Indian Institute of Technology Kanpur

National Programme on Technology Enhanced Learning (NPTEL)

Course Title
Engineering Thermodynamics

Lecture – 26
Exergy

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So let us start this lecture with a thought process about entropy as the entropy of the universe is on increasing train.

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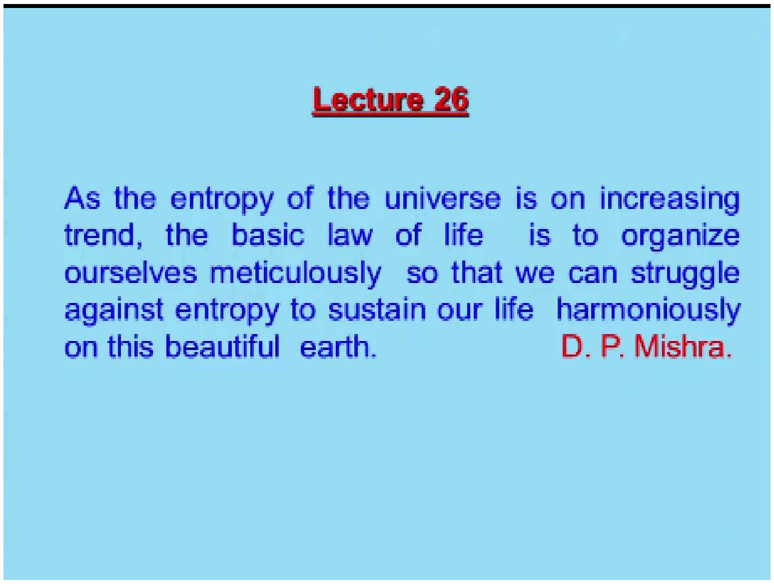

That you know a lot of people have talked about it the basic law of life is to organize ourselves meticulously, so that we can struggle against the entropy to sustain our life harmoniously on this beautiful earth, so if you look at we have looked at the basically the second law of thermodynamics very extensively and talking about the quality of energy, so based on the quality of energy then the energy can be divided into two categories.

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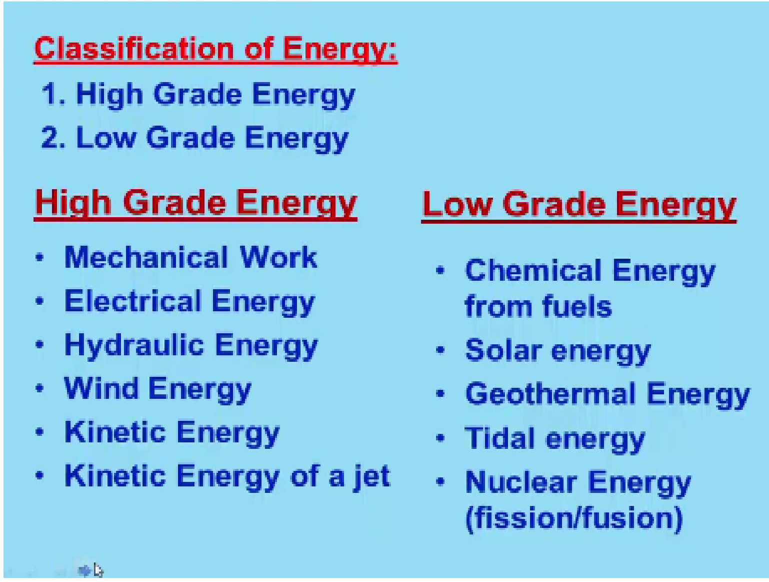

One is high-grade energy the other is the low grade energy, so if you look at we want to we have classified this way can you give some example what are the high grade energy water will be the low grade energy any idea we have already discussed but let us now say that high grade energy means it will be mechanical work it can be electrical work it can be hydraulic energy it can be wind energy it can be kinetic energy you know like or kinetic energy from a jet like you know in the case of jet engine we use it for producing thrust right.

Or in the rocket engines you know like so but if you look at the low grade energy is basically the chemical energy from the well solar energy geothermal energy tidal energy nuclear energy whatever you know we really will be using as an energy source is basically low grade energy, so the objective of the thermodynamics is to basically convert this low grade energy into the high grade energy in the best possible manner, so that utilization will be maximum.

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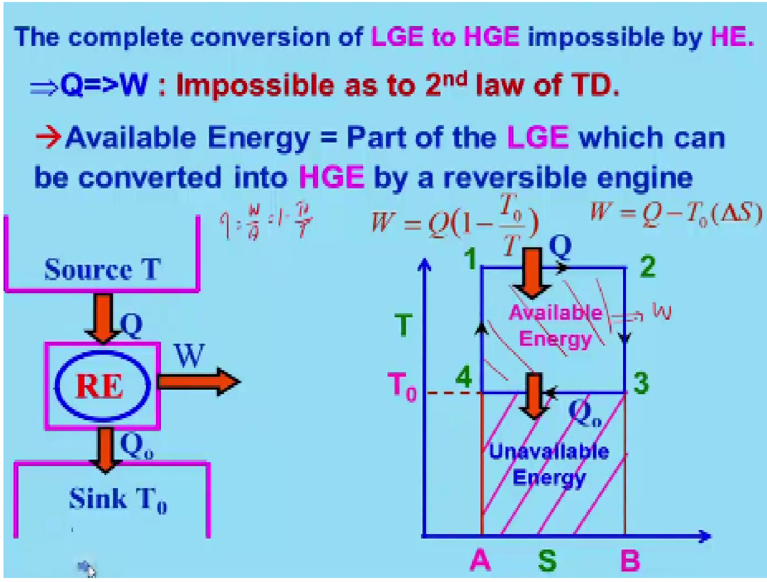

So we have seen that the complete conversion of this low grade energy to high grade energy is not possible by heating it according to the second law of thermodynamics, so therefore I mean like that means certain amount of heat has to be rejected right to the sink whenever a engine is taking certain amount of heat from the source it has to reject certain amount of it, so that you know the work can be done and available energy basically we can from this we can say the available energy is basically part of the low grade energy which can be converted into high grade energy right by a reversible engine we call that amount of energy is basically available.

