $S_0$ are constant values, for a given particular system of a given working substance.

Therefore, sometimes, this is used as the availability function. Sometimes, it is used as the specific availability function, in some books phi is denoted as specific availability. It does not matter. There may be many conventions. So, all small, that means per unit mass. So, maximum work per unit mass will be the difference of this specific availability concept or specific availability. We usually call this function itself as the availability concept is clear. Now, availability balance of a closed system.

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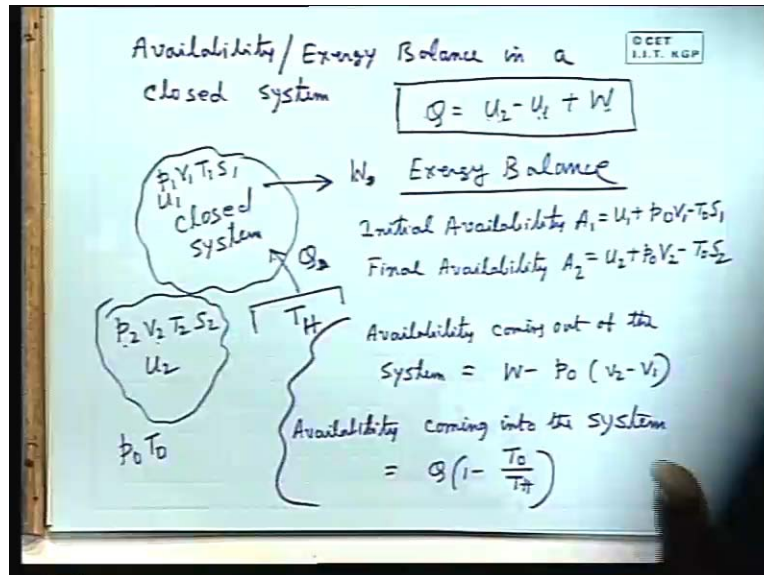


This is very important availability

Yes. Obviously, from the very beginning, I told you that we have to define basic concepts. We have a system at certain state. Just imagine one thing. Today, we have closed system whose pressure and temperature is same as that of the surrounding temperature and no process is available. You know process is possible. So, availability is zero, because you tell it is at dead state. But the same system, if you consider in the first week of January this availability was zero at the same pressure and temperature, but that time ambient temperature was much less.

We take that system to a very high altitude, where the pressure is less, because it has to interact with the environment and come to the dead state. During that process, what is the maximum work obtainable? By definition itself, the environment is coming.

We get some heat from some temperature. If I ask you what is the maximum work we have to obtain, then you think of Carnot's efficiency and immediately we think of an environment temperature, where heat has to be rejected, because second law tells that all heat cannot be converted in to work. Otherwise, the environment could not come into picture; that means, we will have to think of a heat rejection concept. Heat rejection temperature and the minimum heat

rejection temperature possible is the environment temperature. We cannot create a temperature below the environment out of nothing then will have to create something else. We will have to run a refrigerant. So, naturally possible minimum temperature is the environment temperature. That means, we will have to consider a Carnot engine working between that high temperature from where heat is coming and the environment temperature as the temperature of heat rejection.

So, that way, in the concept definitely the environment comes in to picture. This is inherent in the definition of availability. Therefore, when we prescribe the availability of heat at certain temperature with reference to this environment, availability of a closed system at certain state means this state is not same as the environment state or at the dead state with respect to prescribed environmental condition. Now, which is most important is the availability balance, again, exergy all these things this synonymous term availability or exergy balance in a closed system.

You have to also read and think thermodynamics. one has to think only in the class it is not like mathematics or fluid a part of fluid mechanics are most of the mathematical equations are they are only sufficient but you have to read.

Availability and exergy balance in a closed system. Now, let us consider, in general a closed system closed system. Here, I consider there is a reservoir or a thermal reservoir at T1 from where heat is coming to the system. Let $Q_1$ amount of heat has come. Work delivered by the system is $W_1$ and the system while doing so, the system change. The system property is given initial property $p_1, v_1, T_1, S_1, u_1$ and the corresponding properties, when the system comes to state 2, this is not a dead state; that means, a closed system is there whose initial properties are $u_1$, $v_1$ $T_1$. All are not independent, but I am showing as much as it is possible.

