Concepts of Thermodynamics
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Lecture – 56
Exergy Analysis: Examples (Contd.)

We continue with problem solving on reversibility and Exergy. So, the next problem is problem 8.4.

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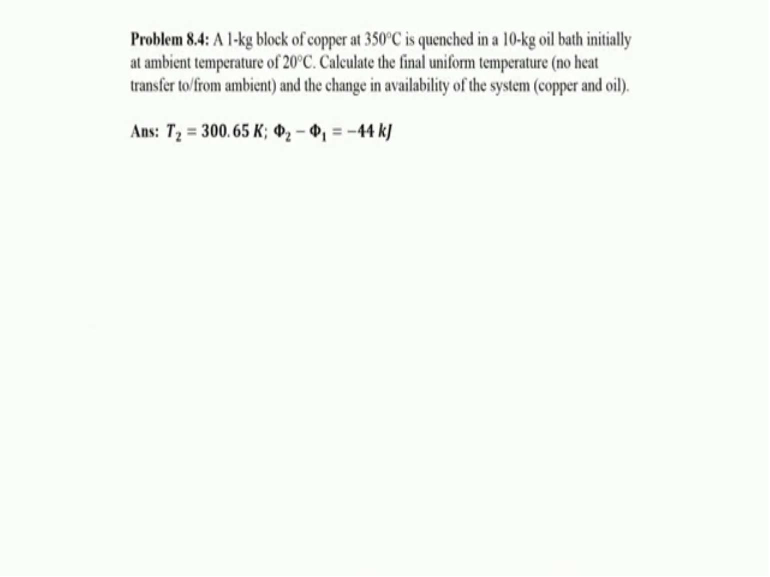

Problem 8.4: A 1-kg block of copper at 350°C is quenched in a 10-kg oil bath initially at ambient temperature of 20°C. Calculate the final uniform temperature (no heat transfer to/from ambient) and the change in availability of the system (copper and oil).

Ans: $T_2 = 300.65\ K$; $\Phi_2 - \Phi_1 = -44\ kJ$

A 1-kg block of copper at 350 degree centigrade is quenched in a 10-kg oil bath initially at an ambient temperature of 20 degree centigrade. Find calculate the final uniform temperature assuming no external heat transfer and change in availability of the system copper and oil. So, availability is exergy it is the same.

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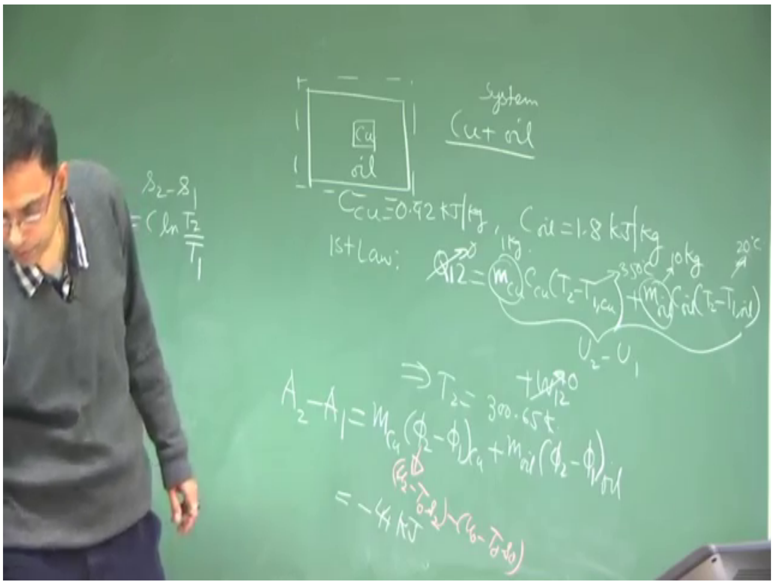

So, the situation is you have a copper block in oil and copper plus oil is your system. For solving this problem, you also required the specific heat of copper which is 0.42 kilo joule per kg and specific heat of oil which is 1.8 kilo joule per kg, ok. If you apply the strategy of solving this problem is again like you need to calculate the change in availability for that you require the entropies and for entropy transport you require the heat transfer.

