Engineering Thermodynamics

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Week-08
Lecture-38
Exergy

Welcome to the part of exergy. This will be the last lecture about exergy. In this lecture, we will talk about the balance of exergy related to control volume. Let's start with exergy balance control volume. Control volume means flow system. And in this exergy change in control volume can be done in three ways. First, through work, second through flow, through mass in and mass out, and third through heat transfer. will be in different forms and some will be destruction and the rest will be in the exergy of change in control volume Let's move forward with the general exergy balance that we did in the last lecture which we did for a closed system Here you will have a flow system and in this mass in and mass out will also come so your x is heat and due to heat interaction the exergy and the control volume is connected to the heat and the second network is connected to the work so this is the heat in and the work out that's why there is a minus in this plus the mass in, minus mass out, minus x destruction which is destroyed and the rest is the change in control volume.

$$X_{heat} - X_{work} + X_{mass,in} - X_{mass,out} - X_{destroyed} = (X_2 - X_1)_{CV}$$

$$\sum(1 - (\frac{T_0}{T_k}))Q_k - [W - P_0(V_2 - V_1)] + \sum_{in} m\Psi - \sum_{out} m\Psi - X_{destroyed} = (X_2 - X_1)_{CV}$$

Rate Form

$$\sum(1 - (\frac{T_0}{T_k}))\dot{Q}_k - \left[W - P_0\frac{dV_{cv}}{dt}\right] + \sum_{in} \dot{m}\Psi - \sum_{out} \dot{m}\Psi - \dot{X}_{destroyed} = \frac{dX_{cv}}{dt}$$

For stedy flow system $\frac{dV_{cv}}{dt} = 0 \; and \; \frac{dX_{cv}}{dt} = 0$

$$\sum(1 - (\frac{T_0}{T_k}))\dot{Q}_k - \left[W - P_0\frac{dV_{cv}}{dt}\right] + \sum_{in} \dot{m}\Psi - \sum_{out} \dot{m}\Psi - \dot{X}_{destroyed} = 0$$

For the single stream:

$$\sum(1 - (\frac{T_0}{T_k}))\dot{Q}_k - \dot{W} + \dot{m}(\Psi_1 - \Psi_2)\dot{X}_{destroyed} = 0$$

$$\Psi_1 - \Psi_2 = (h_1 - h_2) - T_0(s_1 - s_2) + \frac{{V_1}^2 - {V_2}^2}{2} + g(z_1 - z_2)$$