Oh sorry that let us come $T_H$. So it is $T_H$, closed system. You take heat from a thermal reservoir $T_H$. A definite quantity of heat Q is going do not give then one otherwise it is Q. It delivers some work W and then it comes to another equilibrium state, where the corresponding properties are like this; that means I use this subscript 2 for that state.

Now, in doing so, we know our energy balance. What is that energy balance? Q is equal to $u_2$ minus $u_1$ plus W. This is the energy balance, first law of thermodynamics. Now, what is exergy

balance? Initially, availability exergy or availability balance. Sometimes, it is written as exergy balance. I told you earlier they are synonymous terms, but depending upon their uses I will use the terminology conventionally. Initial availability $A_1$ is equal to $u_1$ plus $p_0v_1$ minus $T_0S_1$ and final availability with the scale at the dead state $u_0$ plus $p_0v_0$ minus $T_0S_0$. That is always being deducted so that we use this as availability. Final availability $A_2$ is equal to $u_2$ plus $p_0v_2$ minus $T_0S_2$. Now, I find out what is the net availability transferred out. Now, make a balance availability or exergy. Availability coming out of the system, can you tell me what is the availability coming out of the system? That is a concept of availability transfer; like energy transfer. Is there any availability coming out of the system? Can you tell? Then $A_2$ minus $A_1$ is the availability of the state.

Energy has got two distinct statuses; one is the energy in storage which specifies the state of the system and another is the energy transit that is work and heat, because of which the state of the system is changed and at the same time, the energy contained in the system is changed.

Similarly, the availability; also depending upon the state of the system and the energy stored in, there is an availability within the system which is a composite property of the both system and the surrounding. If the surrounding, if we fix it universally, then it is the property of the system and another is the availability transferred which is absolutely transfer of energy, because with the transfer of heat at some temperature T, there is an availability transfer. Similarly, with the transfer of work there is an availability transfer. What will be that availability transfer? That will be the work itself because work is high grade energy.

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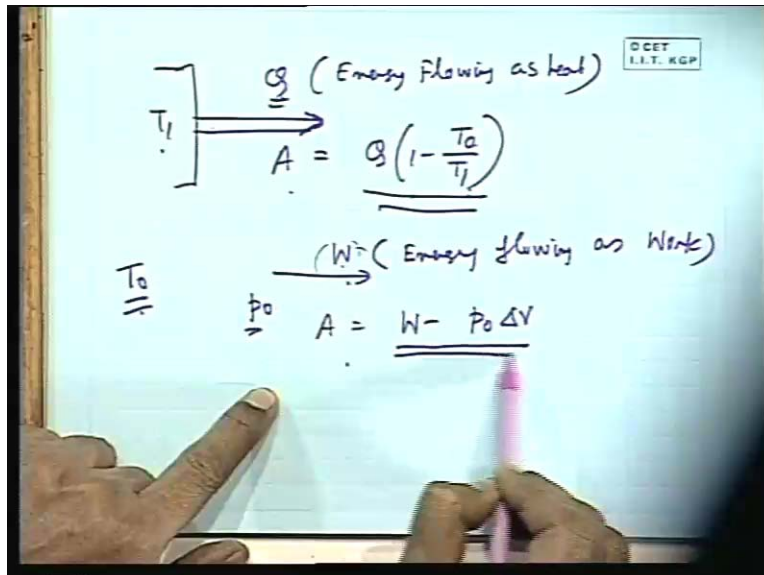


When there is a temperature $T_1$, energy flowing as heat is Q. So, if I fix a temperature environment $T_0$, exergy or availability flowing associated with this energy is Q into1 minus $T_0$ by $T_1$; that means, with this energy flowing as heat, this amount of associated availability is flowing. When we move along with this, this much of amount of mass is moving and this much amount of potential is moving which is quantitatively defined like this. So, with this flow of heat, this is the available energy. Similarly, when work is transferred by a closed system because of its displacement then the energy flowing as work is very important.

Then, the availability flowing will be W minus $p_0$ delta V; $p_0$ is the surrounding. But in a control volume or an open system, when this work is developed by the shaft work, then the entire W is the availability transfer. That may be the same work potential, because work is there. It is not low grade energy.

So, these two concepts have to be made very clear; that means, with the flow of heat energy from a temperature reservoir at $T_1$, there is a flow of exergy or associated flow of exergy with this Q whose magnitude is this, if we prescribe the environment at $T_0$.