So, let us calculate the first law or let us calculate the final temperature concerning the first law. So, this is U 2 minus U 1 plus W 12 which is 0; heat transfer is also 0. Your system is this one and this system does not interact with the surroundings through any heat transfer or any work. So, T 1 oil and T 1 copper these are known T 1 oil is 20 degree centigrade T 1 copper is 350 degree centigrade. So, from this equation you can find out what is T 2. So, mass of copper is 1 kg and mass of oil is 10 kg.

So, you can calculate what is T 2. So, T 2 in this case is 300.65 Kelvin. So, phi 2 minus phi 1; so, what is required is the total availability which is capital phi or let me write A 2 minus A 1. This is nothing, but the difference in the availability between availability of the initial state and final state of copper and oil.

So, this is m copper into phi 2 minus phi 1 of copper plus m oil into phi 2 minus phi 1 of oil, where phi 2 is u 2 minus T 0 s 2 minus u 0 minus T 0 s 0, right. Similarly, phi 1 just replaced 2 with 1 and again for oil it is very similar. So, you essentially need to calculate s 2 minus s 1 for copper and s 2 minus s 1 for oil to calculate this s 2 minus s 1 is C ln T 2 by T 1 there is no R ln T 2 by T 1 because it is incompressible substance that p 2 by p 1 factor is not there. So, if because you know the temperatures of the final state and initial state you can calculate the change in availability in this using this formula and then this is minus 44 kilo joule that is the answer to this problem, ok.

We will move on to the next problem. So, before moving onto the next problem a very important insight about the answer to this problem is phi 2 minus phi 1 is negative, right. So, there is a decrease in availability or exergy and this is because that the entire work potential because of this heat transfer is lost due to irreversibility due to entropy generation.

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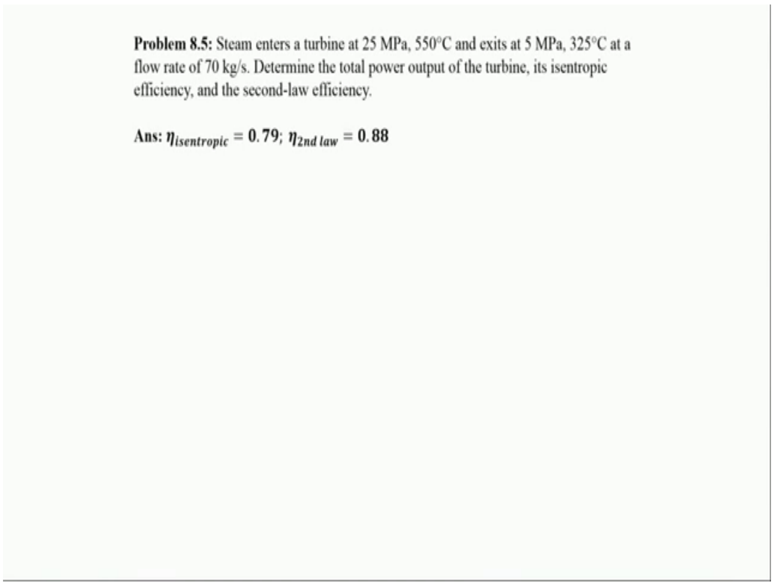

Problem 8.5: Steam enters a turbine at 25 MPa, 550°C and exits at 5 MPa, 325°C at a flow rate of 70 kg/s. Determine the total power output of the turbine, its isentropic efficiency, and the second-law efficiency.

Ans: $\eta_{isentropic} = 0.79$; $\eta_{2nd\ law} = 0.88$

Next problem: Steam enters a turbine at 25 MPa 550 degree centigrade and exits at 5 MPa 325 degree centigrade at a flow rate of 70 kg per second determine the total power output of the turbine, its isentropic efficiency and second law efficiency. This is a very straight forward problem, but again we will try to develop an insight through this problem.