$$\sum(1 - (\frac{T_0}{T_k}))q_k - w + (\Psi_1 - \Psi_2) - x_{destroid} = 0$$

So, x heat is the reversible energy that we will convert to eta times q. Eta is the reversible form of the heat engine. Eta is 1- minus T0 by Tk. Tk is the different part of the boundary from which heat is transferred. So, this is the sum function. So, this is your x hit. In x work, you have taken w minus w surrounding. Which we said is your totally useful work. So, this is your total w minus w surrounding. Because w surrounding is the work on the surrounding. So, you have to subtract this to find out how much is the actual useful work. So, this is the total work out. and plus mass in which is xz is your mass plus minus mass out which is coming out and rest is your destructions and this is your x2 minus x1 so in the form of rate you just have to change in the form of rate so this dot will come here, and of course this is your volume which is the change in the volume of the system and this m dot X dot will come here and here your rate of exergy of the control volume will come. If you know the final state of the control, then you can use x2 minus x1 as m2 phi 2 because x2 is the final state minus initial state and you have to use the exergy of the closed system because we will use the control volume system so it will be phi 2 minus phi 1 So basically internal energy will be useful here when we are talking about the internal control volume. And where you have mass in and mass out, your enthalpy contribution will come out here. so let's move forward with this discussion. If there is steady flow, it means that these terms will be zero. In which your volume part will become zero. It means that W the minus surrounding w will be zero in the rate form and the control volume item we took this one will be zero if it is steady, this will be zero and this part will be zero so what is left is this so this is your expression when you are considering steady flow and if it is single, then you can The summation of the single stream is related to the number of streams. So, you can remove it and consider the single stream. The mass rate of the single stream will be constant. So, m dot psi 1 minus psi 2 is the value. In minus out is the value and this is the x-destruction. Note that the term written here is change in enthalpy, minus T0S1 minus S2, plus kinetic energy change, plus potential energy change, per unit mass. If you want to write this expression in per unit mass, you can write it like this. This is your small q, this is your small w, and the mass is removed from here, and this is small x. You can write it like this. You can remove the mass rate in the per unit mass and you will get this expression. So, in general, in any control volume condition, if there is an accident, then it can come in three ways. One, due to heat, due to work, due to mass. And if it is coming out, then it can come out in three ways. Exergy, due to heat, due to work, mass and some amount of destruction. So, this is in general a graphical form, we can represent it. If we take it in reversible condition, then W is equal to W reversible. In such a case, because it is reversible work, your X destruction will be zero. Because S destroyed is related to your S generation. For your notice, we have already discussed that S destroyed is T0 S generation. So, S generation, entropy generation will be zero, X destruction will be zero, whenever the system is reversible, and process is reversible. In such a case, if it is a single stream and reversible system, then we can call W as W reversible. And then we can bring it here. When S destroyed becomes zero, then you can write it as W reversible. If you do not take it per unit mass, but take a simple total value, then this is m dot psi 1 minus psi 2 plus your x generation, which comes out of x due to heat. If it is adiabatic, then it will also be zero. So, for adiabatic condition, your W minus w reversible single stream will only be m. So, this will be the maximum amount of output that can be produced for this work producing device. And this is what you can say that this minimum work has been done towards the input side, which is work for a consuming device like a compressor. Now we have already said that the second law of efficiency is basically the definition of generic digits. It can always work in the maximum ideal condition. We were using the reference of how much actual work you are doing in it. So, eta is at the maximum efficiency. So, actual divided by eta maximum which we are doing in reversible condition, so we took out from that and then we also said that your second law efficiency can be done by not doing this and you can directly do exergy, generic exergy. So, because exergy is a generic definition, in this way you can define eta as exergy recovered divided by exergy supplied. the amount of exergy we have supplied and the amount of recovery we have done yeah, 1- exergy destroyed. divided by exergy supply. So, this is a generic definition. And we will see how you can use this in different devices. exergy destroyed, we can write it as T0, which is the temperature of the environment, as generation. We wrote this definition later. So, this is a second law of efficiency. Remember, we read about this in the previous lecture. We will discuss this more, but we will try to understand it through steady flow device. And particularly, we will consider the common devices like turbine, compressor, heat exchanger or mixing of fluid.

So, let's talk about turbines. In turbines, we assume that kinetic energy, potential energy, is negligible and this is adiabatic. For this ideal condition, we try to operate the turbine also to avoid heat loss, so it becomes adiabatic. And in such a case, what will be the second law of efficiency of the turbine? The exergy recovered is W out and the spent in it is the difference of inlet minus outlet exergy of the fluid. Out divided by W reversible out You can write this also Or you can write W out Which you are actually taking out Which will be due to enthalpy change And this is your psi 1 minus psi 2 This is your exergy supplied If you want, you can write this also 1 minus T0S generation Divided by psi 1 minus psi 2 You can write this also Like this So, this is a definition and what will be the S generation? This will be S2 minus S1, so this will be the total generation entropy of the second Outlet stream minus inner stream. Second state minus original state. so now if we move forward, we consider adiabatic compressor. Let's discuss it. So, what will be the purpose of this? We will assume adiabatic compressor as such that its kinetic energy potential is negligible. So, what We will supply exergy, it is Win Recovered will be exergy change which is in your outlet stream then your X2 minus X1 will come Si2 minus Si1 will come so your exergy is recovered this part is your second and your exergy is supplied and supplied is also with enthalpy change This is Win and this is reversible in. We can also see it as x is destroyed here. So, 1 minus x is destroyed divided by supply. So, this relation is also there. So, in general we can use this or this. Both are convenient for us.

Turbine,

$$\eta_{2,turb} = \frac{w_{out}}{(\Psi_1 - \Psi_2)} = \frac{h_1 - h_2}{\Psi_1 - \Psi_2} = \frac{w_{out}}{w_{rev,out}} = 1 - \left(\frac{T_0 S_{gen}}{\Psi_1 - \Psi_2}\right) = 1 - \frac{T_0 S_{gen}}{\Psi_1 - \Psi_2}$$

Adiabatic Compressor,

$$\eta_{2,comp} = \frac{(\Psi_1 - \Psi_2)}{W_{in}} = \frac{(\Psi_1 - \Psi_2)}{h_1 - h_2} = \frac{w_{in,rev}}{w_{in}} \; or \; \eta_{2,comp} = 1 - \left(\frac{T_0 S_{gen}}{h_2 - h_1}\right)$$