Similarly, there is a work transfer or work flowing. These are the energy in transit. Associated with that the availability flow is W minus $p_0$ delta V. In case we derive the work from a closed

system, where displacement work is possible and from a control volume on an open system, where the work is developed by the shaft work, then this is simply equals to W. These are very useful relations.

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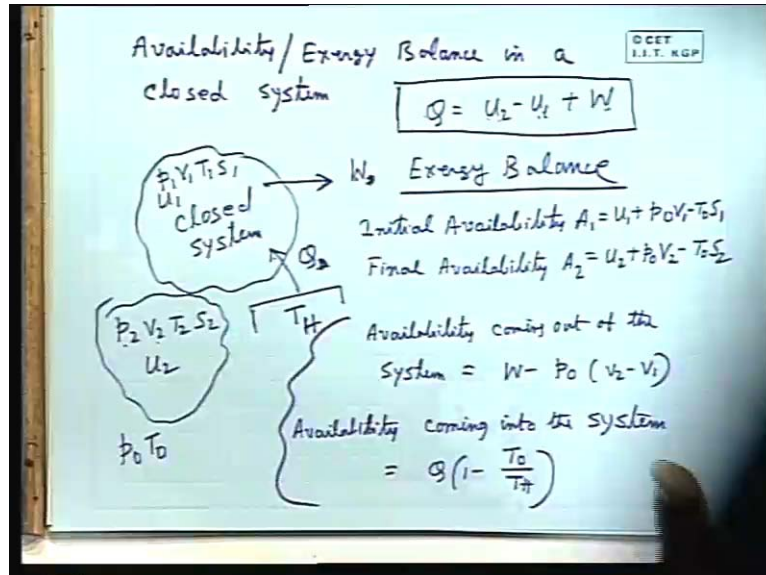


I can write, the availability coming out of the system is W minus $p_0$ into $v_2$ minus $v_1$. So, this is the availability. Now, you tell me, is there any availability coming into the system? Now we know it very well that is Q into 1 minus $T_0$ by $T_H$. Now, we see these are the two, and contain the availability transfer or availability flow. These are the availability; just like this, the change in internal energy and this is the net flow. In energy, the change in internal energy exactly balances the net energy out, because energy is neither created nor destroyed. But here, we will see a difference.

Now I write the $A_1$ decrease in availability.

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What is decrease in availability? It means $A_1$ minus $A_2$. If I want to find out the decrease in availability, like consider there is a decrease in availability. If there is an increase, this will come negative. So, if I write there is a decrease in availability, what will be its magnitude? $u_1$ plus $p_0 v_1$ minus $t_0 S_1$ minus u2 plus $p_0 v_2$ minus $t_0 S_2$. So, that I can write as $u_1$ minus $u_2$ plus $p_0$ into $v_1$ minus $v_2$ minus $T_0$ into $S_1$ minus $S_2$, this is the decrease in availability. Now, what is the net availability transferred out? <mark>(Refer Slide Time: 51:08)This will be this minus this because this is out this is in.</mark> So that will be, Net availability transferred out will be W minus $p_0$ into $v_2$ minus $v_1$ minus Q into 1 minus $T_0$ by $T_H$.

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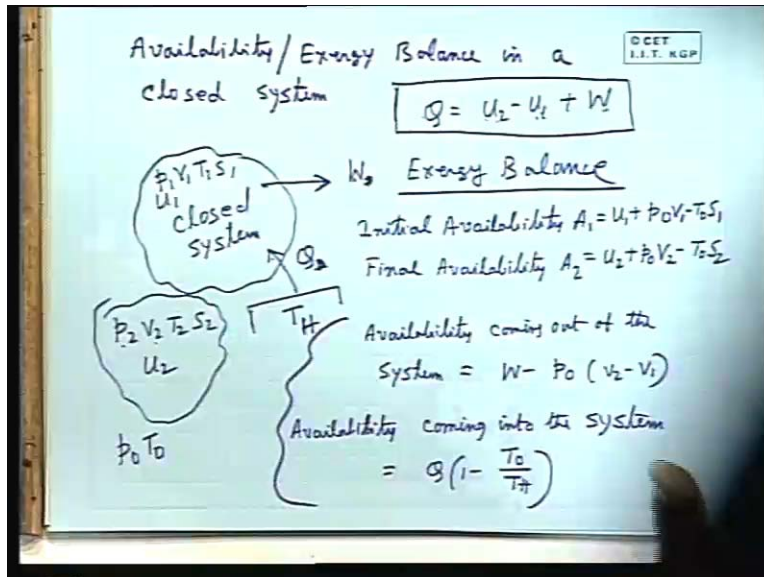