So far to consider that case we will take this you know example which is basically reversible engine of course is the ideal one but to discuss the point we are making that it is observing the Q amount of heat from the source and rejecting Q_0 amount of heat to the sink which is at T_0 temperature and doing the W amount of work right, so now this case we need to find out basically what is the availability take.

So if you look at we know this what will be the efficiency for this engine this irreversible engine irreversible engine means basically Carnot engine right, so by definition that is W by Q = 1 - T_0 / T yes or no in this example, so I can write down that as W is equal to basically Q (1-T_0)/ T can I not write down this simply I mean I will take this side here what you call a me like and then take this side and that will be done you know like okay.

So now we can say that W is nothing but Q - T_0 (Δ s) change in entropy can I say this or not yes or no because if I just take this think you into Q / T and then we can say that is nothing but your change in entropy Q / T and into T_0 that will be, so if I look at the this is the Carnot engine, so therefore that it is taking the q amount of heat from the source and rejecting Q_0 amount of heat to the sink and as a result like you know the amount of energy which will be can be utilized for producing the work you know the network is W rate is basically in this region.

If you look at this is the region and this amount of heat which is going to the sink is Q_0 this portion is known as unavailable energy it is not available for you once it is good to see you cannot really take it out and do the, some amount of work you know.

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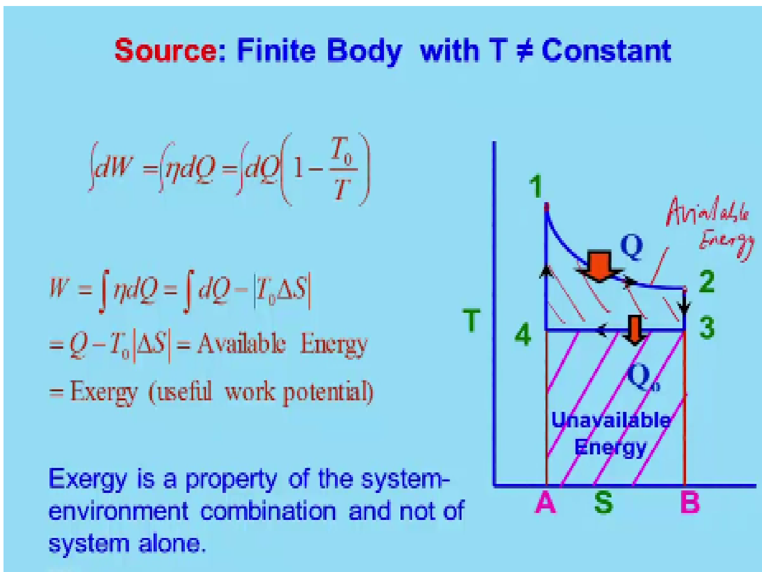

So and that is of course what we have seen a temperature you know like the over source temperature remaining constant sink temperature is remaining constant and we will now consider a case where you are taking some amount of heat from a finite body where the temperature is not remaining constant for example let us say you are having a very you know like a kind of a limited let us say boiler and you are taking some amount of heat from that for using in your engine heat engine.

So then that temperature may dropout with the time, so by that if you look at I am taking some kind of a heat right and from let us say state 1 and it is taking it and the temperature is going down till you know like the process is from state 1 to 2 but however we are saying that it is rejecting Q_0 amount of heat to the sink I mean in that temperature is remaining constant, so the unavailable energy is here and this is your what you call available energy this portion right.

This is your available energy, so we can write down that you know from the efficiency definition right that is dW = η Dq and we know that if it is a reversible engine then I can write on dQ= 1 - T_0 / T, so if I will integrate this one right I can integrate this one right I will get W is equal to basically dQ- T_0 into Δs and this Q - T_0 Δ s is nothing but you are available energy and we call it also the useful work potential right and we call it is also the exergy.

So we will be using exergy and available energy you know interchangeable both are same of course in some places you may find that is a little difference but we would not be using that difference we will be saying that exergy and available energy same, so if you look at to our life what is excessive then what is the available energy is basically your talent whatever you are having in the circumstances you can use it right but if you would not use that you know it will be useless even it may be with you may be a talented person but it cannot really express in terms of your productivity at the work.

So that is the amount of energy what is available which can be converted into the useful work or the reversible work that is known as available energy, so exergy is a property of the system and environment combination not a system alone why because it is saying that it is giving to a thermal reservoir right which is at let us say some temperature like a low temperature right, so therefore it is a property availability or exergy whatever you call we can use as a synonyms you know exergy is the synonyms for available energy.

And is a property of the system and its surrounding right or you call it environment in this case together is not a property of alone the system because earlier we are saying the entropy is a property of the system right.