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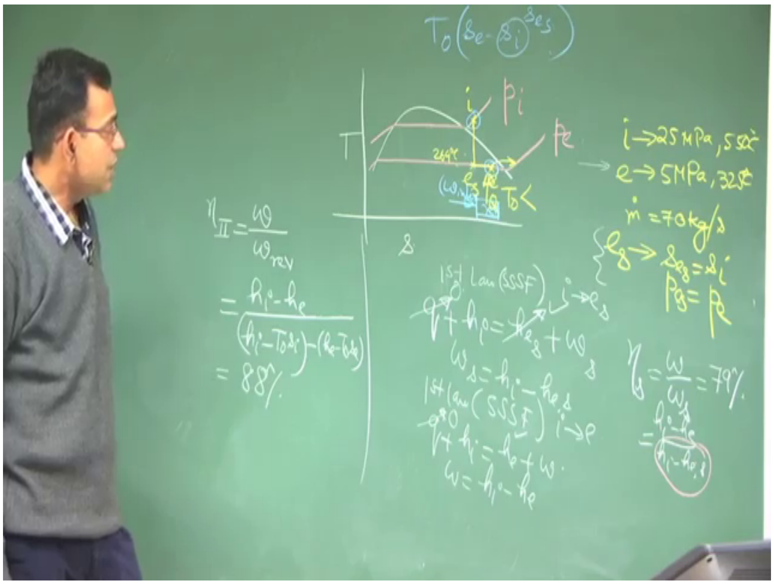

So, let me make a schematic we have solved a very similar problem in the previous lecture. But, I want to get little bit deeper into the aspect of second law efficiency and isentropic efficiency. So, you have the pressure, this is the inlet pressure and this is the exit pressure of the turbine. The state i is given so, let us draw the states in states points in this diagram.

State i let us write somewhere 25 MPa, 550 degree centigrade. Then state e which is somewhere here e is 5 MPa, 325 degree centigrade, m dot is 70 kg per second because we intend to also relate with the isentropic efficiency and a virtual isentropic process. We will also be concerned about the state e s which is a hypothetical state es it is given by s e s is equal to s i and p e s is equal to p e.

So, in this case let us see what is first you have to calculate. The first thing that you have to calculate is what is the isentropic efficiency and what is the second law efficiency. So, to calculate the isentropic efficiency you also after know what is the reversible adiabatic or isentropic work. So, you apply the first law steady state steady flow between i and e s. So, you have q plus h i all the terms you are writing per unit mass.

So, from the state e s we know how to calculate h e s; in one of our previous problems we have addressed it, so, I am not getting into the details. The turbine is adiabatic in this case. So, w s is h i minus h e s. Similarly if you apply the first law for the process between i 2 e you have q plus h i is equal to h e plus w actual. State e is already given.

So, h e you can find out from the table. So, w is equal to h i minus h e. So, the isentropic efficiency is w by w s, very straight forward and this is coming out to be 79 percent ok.

Then, you have to also calculate the isentropic efficiency, right. So, to calculate the isentropic efficiency oh sorry, second law efficiency write you have already calculated the isentropic efficiency, next you have to calculate the second law efficiency. So, interestingly this expression here become h i minus h e by h i minus h e s. We will see how it relates to the second law efficiency. So, second law efficiency, how it is defined? It is w by w reversible.

So, w is again h i minus h e and w reversible is h i minus T 0 s i minus h e minus T 0 s e, right. Now, by looking into the expression for second law efficiency and isentropic efficiency, can you tell what is the conceptual difference? The conceptual difference is that in this case the comparison is between the same end states, this is the actual work this is a reversible work that could be obtained with the same end states that is definitely less than the reversible adiabatic work between the states i and e s; e s is a hypothetical state it is not the actual end state. In reality, the end states are fixed.