Now, W is Q minus $u_2$ minus $u_1$

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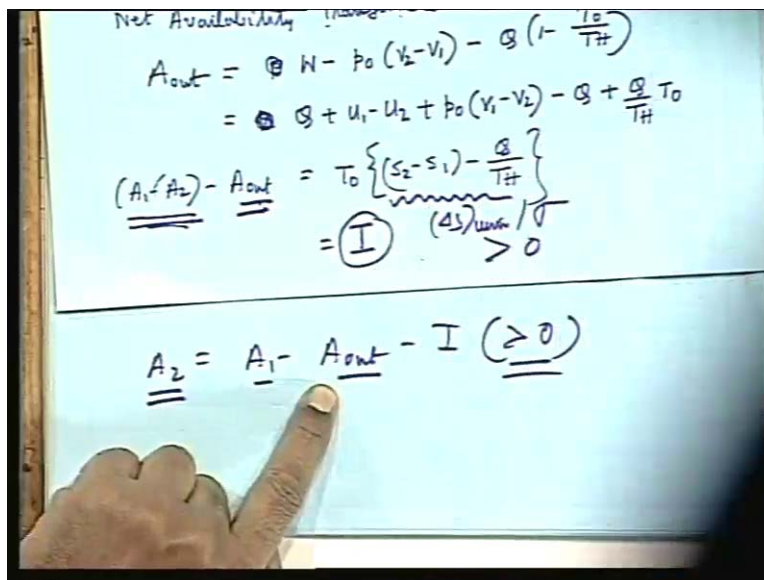


If I write, this will be Q minus $u_2$ minus $u_1$ plus $p_0$ into $v_1$ minus $v_2$ minus Q plus Q by $T_H$ into $T_0$; Decrease in availability and this is the availability transferred out. So, if I just divide it, this availability is transferred out $A_{out}$. So, if I make A1 minus A2 minus $A_{out}$ should I get zero? This is cancelled. So, I get $T_0$ $S_2$ minus $S_1$ minus Q by TH. That means, this gives us the concept.

Now, $A_1$ minus $A_2$ is the decrease in availability and this is the availability transferred out. Exactly you are following the inertia. It should be zero in case of energy, because what is the net out that will cause the decrease.

But here, you see decrease is more than what is out of the system, because this is universe or sigma entropy generated and this is the irreversibility which is always greater than zero. That is for a natural process or irreversible process; we see that the decrease in availability is more than the availability out of the system.

Whenever an interaction is taking place, where a system changes from one state to other state with availability flow in and flow out, along with the energy quantity, then the energy quantity makes a balance like that. No energy is destroyed or created; that means, the net energy flowing out must account for the energy decrease within the system or net energy flowing accounts for energy increase in the system availability does not do so.

The decrease in the availability is more than the availability out. That means, availability is destroyed in the system. If we write this, we will see I.
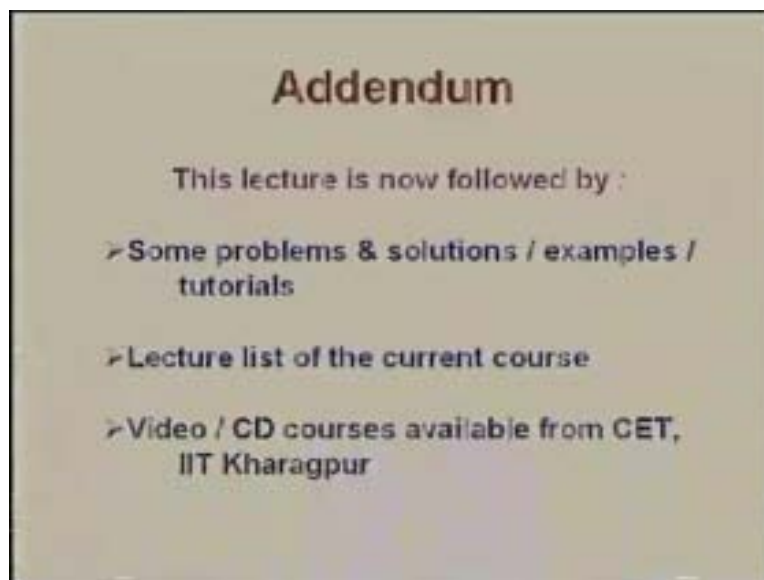
Now, I can write $A_2$ is equal to $A_1$ minus $A_{out}$ minus I which is always greater than zero by the second law of thermodynamics; that means, our final availability stored in the system in its final state is less, not only by the availability which has been extracted from the system, plus something is destroyed. That means, due to this type of availability transfer process associated with the transfer of energy, some availability is destroyed because of the irreversibility. If the process is reversible, then this is zero. Then availability at the final state is the availability of the initial state minus the net availability out of the system, which is synonymous to the energy balance equation.