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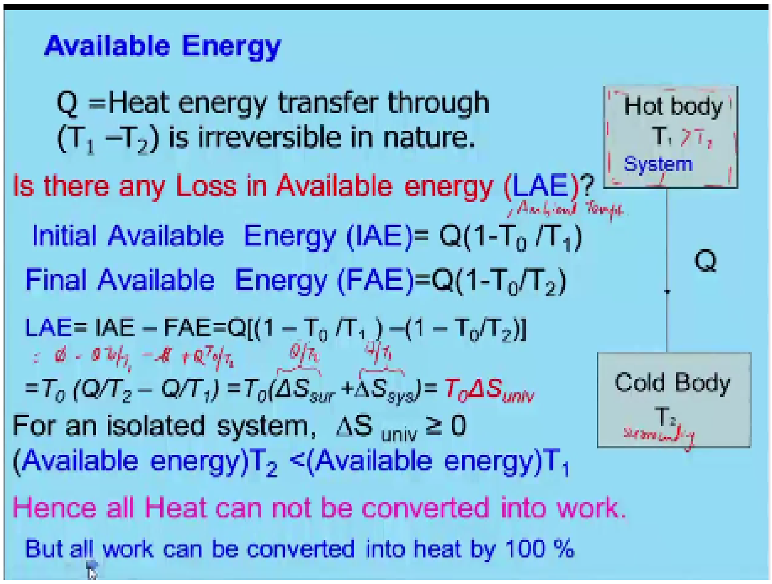

So also the internal energy I so the available energy we can consider another example like let us say there is a hot body here which is at temperature T_1 and there is a cold body at temperature T_2 and the heat will transfer some amount of Q keep in mind that $T_1 > T_2$ okay, so if I say that I want to find out during this process what is the change in available energy right, so keep in mind that the T_2 need not to be the ambient temperature it may be you know higher or it may be lower whatever it may be right.

Let us say T_1 is something let us say 1000 Kelvin and the T_2 is 500 cal let us say for example right then what will happen some amount of heat will be transferred from the hot body to the cold body and we can consider this as a system and naturally what will be its surrounding if I look at this is my system what will be surrounding will be this or not right for this right and the heat energy transfer to the temperature basically gradient because $T_1 > T_2$ in this case and it is an irreversible process right.

You cannot really get back those things right you cannot, so is there any loss in available energy right because this is certain amount of energy is available here right what is that loss what we need to look at it loss in available and let us look at that if this process is goes on you know like it takes place the initial available energy what it would be that is Q $(1 - T_0) / T_1$ what is T_0 here that is the ambient temperature that is you know which will be let us say for example you will say here now our ambient temperature around will be something 40 ^{0}C so it will be 40 ^{0}C if you go to winter it will be 25^{0}C or 20^{0}C right.

So that is the ambient temperature right and T_1 is the temperature with you, so therefore this initial available because if I want to sync I can use the you know air as in my sink right or I can take another reserve and take is a sink right that means beyond that I cannot really go it will be not possible so therefore initial available energy is a Q1 – T0/ T1 similarly for the coal body right what will be final available energy it will be Q1 – T0/T2 right because once it will come in contact there will be some heat until the temperature t1 becomes the equal to t2.

So therefore that is the energy whatever available at temperature t2 right therefore we are calling it as a final available energy, so the loss in available energy that we are using a short form LAE = initial level of energy minus final available energy so and that is nothing but Q 1 –T0 / T1- 1 – t0/t1 so if you know simplify it you will find it out basically this is Q - Q T0/ T 1- Q = T0/ T 2 and Q.

It this will cancel it out so therefore you will get T0Q /T2 – Q/T1 and if you look at this t0 and then Q/T1, 2 is nothing but your will be what will be the system this one is not, okay so and the surrounding will be what because you are taking the q is from here right and that will be negative when the heat is going out of the system is known as negative sign so this become basically or to call this Q which is going to the surrounding it became positive.

So therefore system and surrounding like you know this will be basically is equal to Q/T 1 and this is Q/T2 okay and that is nothing but T0 into change in entropy of the universe system and surrounding this is surrounding okay, so for an isolated system what it would be the we know the change in entropy will be of the universe will be greater than equal to 0 if I am system surrounding together I am considering that means there is no.

And which indicates if I look at this expression right it indicates the available energy at temperature t2 right is less than the available energy at t1 and that is the obvious thing because the energy whatever we are taking this Q you know that is the thing that is at higher temperature therefore that is a quality of energy is higher therefore available energy will be higher we have earlier discussed that right.

That quality of energy will be dependent on the temperature if the temperature is higher the quality of energy will be high so hence all the heat cannot be converted into work that we have seen from the second law of thermodynamics but however all the work can be converted into heat by one hundred percent that means if I want to convert the work into heat it is one hundred percent you can convert right but the reverse is not.

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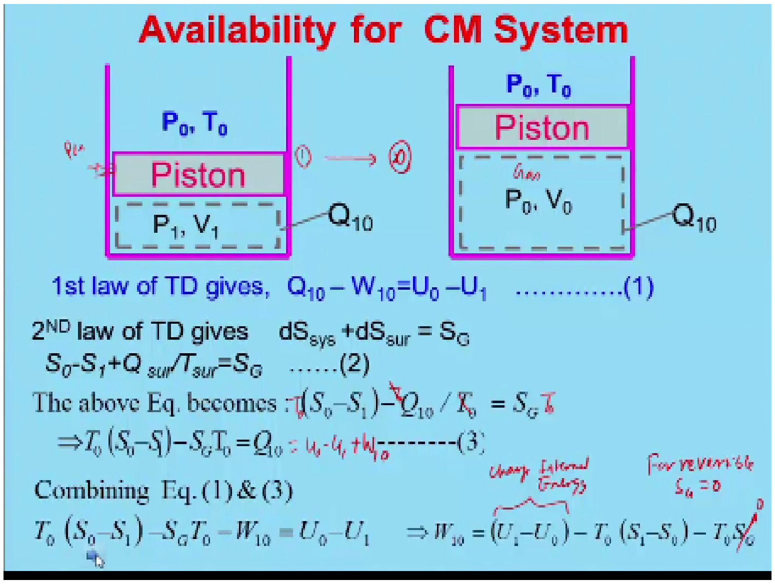

So let us look at the availability for a control mass system we will consider a piston cylinder arrangement which contains gas at pressure p1 and volume v1 and there is some heat interaction here q right and of course the ambient pressure is P0 and T0 and let us say when of course it is at fixed you know it is fixed and then there will be fixed I will release this is a you know kind of a pin I will remove this pin right what will happen removing this wind piston will go up yes or no and it will go up till this pressure of this gas right.