So, i and e are fixed, e s is just a hypothetical state; i and e are the fixed states. The numerator in second law efficiency is the actual work that you get with this fixed states and the denominator that if the entire process was reversible between these two states what could have been work that you have obtained that is different from a reversible adiabatic process between i and e s. So, here your perhaps comparing one apple with an orange. This is work between states i and e; this is work between states i and e s.

So, there is there are disparate basis of comparison. Here the basis of comparison is more consistent because you are comparing with the same end states i and e. This is just the reversible work between the same the end states i and e and this is the actual work between the states i and e this reversible work need not be adiabatic.

So, then what is that reversible work that you could obtain? To get an insight imagine the process like this. So, you could break this up into two parts; one is from i to e s, another from e s to e. So, to make a reversible process from e s to e you need a heat transfer, right so and that heat transferred is like in this case integral T ds from e s to e. So, that heat transfer so, look at the temperature of this temperature is 325 degree centigrade. So, so this is around 300 325 like.

So, if it is in a two-phase region both are 325 degree centigrade because saturation pressure is not changing from saturation temperature is not changing from e s to e. So, it is 325 degree centigrade.

Student: Sir, e is in the two-phase region?

E is in a 2 phase region.

Student: Then how can we use pressure and temperature as the (Refer Time: 16:01)?

No, no, no we will which one?

Student: 5 mega Pascal and 325 degree centigrade.

It will, yeah. So, this state 5 mega Pascal and 325 degree centigrade this is a very important question this 5 MPa and 325, so, I have drawn it conceptually here, but it may actually be you know in little bit in the superheated region also because when you specify so, just look into the table and say what is the saturation temperature at 5 MPa?

Student: 264 degree.

264 this is superheated actual. So, normally the exit state of a turbine will not very commonly be in a superheated state. So, normally the quality at this state will be given. So, in this particular problem it comes to the superheated state. So, it is better that I show it here. So, normally the exit state is governed by this pressure and the quality and the quality is very close to 100 percent. In this case because pressure and temperature both are given now both are independently given means it is not a two phase region and the saturation temperature at 5 MPa is less than 325 degree centigrade.

So, this is little bit superheated may not be very highly superheated, but little bit superheated. So, and what is this saturation temperature?

Student: 264.

264 degree centigrade. So, from 264 to 325 that is the change in temperature as you go from e s to e. So, from e s to e you require a heat transfer right in a reversible process what will arrange the heat transfer or you do not have any source or anything. So, you have to arrange that heat transfer from the ambient. Ambient the key issue is that ambient

is at lower temperature. So, ambient is at T 0 which is less than all this. So, T 0 is less than these 264 or 325 all this.

So, because T 0 is less so, from a lower temperature to a higher temperature system if you want to have a heat transfer, but still you have to have this heat transferred to have the change in state from e s to e to take place and that in a reversible manner. So, you have to arrange for a reversible heat pump across the ambient that will effectively transfer heat from T 0 to this that reversible heat pump will require a work input, right.

So, you have to arrange for a reversible heat pump which requires a work input although reversible, but still it requires a work input and that part of the work therefore, you do not get as a work potential. That is why you see it is not h i minus h e, but h i minus h e minus of T 0 into s i minus s e that minus of T 0 into s i minus s e or s e minus s i whatever this is essentially because s i is equal to s e s. It is essentially the heat transfer associated with this process, ok.

So, you are having a basis where the potential is not to the full h i minus h e there is a less utilisation possibility because you also are allowing a heat transfer and there has to be a reversible arrangement to achieve that heat transfer in exchange with the ambient.

Student: Sir I have a question that the expression for reversible work comes out something like h i minus h e. So, it is for any reversible process between the inlet and the.

It is for any reversible process between the inlet and the exit.

Student: But, work is a path function.

No, no, no it is for any reversible process with no heat transfer. If there is a heat transfer there is an associated reversible work which is plus u into 1 minus T 0 by T h, right, but here where are assuming what the work potential is due to the change in state between i to e without any heat transfer. But, even in this process if you break it into two parts the second part will require an internal heat transfer and that can be arranged only through an ambient by employing a reversible heat pump, ok.