Therefore, we see, in this process also availability is destroyed the way we saw that heat is destroyed that availability with respect to heat energy is destroyed, when we make a natural heat transfer process from a higher temperature to a low temperature. Similarly, in a natural process executed by a closed system, through the interactions of heat and work with the surroundings, the availability is destroyed. This availability is the work potential of the energy and this is defined as the quality of energy.

Therefore, we can say that quality of energy is destroyed in all natural processes. Therefore, we see in all natural processes, entropy of the universe is generated while the quality of the energy contained in universe is being degraded; that means, is reduced. That is what is known as law of degradation of energy.

A very simple example with IITians that when you come to the IIT your quality is at some value, which is being degraded throughout the four years teachers are not responsible for that you yourself are responsible for that for the natural processes. Because the work potential of a person just after j is much more than the person who goes out of IIT but teachers are not responsible.

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**Addendum**

This lecture is now followed by :

➢ Some problems & solutions / examples / tutorials

➢ Lecture list of the current course

➢ Video / CD courses available from CET, IIT Kharagpur

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## Tutorials

➤Questions related to the topics of a lecture are included after each lecture

➤Solutions are provided at the end of the next lecture

➤It may not be possible to provide solutions to all problems

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## Summary

- The entropy balance equation in a process can be written in any of the following forms :

(I)   $[\Delta S]_{system} + [\Delta S]_{surroundings} = [\Delta S]_{universe}$

(ii)   $[\Delta S]_{system} - \int \frac{\delta Q}{T} = \Delta S_i$

where $\Delta S_i$ is the entropy change due to internal irreversibility.

- The second term in the left hand side of the above two equations is sometimes referred to as entropy efflux or entropy flow out of the system.

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- The entropy balance equation for a process can also be written in a form :

$$\left[\Delta S\right]_{\text{system}} - \int \frac{\delta Q}{T_0} = \Delta S$$

where $T_0$ = temperature of heat reservoir but not of the system.

Under the situation, $\Delta S$ in the right hand side is the change in entropy due to both external and internal irreversibilities, i.e.

$$\Delta S = \Delta S_e + \Delta S_i$$

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- Irreversibility I in a process is defined as

$$I = T_0 \sigma$$

where, $T_0$ is a reference temperature which is usually the ambient temperature.

$\sigma$ is the generation of entropy, i.e.

$$\sigma = \left[\Delta S\right]_{\text{universe}} = \Delta S_i$$

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- Availability transfer in a closed system is associated with heat and work transfer and is defined with respect to a specified environment at $T_0, P_0$
- The availability transfer associated with a heat transfer of Q from a heat reservoir at T is given by

$$A_T = Q\left[1 - \frac{T_0}{T}\right]$$

- The availability transfer associated with a work transfer of W to a closed system is given by
$$A_T = W - p_0 \Delta V$$

where $\Delta V$ is the change in the volume of the system.

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- Availability of a system is always defined with reference to a prescribed environment.

- When a system comes to thermodynamic equilibrium with the environment, the state of the system is referred to as dead state.

- At dead state of a system, no mass or energy interaction takes place between the system and surroundings.

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- Availability of a closed system at a state different from the dead state is defined as the maximum useful work obtained in a process by which the system comes to its dead state.

- Availability of a closed system is defined by a function known as availability function $\phi$ as

$$\phi = U + p_0 v - T_0 S$$

  where $P_0$ and $T_0$ are the pressure and temperature of the environment.

- It is apparent that availability is a composite function of system and surroundings.

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- Availability balance of a closed system in a process:

  Decrease in system availability = Net availability transferred out from the system + Irreversibility.

- It appears from the above equation that irreversibility equals to the destruction of availability of the system.

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- Since availability is the useful work potential of a system, it is termed as the quality of energy stored by the system.

- In any natural process, the availability of a system is always destructed due to irreversibility.

- The above statement is known as law of degradation of energy.