Is reaching the p0 v0, p0 the same pressure right and if you look at this is my state one and it is going to state 0 because that is the dead state it is not it cannot go beyond unless you give work done the piston cannot move up because already reach the equilibrium you know with the ambient pressure so the according to the first law of thermodynamics that is Q 1 0 -W 1 0 =, u0 – u1 right this is a zero state and this is the fast state right means I call it dead state in this case.

So second law of thermodynamics will be basically system plus change in entropy of the system plus the change in entropy of surrounding is equal to SZ the entropy generation right and the system what you call we can say that s0 – s1 that is the change in entropy of the system surrounding will be Q is going that is you know divided by t surrounding T surrounding in this case what it would be it will be T0, yes of no?

And Q surrounding will be nothing but Q 10 right and keep in mind this is heat is going out let us say if I say from the system surrounding so therefore it will be minus right Q 10/ T0 = SG that means right from the equation two you can get change in entropy that is s0-s1 okay during this process minus q10/ T0 = SG and I can rewrite you know I can just multiply to here the T0 in this case and it will be T0 here and T0.

So this will cancel it out you will get T0 s0-s1-SG T0 = Q10 right so if I combine this equation 1 and 3 right what I will get I will get basically in place of q10 I can write down you know U0 /U1 + W10 can I not right and when I combine this equation so when I will just change that when I will get T0 s0-s1 – SG x T0 and minus w10 = U0-U1 of course one can say that the what is the work done here the work done w 10 right by the piston right is equal to u 1 – u0 change in internal energy right.

That is the change in internal energy minus T0 s 1- s0 that is a change in your entropy into multiply by temperature is minus s0 SG is the entropy generation right so that means this amount of war one can do right if it is a reversible process so what will happen we have not talked about whether reversible irreversibility okay till now if it is reversible process what will happen is you will be 0 right this SD will be zero for reversible process is SZ will be 0 right.

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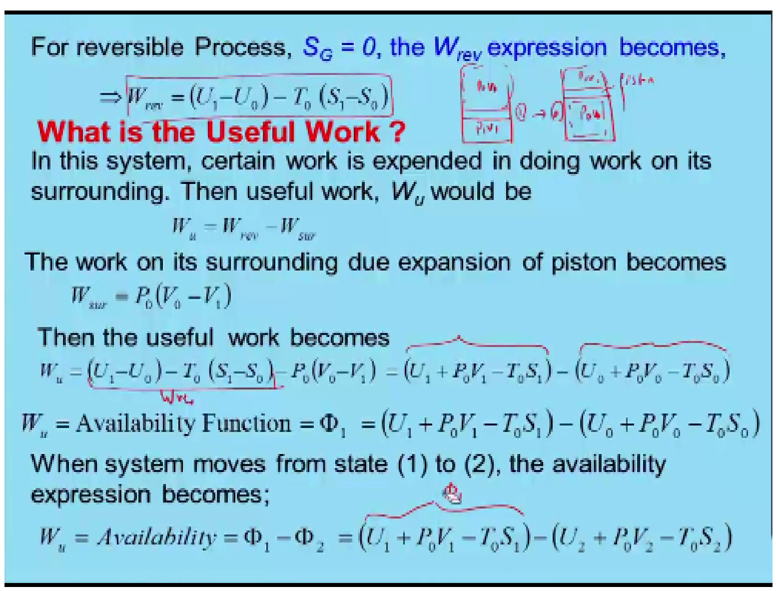

So if you will do that is we can get that expression reversible work will be change in internal energy that is 1 –u0 – T0S1 –S0 right now what is the useful work is it that you know reversible work is the maximum work but what is the useful work for this system this example if you look at what it would be because when the piston is moving up right in this example what is happening it is doing some work on the ambient air yes or no that of course we have not considered now we will be considering right.

So as I told certain work is expended in doing work on its surrounding itself the surrounding atmosphere air is being pushed right for example if we take a piston cylinder here right and this is p0 v0 so there is something gas is there let us say and when it will go to the next one right it is here this gas has been volume like p0 v0 this volume will be changing right the piston has moved here right of course at this point this is P0 V0 and this is p1 we want in the start with this is going 120 state.

Now the useful work you know will be basically reversible you work minus the work done on the surrounding by the piston in this example okay so the work done on its surrounding due to expansion of the piston are the movement of the piston what it would be it will be P0 x V0 – V1 earlier it was start with v1 and it becomes V0 right so I can say that is the movement what is taking place the change in the volume right so that is the work done by the on the surrounding by the piston movement.

So the useful work will be become basically WU is nothing but your this portion reversible work that is u 1 – u0 – T0(S1-S0) that is the reversible work right that is the reversible work right this portion is here reversible work and this is your surrounding work and I can write down this as u 1 + p0 v1 – T0 S1 right I can separate it out and I can say that u0 + p0 v0 –T0 S0 see this is simple so these quantity right and we call it basically what you call availability function itself right.

