# Concepts of Thermodynamics
## Prof. Suman Chakraborty
## Department of Mechanical Engineering
## Indian Institute of Technology, Kharagpur

## Lecture – 55
## Exergy Analysis: Examples

In our previous lectures, we were discussing about reversible work, irreversibility and Exergy – these 3 important concepts and now, we will solve some problems which will illustrate the use of these concepts.

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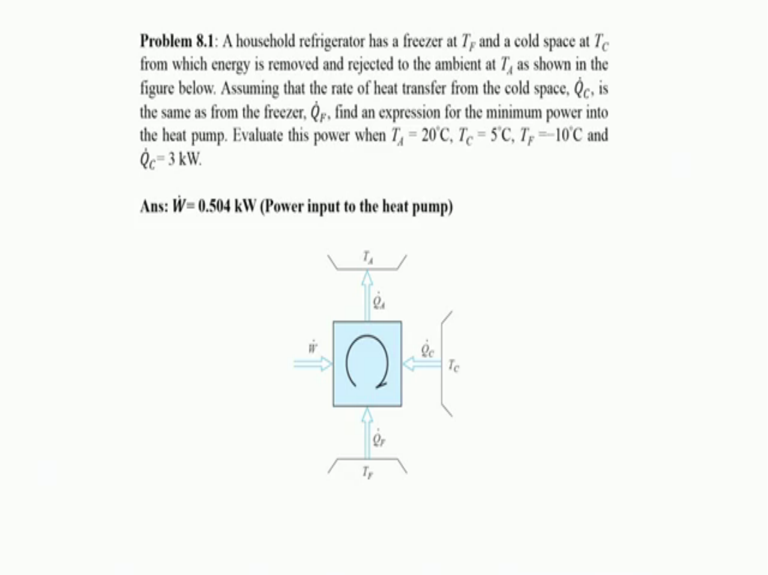

**Problem 8.1**: A household refrigerator has a freezer at $T_F$ and a cold space at $T_C$ from which energy is removed and rejected to the ambient at $T_A$ as shown in the figure below. Assuming that the rate of heat transfer from the cold space, $\dot{Q}_C$, is the same as from the freezer, $\dot{Q}_F$, find an expression for the minimum power into the heat pump. Evaluate this power when $T_A = 20^{\circ}C$, $T_C = 5^{\circ}C$, $T_F = -10^{\circ}C$ and $\dot{Q}_C = 3$ kW.

**Ans: $\dot{W} = 0.504$ kW (Power input to the heat pump)**

So, we will start with problem 8.1; a refrigerator has a freezer at T F and cold space at T C from which energy is removed and rejected to the ambient at T A as shown in the figure. Assuming that the rate of heat transfer from the cold space Q dot C is same as that from the freezer Q dot F. Find an expression for minimum power into the heat pump I mean which is in this case is a refrigerator not a heat pump, but conceptually they work in the same way you have to find out what is the minimum power input.

So, minimum power refers to a condition when the minimum power input refers to a condition when the irreversibility is a minimum and that means, it is a reversible refrigerator. So, that is the concept that you have to understand. Maximum power output will correspond to a energy producing device for a reversible heat energy engine. Energy absorbing device will require minimum power input to run the device for a reversible heat pump or a refrigerator. So, this when it is maximum and minimum you have to understand carefully; when it is energy producing that energy is maximum because of minimum losses and when it is energy absorbing that energy required is minimum to run the show.

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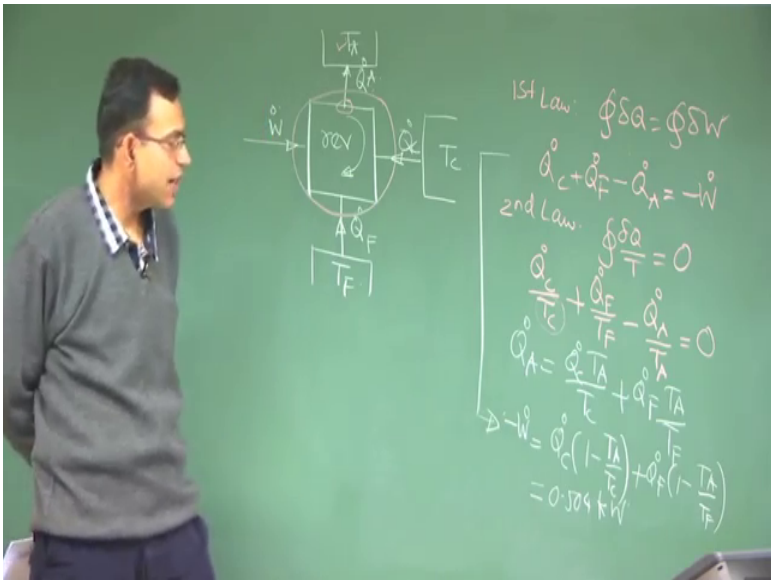

So, let me make a schematic of this problem. So, you have Q dot C with the temperature T C W dot Q dot A, Q dot F. So, this is a cyclic device which is the refrigerator in this case and it is most important is it is reversible ok. So, what are the basic equations that you need to apply for a reversible refrigerator in this case; one is cyclic integral of heat equal to cyclic integral of work which is the 1st law.