So, if you calculate these values. So, s i, s e all these things you can calculate if you calculate all these values you will see that the second law efficiency is 88 percent. See the first law efficiency or I mean not the first law the isentropic efficiency it is 79 percent; that means, the denominator here appears to be more than the denominator here, right.

So, this already takes into account the less potential because of the need of this employment of the heat pump to have the heat transfer across the states i and e; in this case it does not take that into account. So, the potential that you are considering as a h i minus h e s is not the true potential. The potential that you are considering between the end states these are this is the true potential, right. So, you have to compare it with the true potential and not the hypothetical potential and that is why the second law efficiency is much more scientifically correct to assess the performance of a device as compared to the isentropic efficiency.

We will solve a couple of more problems. So, the next problem let me erase the board. Air flows into a heat engine at ambient conditions of hundred kilo Pascal.

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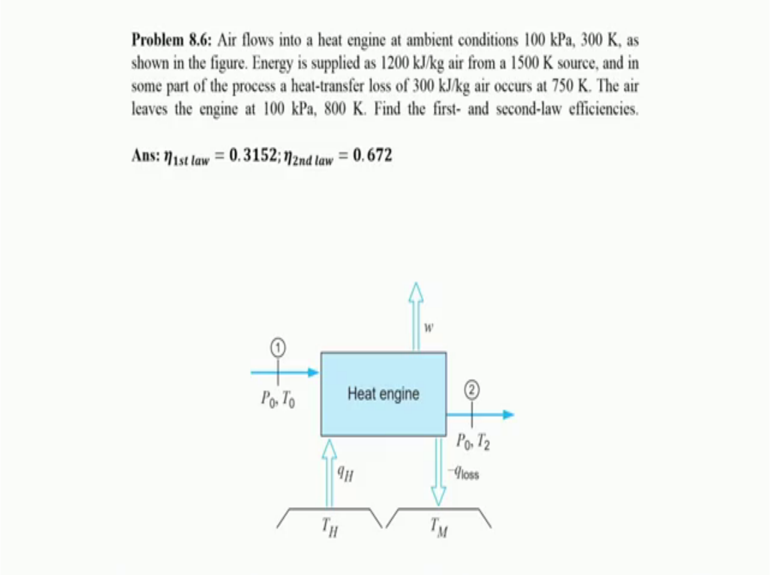

Problem 8.6: Air flows into a heat engine at ambient conditions 100 kPa, 300 K, as shown in the figure. Energy is supplied as 1200 kJ/kg air from a 1500 K source, and in some part of the process a heat-transfer loss of 300 kJ/kg air occurs at 750 K. The air leaves the engine at 100 kPa, 800 K. Find the first- and second-law efficiencies.

Ans: $\eta_{1st\ law} = 0.3152; \eta_{2nd\ law} = 0.672$

And, 300 Kelvin as shown in the figure energy is supplied as 1200 kilo joule per kg of air from a 1500 Kelvin heat source and in some part of the process the heat transfer loss of 300 kilo joule per kg of air occurs. The air leaves the heat engine at a 100 kPa 800 Kelvin find the first law efficiency and the second law efficiency.