That is the Ø1 and D says with the for the state 1 and this is the dead state right if you look at this we call it as a dead state right this together will give me ability function Ø 1 and when a system moves from one to two right we have said state that it is going from state one to dead state that is the 0 we are calling and when it will be then what it would be it will be nothing but Ø1 - Ø2 right and this term will be cancelled it out in this case so therefore we are getting U_1+P_0V-$T_0$$S_1$ right and this is for basically Φ 1 this is y 1availability function for the state one right. Of course do not consider that because this is being canceled it outright and this is for the state proof right.

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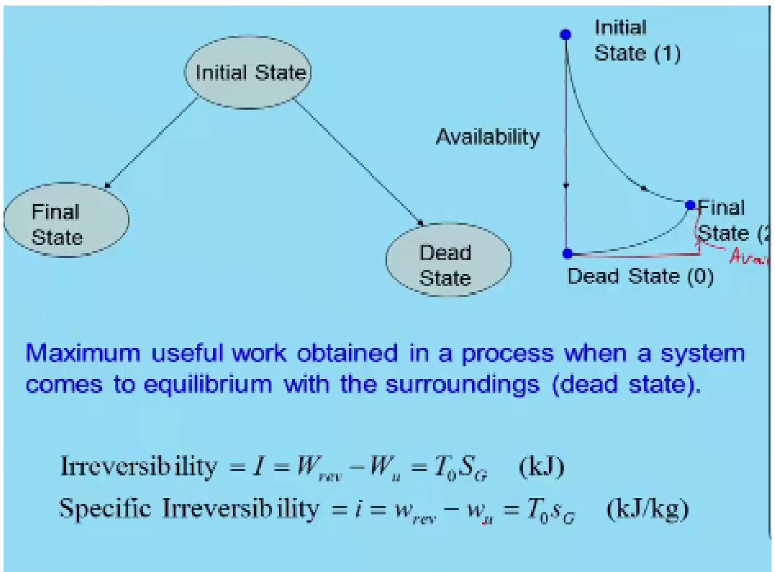

So if you look at I mean we have seen that let us say you are at initial state right state 1 and this is my dead state right and it is you have gone from state 1 to the state. To write that means what is the availability for super state one is concerned this is one right for the availability first state to is concerned this one right this portion is the availability for state two. Are you people getting what i am saying and then you know if we wants because all we are doing saying that availability is basically with reference to the dead state.

Right i will give an example right which we generally happens you know like if you keep the money in the bank right let us say 5000 rupees you can spend the money till what you come what thousand rupees you can say okay bank cannot give beyond let us say thousand rupees right so if you look at it as reach the dead state right. So kind of things and if you look at like that means this is availability right okay and I will give one another example suppose you are very alert in the morning time right I hope you are not right.

So generally the people are very alert in the morning time then you know in the evening time they will be very tired and you cannot really look that means you have reached a dead state is then you have to go for sleep and take rest it is you minute and then come back and do work right. So availability basically will be saying that how much work you one can do with respect to your reference that is the dead state.

And maximum useful work obtained in a process when a system comes to equilibrium with the surrounding that is a dead state what we consider as basically the maximum useful work and the irreversibility what it would be that is the basically reversible work right minus the useful work which will give me the irreversibility. This is basically is well because the entropy generation with a reference to the temperature that will give me what you call either energy being lost in their reversibility.

And keep in mind that in the piston example like if we the piston is moving up and then doing some work on the surrounding you cannot get it back it is a reversible right. So specific irreversibility will be I is = reverse we will work - the what you call the useful work that is T_0 into NC that is the specific and it snit is kilo joule per kg so what we have seen this is for the control mass system but we need to handle also the control what you call volume or the flow systems right and we are considering the flow process to be steady for our this thing.

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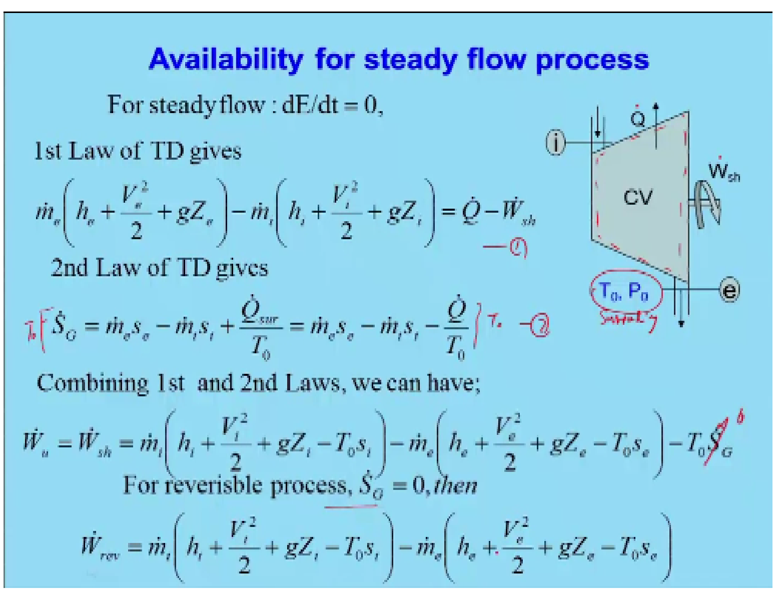

So let us say that there is a expansion of the gas in a turbine is taking place and it is entering at a you know at the inlet and it is leaving at the exit and some work is being done because the turbine expansion is going on and you can consider this as my you know control volume kind of things. And the reference here this is your surrounding right if you look at this is you surrounding and some heat is going right and this is your dead state you can say it is a sink kind of thing right this is your surroundings.