Now let's talk about heat exchanger. In which we are not mixing the fluid. but one exergy increases one stream and the other one decreases. So, note that there is a cold stream and a hot stream. So, exergy decreases the hot stream and the cold stream increases by recovering. This means that the exergy recovered means that the cold stream exergy increases, it recovered. and exergy supplied or expanded means the amount of exergy spent by the decrease of the hot stream. So, according to this, you can draw the second law of efficiency. So, in the second law of efficiency, the exergy expanded supplied is in the denominator. So, you will heat it because you will supply the same amount. So, look at this diagram of psi1 minus psi2. So, from here it is 1 and from here it is 2, this is inlet, and this is outlet 2 So what will change? Psi 1 minus Psi 2 because it is decreasing So m dot Psi 1 minus Psi 2 And the same your cold stream is increasing So Psi 4 minus Psi 3 So this is your recovered and we can write it as we did in other examples 1 minus T0 this is your destruction, and this is your supplied You can also detail about X generation. If you look carefully, you can see that both the fluids are generating entropy. In this way, you can add the changes of delta S generation to both the streams. If you add delta S, you will get S generation. For that, m dot s2 minus s1 plus m dot cold s4 minus s3 This will be your s generation We have assumed that this whole system is not getting heat transfer If this was heat transfer, then there would be some loss There would be more support from here In this case, you have to add more terms in s generation where you have to add some element, some additional term like heat loss which for example if you say that there is Q loss there is some other loss then you can also add 1 minus T0 by T boundary whatever boundary you want to apply by adding that you can also add its generation which is due to heat loss and you can also get S generation similarly mixing chamber In this case, the heat exchanger is not mixing the chamber. But in the mixing chamber, hot stream 1 is mixed with cold stream 2. In such a case, you can also extract the eta. Because in this case, the same concept will be applied. In which the exergy that is expanding is of hot stream. And the exergy of cold is recovering. you will do cold. But the final stream is fixed, it is mixed, it is 3. So, understand it in a way that this is 1, this is 2, this is mixed and this is 3. So, the supplied below is more than hot, which is 1, it is hot, this is cold, and this is 3, so 1-3, this amount of your exergy is supplied. and 3-2 is the amount recovered but this is the mass of coal because it is according to the cold stream So now you know how to do this Actually you can do this as a generation so this will be 1 minus T0 as generation divided by m dot out psi 1 minus psi 3. Now to find S generation, you have to find the final entropy of the S3 minus mhot S1 minus mcold S2. We will add a dot here because it is a rate. So, this is your total. This will be the S generation. So, you can do it like this. So, I hope you understood a little bit. How can we get this eta. The best way is to understand it as an example and practice it. Now let's take an example of a steam turbine. So, this is your exergy analysis on this steam turbine.

$$\eta_{2,HX} = \frac{\dot{m}_{out}(\Psi_4 - \Psi_3)}{\dot{m}_{hot}(\Psi_1 - \Psi_2)} \; or \; \eta_{2,HX} = 1 - \frac{\dot{s}_{gen} T_0}{\dot{m}_{hot}(\Psi_1 - \Psi_2)}$$

$$\dot{s}_{gen} = \dot{m}_{hot}(s_2 - s_1) + \dot{m}_{cold}(s_4 - s_3) + Q(1 - \left(\frac{T_0}{T_b}\right))$$

Here the steam is entering at 3 MPa at 450°C. Which is coming from this rate of 8 kg per second. And is exiting at 0.2 MPa at 150°C. The outside environment is 25 degrees Celsius and 100 kilopascals. And along with that, the energy loss is 300 kilowatts. This means that the turbine is not adiabatic. Usually, we have done the process where we have taken the isentropic process. That is why we have taken it. But in this, we cannot consider the isentropic process because it is not adiabatic. So, we have to extract the actual power output, the maximum power possible, and the second law of efficiency, the acceleration destroyed, and the acceleration of the steam at the inlet conditions. So, in a way, you will be able to understand everything which we have written so far. So, let's start. First of all, you have to understand that you have to use this steam table. So, you will have to use the stream tool. Secondly, you will have to take some assumptions. Firstly, it is steady. So, we can understand that you have the dotted line of the control volume. Its delta m is zero. Delta energy is also zero. And delta is steady. So, this is also zero. Delta x of the Cv. This is also zero. Because it is a steady flow. So if you write the Inlet condition, you will have to use the table And the table of Inlet will be found from A6 In which you will get h1, S1 And in the exit condition, you will also get the table from A6 In which you will also get H2, S2 Let's consider it as 1 and consider it as 2 And the table of dead state will be found from A4 in which we will assume that h0 is hf at 25 degree Celsius and S0 is Sf at 25 degree Celsius now we have to find out the actual power output of this so for that first we will do e in minus e out equal to dE system by dT which is j which is steady state so E in minus E out will be your what is E in this because A is getting energy so m dot h1 will come what is your W out in E out plus we are putting Q out in dot because this is sub rate form plus exit say m dot h2 ticket or to kill me my leaky kind of energy potential energy can change it was a zero a to your expression are there now is quite please rearrange can energy is go up the blue dot out yeah I got m dot h2 m. is given in this table So you know this too h2 is also given in this table So you know this too Q dot out is given as 300 kW So this is 4306 kW This is W dot out.