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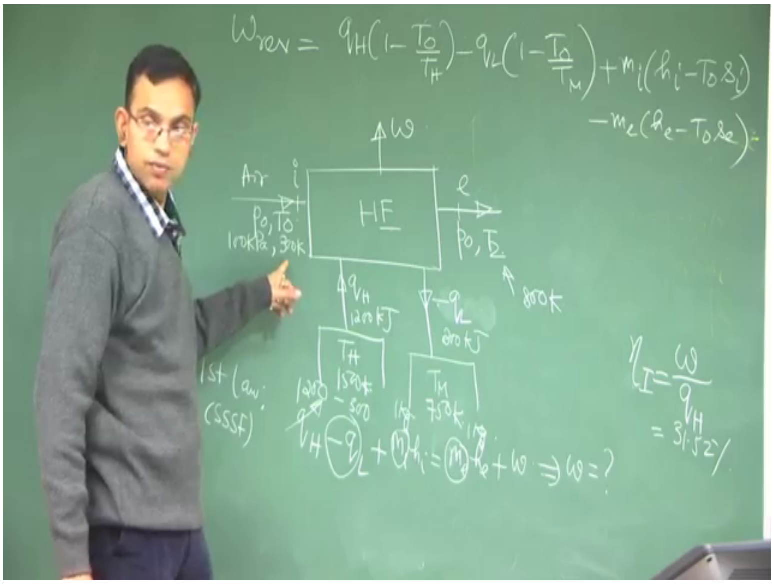

So, let us calculate this. So, you have a heat engine it is interacting with various thermal reservoir. So, you have a q H of 1200 kilo joule from T H at 1500 Kelvin, you have q minus q L which is. So, let us write this as minus q L with the magnitude of q L as 300 kilo joule. So, magnitude is 300 kilo joule minus because heat is transferred from this is what is given in the schematic of the problem. So, I am trying to be consistent with the schematic of the problem and then this T m 750 Kelvin.

So, you have air at p 0 T 0 you have state i and state e you have air at p 0 T 2. This p 0 is 100 kPa and this is 300 Kelvin and this is 800 Kelvin. So, you have to calculate the first law and second law efficiency. So, the first law efficiency will be like what amount of heat transferred to the system is converted into work. So, in this case ok, there is a work done also.

So, first law you have cyclic integral of heat equal to cyclic integral of work. So, always start with the basic equation.

Student: (Refer Time: 26:57)

Heat engine cyclic process.

Student: Sir, control volume (Refer Time: 27:19)

We can use the steady state steady flow equation here. Yes, this is a flow process. So, we can use the steady state steady flow.

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But, it is a heat engine at the end. So, it will work in a cycle. So,, but you know the heat engine itself allows some flow to take place. So, q H minus q L plus m i h i ok so, 1200 kilo joule. So, for everything we can calculate in terms of 1 kg per air or 1 kg of air. So, q H is 1200, this is minus 300. So, minus 300 q L is 300, so, minus 300. This is 1 kg, this is 1 kg h i minus h e. So, this will be C p into whatever T i minus T e.

So, you will get w from here. So, the first law efficiency essentially talks about what is the work which you get as a function of what heat is supplied. So, w by q H. So, this is 31.52 percent ok. The second law efficiency compares the w with the reversible work. So, what is the reversible work the reversible work is associated with these two heat transfer and then the change of state. So, the reversible work is q H into 1 minus T 0 by T H minus q L into 1 minus T 0 by T M then plus m i into h i minus T 0 s i minus m e into h e minus T 0 s e, right.

So, this is the work potential due to the change in state and this is the work potential due to heat transfer. So, everything is known the change in entropy you can calculate by the formula like integral of C p dT from C p dT by T from 300 Kelvin to 800 Kelvin minus R ln p 2 by p 1 is 0 because the pressure is does not change. So, if you substitute this value I do not have the exact value of this, but I have the answer to the second law efficiency this is w by w reversible this is 67.2 percent.

So, this is more practical because it is comparing w with a possible reversible process considering exactly the same inputs and this considers know w as compared to q H, but you also have q L which is obvious and that will make your efficiency of apparently low. But this is what is your comparing your actual work with the maximum possible work within the given constraints not with the q H. So, work is compared with work not work is compared heat ok.

So, we will work out one more problem the possibly the final problem in this chapter before we move on to another chapter.