So for a steady flow process we know the change in energy will be basically =0 with respect to time and we can write down the first law of thermodynamics as for the control volume that m.e x v^2/ 2 g JD - mi hi + b/ 2 in g ji is = amount of heat you know which is being transferred that is the heat rate and also the work-rate shaft work right and second law of thermodynamics will be basically = the entropy what you call generation is = the m.eac –m.isi x Q. surrounding it t_0.

Keep in mind that heat is going out from the system boundary therefore it will be negative the Q./T_0 Q. but Q. /negative. Now what we will do in place of these I can say I can multiply this equation you know by t_0t. So this will be T 0 so if IT 0 this will be cancelled it out and then you will multiplied here and then use this equation if I say this is equation 1 and this is equation 2combined we can get a relationship that is soft work is nothing but you the enthalpy change you know like and then kinetic energy and potential energy and also there is a new term which has come T 0 s I of course x the mass flow rate at the inlet.

Similarly in the exit this is at the exit right and –t0 s.g right. So if for a reversible process of course the entropy generation will be 0 right because this is a reversible process so you can get the well what is basically the change in energy and also the what you call we will define this term availability right we will be doing that so this is also change in the exit.

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The reversible work (availability/exergy) can be expressed as

$$\dot{W}_{rev} = \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gZ_i - T_0 s_i\right) - \dot{m}_e\left(h_e + \frac{V_e^2}{2} + gZ_e - T_0 s_e\right) = \Psi_i - \Psi_e$$

where, Ψ = Availability Function

$$= \dot{m}\left(h + \frac{V^2}{2} + gZ - T_0 s\right) - \dot{m}\left(h_0 + \frac{V_0^2}{2} + gZ_0 - T_0 s_0\right)$$

For multiple streams device (heat exchanger, etc)

$$\dot{W}_{rev} = \sum_{i=1}^{n} \Psi_i - \sum_{i=1}^{N} \Psi_e$$

Irreversibility $= I = \dot{W}_{rev} - \dot{W}_u = T_0 \dot{S}_G$ (kJ)

Specific Irreversibility $= i = w_{rev} - w_u = T_0 s_G$ (kJ/kg)

So the reversible walk that is the availability or the exergy can be expressed as basically the what you call the availability at the inlet minus the ability to exit and this sigh I have used that is basically availability function and people call exergy function also and keep in mind that this we can basically the ability function is written with respect to in the similar way what we have done for the control mass system with respect to dead state.

These are all dead state 0 means dead state kind of things right and if you take inlet and outlet this term this term will be basically cancel it out. So if there is a multiple stream device right heat exchanger kind of thing what will be the reversible work right that will be nothing but your interrupt what we call availability function change for the of course if it is several kind of a what you call inlet will be there then it will be if it is let us say n number of inlet then you can say availability at the inlet.

And similarly availability in the N it can be different you know like at the exit and you can get what will be the useful walk basically right in this case the what you call the reversible work and they useful work with the same right because A is reversibility you can calculate W. reversible - useful = t0 SG right because in case of reversible work right what it would be because SG will be 0 right z will be 0 in case of reversible walk right so therefore T not SD is coming right and specific irreversibility is nothing but a reversible work minus the useful work that is T 0 is it is similar to that of the control mass system.

Right so question arises how to evaluate performance of a device. Right that we need to work it out and find out because second law of you know thermodynamics will help us to evaluate and what is the extent of you know improvement we can do by what you call minimizing their reversible that we can do. So the purpose of a device can be evaluated in terms of thermal efficiency and COV that we have seen EOP is basically for the refrigeration system and the heat pump system right whereas the thermal efficiency will be using for the heat engine.

The maximum work from a device can be achieved basically by improving the thermal efficiency and also using higher quality of energy right that is the one way of improving or maximizing the walk so let us consider a turbine here and in which the gas is expanded right from p1 to p2 t2 and some shaft work is being produced. If you look at this is the constant pressure line and you know pe1 and there is another constant pressure line p2 and if you look at this expansion is taking place from state 1 to 2 this is known as isentropic expansion.

Right this is isentropic expand where the entropy is remaining constant in this case s 1 is = s 2 s like entropy is remaining constant here right and this is the actual process actual expansion that is from state to state 1to state 2 right. So therefore we can define the efficiency and this is an isentropic process that is w ratio of / the reversible work done. Right and what is this work done if I consider that is a change in kinetic energy change in potential energy = 0 and steady flow process then will get w is nothing but h 1 - s2 and forgive you for reversible processor isentropic process that will be h 1- s 2 s.

So if you look at this is this portion is the isentropic expansion that is the ideal and h1 -s 2 is the real. So if you consider let us say there is a heat engine which is having efficiency of 30%t right and there is another heat engine which is operated between what you call another source that is which is at thousand Kelvin and of course the sink is same for both the engine then it is also efficiency is thirty percent right.

Both are having thirty percent efficiency and that and where has like you will see that from the Carnot efficiency right we will say that this efficiency for the which is operated the heat engine a between the source temperature of 600 and sink temperature fifty percent whereas theory the heat engine be it is the Carnot efficiency is basically right seventy percent the means in which engine case there is annul like more scope for improvement definitely the heat engine be right there is a lot of improvement can occur although you can say look both are having thirty percent efficiency.