Next question is Let's see the part of this How to solve this Maximum possible power output Maximum possible power output is reversible We are talking about reversible power output. This will happen only when you assume that the system is in a reversible process. It means that its strategy is destroyed and that is zero. Entropy generation is zero. So, if we assume that this thing is reversible, we can assume it. And Xin, then we have xout minus xdestroyed. is equal to dx System by dt, steady state, so this is also 0, this is also 0. It is said that xin minus xout is done. Now in this, you have to remove xin and xout, because of which it is coming. And here your xin is seen. So you have xin because of the mass and flow rate due to which mass in mass out and to avoid heat transfer contribution we can remove maximum condition which is maximum output we can remove this part immediate surrounding with which the boundary T0 will be 25 degree celsius with which your heat transfer will be zero from this boundary because it is already system then you Consider that Xin is m dot System 1 and Xout is W dot Reversible Out Plus Xout Heat is heat is 0 plus m dot psi2 0 because it is on the boundary so in this case you have an extended system so your xig contribution of heat is 0 now you have an extended system basically and with this you can find out maximum reversible out contribution now what you have to do is Now we have to calculate this as m.psi1-psi2, which is reversible out. Notice that this example is exactly the same. If we look carefully, we have written it here as well. Even before this discussion, this one, which is reversible work, m dot psi1 minus psi2. We are doing exactly the same. And we derived this and brought it here as well. Now you have to get this psi1 minus psi2. To write it, you need to use M dot h1 minus h2 minus t0s1 minus s2 and neglect the kinetic energy and other things because this will be left and W reversible out Now here you have to use S1, S2 and H1, S2 which is taken out from the steam table and M dot h1 minus h2 minus t0s1 minus s2 is known so when you plug in, it will come out 5072 kW So this is your reversible maximum output, which is more than 4306. And you can actually remove the efficiency of this. This is the question for you to remove the second law of efficiency. So, when you remove it, the second law will be your ET, in which W out divided by W reversible, which is out. If we take out the limit, it is 5072. Out is 4306. This is 84.9%. So, you are achieving 84.9% in this process. Which is very good. Like 15% loss is going to waste. So what was the destruction? The destruction was the exergy destroyed. Yoga W reversible out minus W out which is 776 kW. So, this amount has been wasted. You can also remove it from T0, S0 or T0, S generation. So, if you remove S generation, then you can also remove entropy generation and directly multiply it with the temperature of the environment. So, this is also the same relation.