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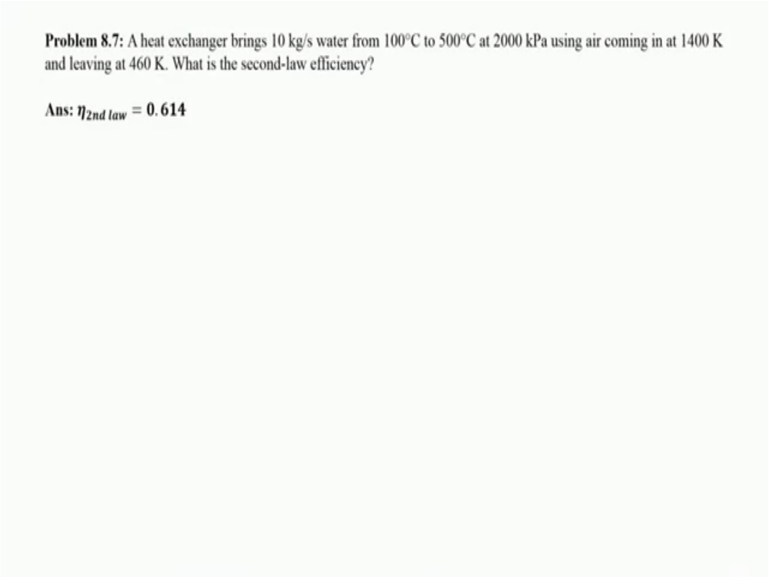

Problem 8.7: A heat exchanger brings 10 kg/s water from 100°C to 500°C at 2000 kPa using air coming in at 1400 K and leaving at 460 K. What is the second-law efficiency?

Ans: $\eta_{2nd\ law} = 0.614$

So, problem 8.7: A heat exchanger brings 10 kg per second water from 100 degree centigrade to 500 degree centigrade at 2000 kilo Pascal using air coming in at 1400 Kelvin and leaving at 460 Kelvin. What is the second law efficiency? This a very typical problem because so far we have calculated second law efficiency with by comparing work with work, but heat exchanger does not do any work. So, how do we rate its second law performance? So, we will learn that through this example.

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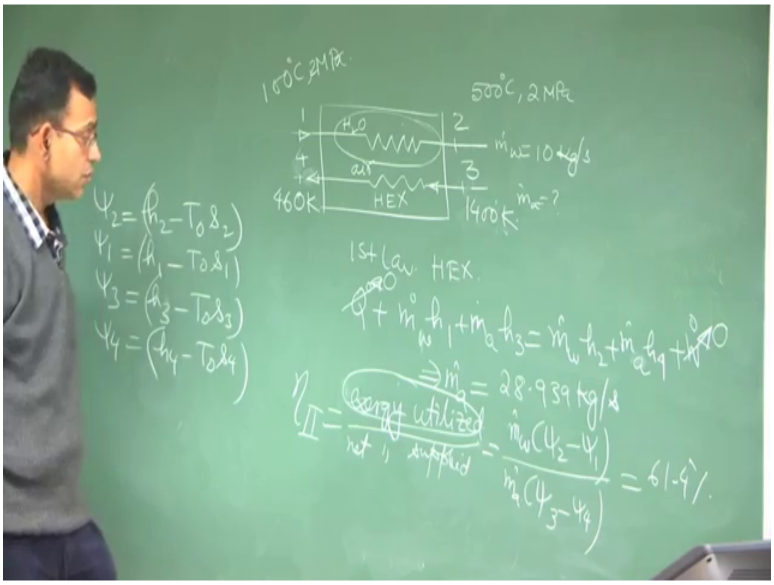

So, you have a heat exchanger in which you have water from state 1 to state 2 this is hundred degree centigrade to MPa this is 500 degree centigrade 2 MPa m dot water is 10 kg per second. There is a line of air say you have 3 and 4; this is air, this is water, this is air. m dot air you do not know that you have to calculate from energy balance, but this is 1400 Kelvin and this is 460 Kelvin ok.

So, what is happening you can clearly see that this water is heated by air. So, what is the purpose, you have to understand this carefully. The exergy utilise depends on the purpose. So, here the purpose is that by using this hot air stream the cold water is heated, ok. So, first of all we have to find out what is the mass flow rate of air. So, we can apply the first law for the heat exchanger as a whole.