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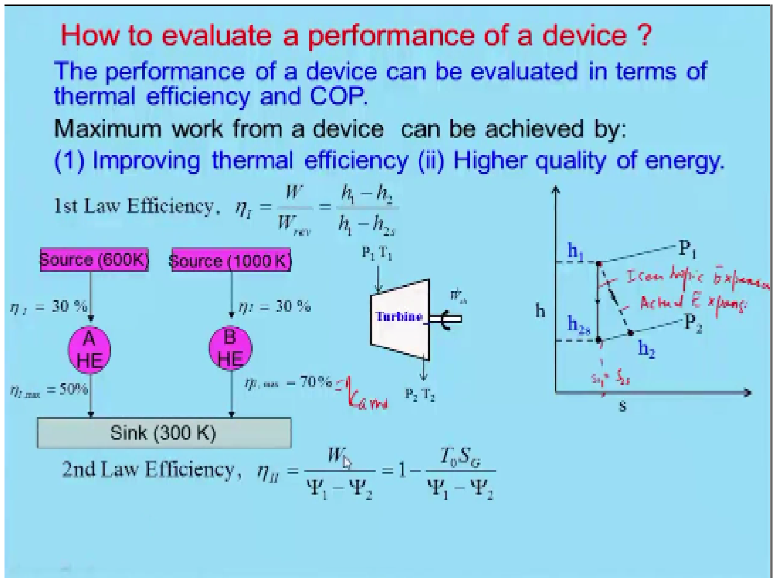

Right that means there is a lot of scope availability you can sixes is available for you to exploit it for improving its efficiency so therefore we need to define a second law efficiency that is the ratio of useful walk change in availability this is basically change in availability right or the exergy that is energy and which is equal to 1-T_0 SG / psy- I won what is this one this is basically irreversibility T right and we will have to basically minimize these irreversibility says that we can get higher second law efficiency.

Of course that is one can do so we have you know of course discuss about that change in kinetic and potential and 0, so let us look at a compression right in the compressor the what you call the efficiency you know first law of efficiency is nothing but you what you call reversible work done work input tote compressor the actual work input right, so if you look at I mean if I want to do this thing h and let us say s what will happen this is the pressure line, so this is 1 to 2 and this process is your to come to s and this is to write and this s is corresponding to the I central process 122 where entropy is remaining constant .

And this is the actual processor therefore s 2 s / s to sinus H1 / s2 -h1 forth compression right and this efficiency we call it as basically isentropic efficiency right this is same as that of the compressor and I of course you can call it is a fast lap efficiency or I sent because references your isentropic processor second law efficiency will be reversible work the same definition / the East will work that is nothing but you side 2 - i1 that the change in availability / the useful work.

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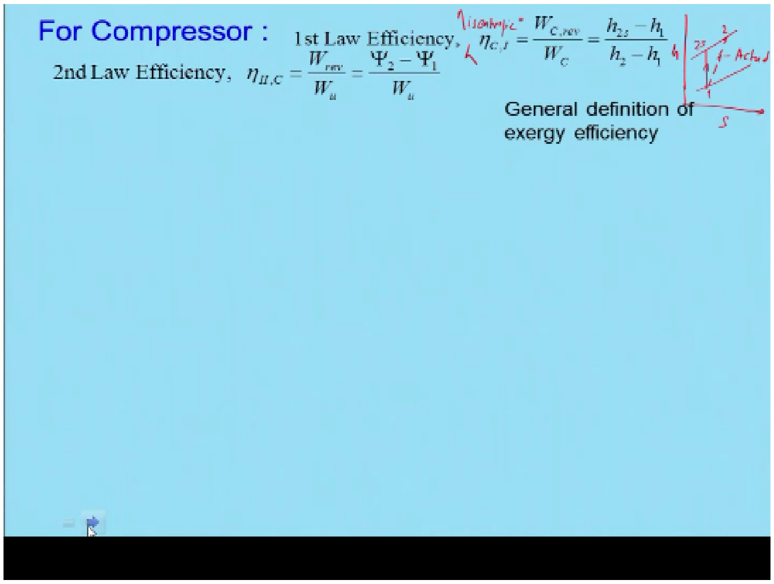

And if you look at the second law of efficiency one can saw a rake energy loss / the exergy supplied kind of things right and the second law efficiency one can say that you know like is nothing but you are what you call the w by w reversible right and w reversible from the Carnot engines we can say right down q h 1 - TL by the and this is this one is nothing but you are the efficiency first law efficiency rate divided by the Carnot law office in C will give you the second law efficiency and similarly for the heat pump or the refrigeration you can think of irreversible will give you the second law efficiency for the heat pump or the refrigeration system.

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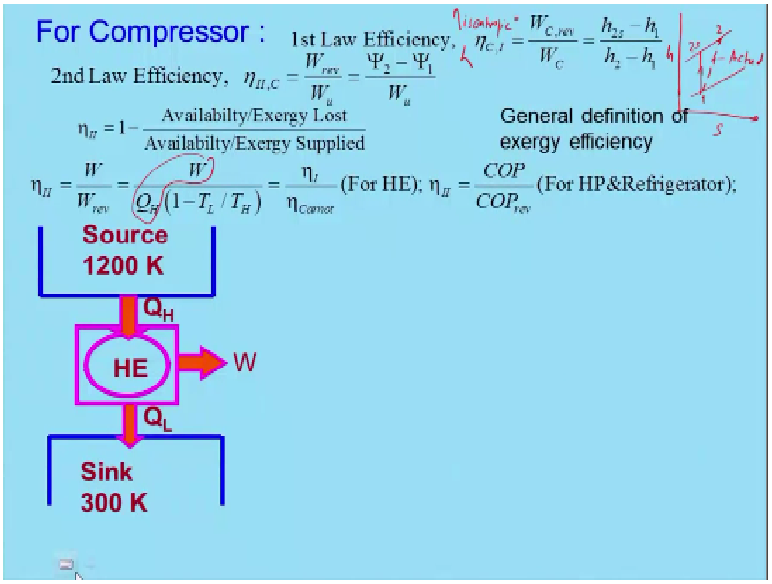

So if we will consider this as they basically heat engine and which is the source is 120 Kelvin from which the key which amount of heat being what you call taken and it is ql amount of it being rejected to the sink which is at 300 Kelvin and it is doing the work w right so the first law efficiency in this case what it would be 1 minus QL / qh and which is happens to a75% let us say right and if you look at the Carnot efficiency right that is a reversible engine right which is nothing but your car not which is equal to 75% .