Now the fifth question was XA g of the steam at the inlet condition So this is not a very special calculation This is simple H1 minus H0 S1 minus S0 V1 square by 2 plus g Z1 We will assume that this part is negligible This part is for environment and we can also take out the environment from here which is from this table. So we will plug in this value H1 and S1 are known T0 is known to be 25 degree and 298 Kelvin So when we plug in, it will be 1238 KJ per kg We have not counted the kinetic energy and potential energy If you multiply this 8 kg per second So, this will come out If we multiply it by 8 kg per second It will come out as 9904 kW So, its initial exergy was 9904 kW And actually the work you took out is 4306 So, only 43.5% The energy that you have availed, you have availed this energy. So, you can do such an analysis. That's why this is a very valuable formulation, a very valuable method. It is a very good method, which you can understand to any system, how much capacity it has, how much we can work with it, and how much we have been able to work in our processes. Let's take another example. This is the second example in which we are taking air. In the first case, we took steam. In this case, we took air, and this is the Exergy Balance charging system. So the question is that you have a 200 meter cube rigid tank which has 100 kPa and 30 KPa air and compress it to 1 MPa and keep the temperature same 300 K compressed air will come from compressor which will go from atmospheric air condition which is coming from this condition so it will be compressed and eventually will go from this condition so the question is because the initial condition is P0 and T0E so we have to find out the minimum work required for this process so that the air in our tank can reach 100 kPa to 1 MPa ok so this is the question so the minimum work required is you have to do reversible work for this so it is reversible, means X destruction destroyed will be zero. But before solving the problem, we will assume that air is the ideal gas and ke and pe are negligible and the property of air will always be constant throughout. Now we can balance x in with x out minus x in as destroyed which we are saying is reversible, so it is zero. and delta x is stuck so here we will get change because we can't zero delta x here we have x2-x1 and here is your xin what will be in xin? in xin we have w reversible in which we want to remove plus the mass which is m1 psi 1 ok and this is the initial mass which is this one now in this pay attention that the reference of psi 1 environment is the same. This will have H minus S0, S minus H0. And that S0 is the condition of your environment, which is 25°K. We have taken 300°C here, so it is 300°K. So in this case, when environment is the same, when T0 and P0 are environment as well as air, then this part will be different with respect to your environment, so here psi1 is 0 and this is the s-duction and this is the s-destroyer, which is 0 and this is the m2 the final 2 into the x-ray of this system minus m1 phi1 ok? so this is your equation and you can call this w rev in is equal to m2 phi 2 minus m1 phi 1. Now let's talk about phi 1. When psi 1 was written, then psi 1 is taken for the flowing system which will have h1 minus h0. Now the initial state of phi is its exergy is phi, let's assume phi1 and in phi1, u1 minus u0 minus t0 will be there so u0 and u1 and t0 will be same because initially the condition was at 100 kPa and 300 K which was the environment condition what does this mean? phi1 will also be 0 so wrev in is a simple m2 Now to take out M2 you should know the final conditions P2V divided by RT2 and V you know 200 meter cube P2 you know because Pt is 1000 kPa T2 you know 300 Kelvin and R you know because your 0.287 kPa cube per kg Kelvin So this is the amount If you want to extract phi 2, you have to extract U2 minus U1 plus P2 P0 V2 minus V0 minus T0 S2-S0 plus kinetic energy part which we are neglecting plus kinetic energy plus potential energy which we are neglecting Now notice this is the Idle gas So, in the ideal gas, the temperature is not changing, only the pressure is changing in this process. So, because the ideal gas depends on the temperature, U2 and U1 will be same, so it is 0. so we have only two terms, V2 minus V0, T0, S2 minus S0. you can take out this equation using the ideal gas equation so P2 we will write this that you can represent this as P0 V2 V0 that P0 RT2 by P2 minus RT0 by P0 you can write this as RT0 P0 by P2 minus 1 because T2 is T0, so you can take it as a common. Similarly, what will be T0 S2 minus S0? We can take T0 as an entropy for the ideal gas. ln T2 by T0. Since it is the same, T0 T2 is equal to same, T1 will be 1, so ln1 is 0. Minus R ln P2 by P1 P0. which will remain, so this expression comes out Rt2 ln P2 by P0. So, you will plug in this expression. And you have information that you know T0, P2, which is final, which is 1000 kPa and P0 is also known. So, when you plug in, you will get the whole expression, so the value of phi2 will come out. 120.76 kJ per kg So, this way your W minus Riv minus In because M2V knows, so this will come out your 281, approximately 281 MJ Ok So, W minus Riv minus In, the reversible minimum work comes out to be 281 MJ So, through examples you have seen how to do exergy in balance control volume and through that you can answer many questions. So, I hope that you have understood exergy which is a work potential of any system and we have seen how you can do heat work and how you represent the flow that is contributed. We saw how it is connected to reversible work and reversibility. And how you can connect the second law efficiency with expanded and recovered exergy. And how you can connect it with S generation, the destroyed exergy. fixed mass for non-flow system and closed system. Then we did for flow system also. After that we did its examples. Particularly, we have decreased of exergy principle which we said is equivalent, same principle which we talked about increase of entropy. It is the same. But we have presented it in a different way. And with this... in the analysis of the efficiency of the device, how we can use it. So, I hope you have understood the concept of exergy and how it can be used in engineering applications. Then we will start a new topic in the next lecture. And then through some exercises, which will be completely device-based. We will discuss how to apply this concept in cycles. I hope you get this understanding. We will meet again with a new topic in the next lecture. Till then, I will take your leave. Namaskar!