So, Q dot summation of m dot h i.

Student: Sir, when the water is getting heated by the (Refer Time: 35:39) temperature of the water is more than temperature of air? State 2 and state 4.

No, no, no. This is this is 5 at this will typically be it may be a counter flow heat exchanger, right. So, I mean the exit state will be greater than this 4 1400 degree so, 1400 Kelvin. So, still there is heat transfer from air to this where the entry of air is actually you know it is not exactly the same is just the opposite. So, this and it just to correspond to the proper physical configuration this is 3 and this is 4. So, this is 300 Kelvin and what is that sorry 460 Kelvin no, the entry, entry. This is 460 Kelvin.

Student: You wrote the same thing.

Anyway.

Student: You wrote the same thing.

So, this will be put. So, this is 1400 Kelvin, right and this 460 yeah, sorry I just wrote the same thing. So, this is 1400 Kelvin, this is 460 Kelvin and you can see that in all cases now the water fluid has the high temperature. So, it does not disobey the second law. So, this I mean alteration of schematic was necessary because if we kept 3 here and 4 here then at some place the water fluid will have a lower temperature than the colder fluid that will violate the second law.

So, this is called as counter flow heat exchanger instead of a parallel flow. So, this in exit of this is same as entrance of this. So, it is not given, but from the data this is what we can draw consistent with the physical picture. This is greater than this temperature, this is greater than this temperature. So, there will be a flow of heat always from the air to the water; had it been drawn in the other way that what happened.

So, now, of course, then it becomes m dot I mean the equation remains the same just conceptually the figure needs to be altered the equation remains the same. So, you have the work done as 0, the heat transfer as 0 because there is no external heat transfer, then m dot water is known. So, from here you can find out what is m dot air. So, m dot air yeah. So, m dot water into h 2 plus m dot air into h 4. So, m dot air into h 3 minus h 4 is integral of C p dT from 3 to 4 T 3 to T 4. So, if you do that you will m dot air as 28.939 kg per second.

Now, the conceptual part of the problem; so, how to calculate the second law efficiency?. So, look at the fundamental definition of the second law efficiency. Second law efficiency is the exergy utilised it does not define it in terms of heat, work etcetera it defines it in terms of exergy. So, exergy utilised by net exergy supplied. So, exergy utilised depends on purpose. So, what is the purpose here? The purpose is to heat this water. So, exergy will be m dot water into 2 psi 2 minus psi 1, there is increase in exergy that is the work potential of the work water is elevated because of this heat transfer from that the air to the water what is the net exergy supplied. So, it is m dot air into psi 3 minus psi 4.

So, exergy of the air is lost or sacrificed at the expense of increasing the exergy of the water; so net exergy is balanced but, with irreversibility. So, it is not exactly balance because the whatever is exergy input to the system is equal to the exergy output plus irreversibility, there is no work done here. So, the exergy that is supplied by the air is not been able to completely convert it into the exergy gain of water and that is because of the irreversibilites associated with the process. Had that been the case where the exergy supplied by air is fully converted into exergy gain by water then this would have been 100 percent that it is not 100 percent.

So, if you calculate this will be 61.4 percent and just to remind you about the expression for psi 2 for example, h 2 minus T 0 s 2, psi 1 is h 1 minus T 0 s 1, psi 3 is h 1 h 3 minus T 0 s 3 and psi 4 is h 4 minus T 0 s 4.

So to summarise we have solved quite a few problems on the second law analysis and exergy and we could generalized the understanding not just for work producing and work absorbing devices, but for cases where no direct work output is involved, but still the exergy can be used as a parameter to understand the device performance because the exergy transport essentially the balance between the exergy supplied and exergy utilised that imbalance rather talks about the irreversibilities in the system which are nothing, but the inevitable losses in a practical device.

Thank you very much. We will continue with a new chapter in the next class.