That means what it would-be then second law efficiency second law efficiency is the ratio of the first love efficiency first clap efficiency for the reversible process of the contact therefore it is one hundred percent efficient right second law efficiency is one hundred percent right of course if you get that is very you know good like you basically what it says it says that there is no scope for any improvement of this engine if the second law of every since one hundred percent in other words it says also that that this is a reversible device otherwise it cannot really happen to have one hundred percent efficiency right so let us consider the amount.

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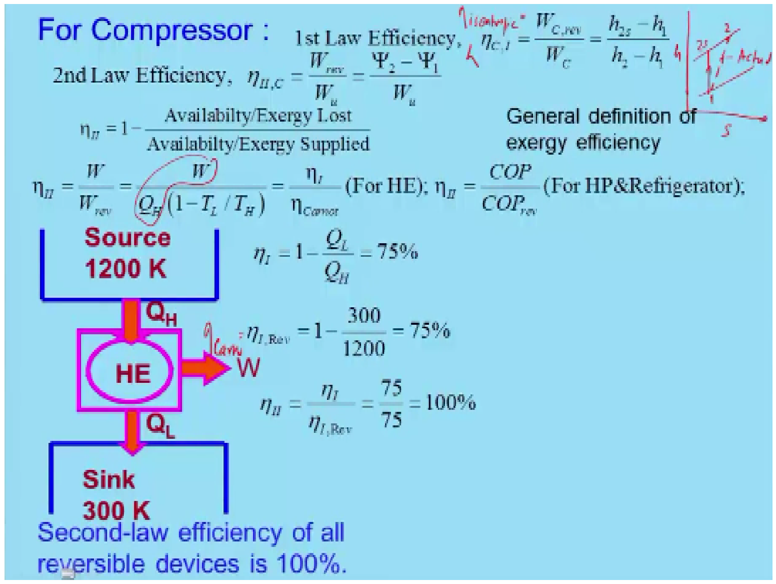

Of what you call will say this is our hot tea right which is at certain temperature right and it is you know you can take system is system boundary as the hot tea itself copy itself and then Q amount of it is going if it is going out you know you cannot really to the ambient temperature which is at T_0 right p_0 kind of things so then that amount of heat is basically going west that means this heat is cannot be really can be utilized because it has gone to the tested so second law efficiency of naturally occurring processes is zero as none of the work potentiate.

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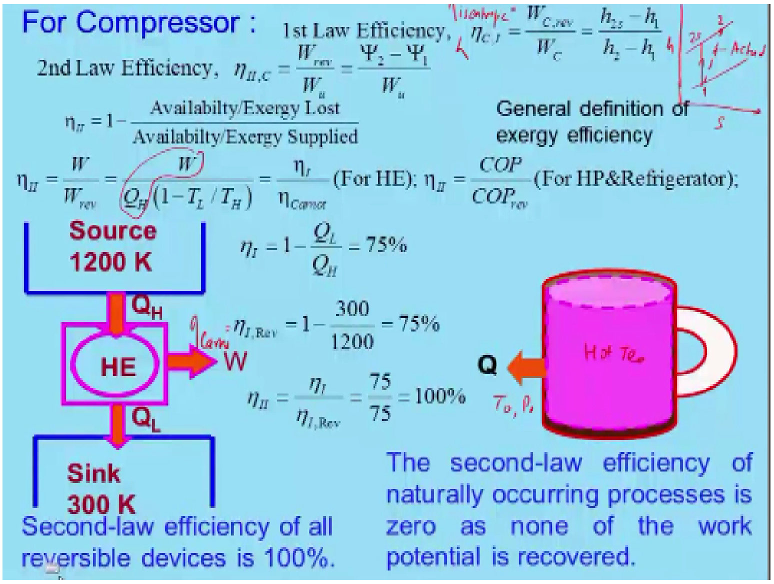

It is recovered right so you cannot really recover kind of things so if you look at like if I consider that basically the availability concept like I mean lot of amount of energies are available for example like if you consider the sea is having lot of water they know like and then it is at temperature let us say ambient temperature force in the you know like this thing if you consider multiply that will be something you know billions are not billion sir it will be several billion of you know Jules will be there but we cannot utilize it because its availability is almost zero right so therefore we can similarly if you consider the air around the art it is having a large amount of energy.

Would do a calculation let us say how much amount of air will be there in the around the arc and it is at temperature T and then you multiply it with a CP and then you calculate it will be enormous you know even if you tap that you know ten percent twenty percent energy we do not we will solve the problem of energy scarcity you know like energy whatever but those we cannot use because those are availability is zero tested so I mean like this is the things what will be having that what you call the availability concept and energy.

And it is very useful things for to find out the what you call how you can improve the performance of a particular system or a process by what by basically identifying the causes of irreversibility and eliminating them and then you can know so this also talks about the quality of quality of energy kind of things we have seen so it is a very useful concept and which is being used to optimize the system and also the processes such that and with this will stop over thank you very much you.

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