So, let us apply the fundamental laws cyclic integral of heat equal to cyclic integral of work. So, cyclic integral of heat for this device, so, we will just right in terms of the rate. So, cyclic integral of the rate of heat transfer I same as cyclic integral of the rate of work. So, rate of heat transfer is Q dot C plus Q dot F minus Q dot A, right, this is cyclic integral of heat. Cyclic integral of work is minus W dot as per this figure.

2nd law does not; see 1st law concerns about work, 2nd law concerns about only heat transfer because work is a high grade energy, it does not participate in entropy transport. So, 2nd law you have cyclic integral of del Q over T is equal to 0 for a reversible cycle, right. So, this is Q dot C divided by T C plus Q dot F divided by T F minus Q dot A by T A is equal to 0, look carefully that we have taken the temperatures not of the system boundaries here, but the reservation. In this way we have accounted for both internal and external part of the process; whatever is internal plus whatever is external and ensured that it is both internally and externally reversible.

So, now, it is a matter of. So, what is given in the problem let us see. You it is given what is Q dot F and Q dot C, but Q dot A is not given. So, let us eliminate Q dot A. So, Q dot A from here you can write Q dot C into T A by T C plus Q dot F into T A by T F. So, then from this equation minus W dot is equal to Q dot C into 1 minus T A by T C plus Q dot F in into 1 minus T A by T F, this is the final expression. So, in this expression you can substitute Q dot C is 3 kilowatt T A, T F, T C all are given you have to convert those into Kelvin and just substitute and this will be 0.504 kilowatt for this.

See, solving a problem is not about getting the final answer, there is also an insight that needs to be developed. So, let us try to develop an insight of this expression. If you recall that here there is a system to which you have two heat transfers effectively done and you are trying to find out an expression for the reversible one. So, you can clearly see that this is exergy associated with the heat transfer Q dot C this is exergy associated with the heat transfer Q dot F. So, this was initially is an expression that give the river reversible work through exergy balance because it is a reversible system the entire exergy that is supplied is equivalent to the reversible one there is no irreversibility ok.

So, you can see that the same problem can be perceived from exergy and also directly from a consequence of the 1st law and the 2nd law. Let us go to the next problem, let me erase this.

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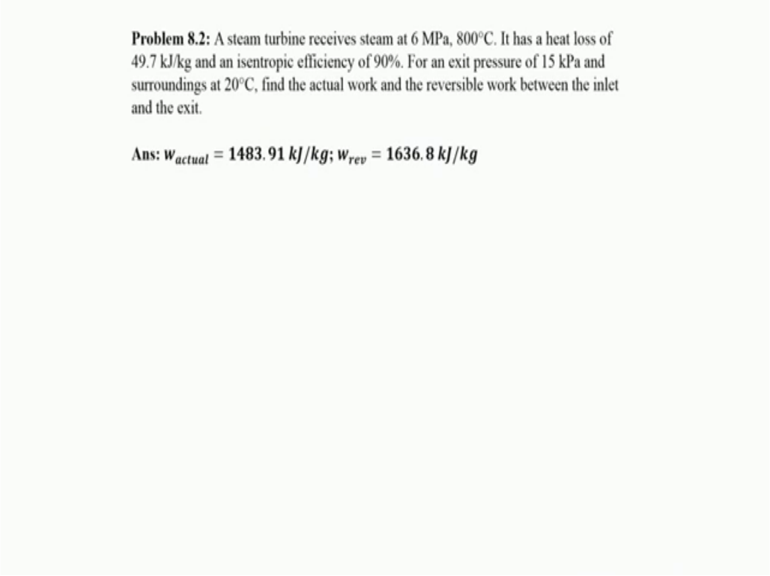

**Problem 8.2:** A steam turbine receives steam at 6 MPa, 800°C. It has a heat loss of 49.7 kJ/kg and an isentropic efficiency of 90%. For an exit pressure of 15 kPa and surroundings at 20°C, find the actual work and the reversible work between the inlet and the exit.

**Ans:** $w_{actual} = 1483.91\ kJ/kg;\ w_{rev} = 1636.8\ kJ/kg$

A steam turbine receives steam at 6 MPa, 800 degree centigrade and it has heat loss of 49.7 kilo Joule per kg and isentropic efficiency of 90 percent. I have not yet introduce what is isentropic efficiency. So, I will do that in context of this problem and then we will discuss further. For an exit pressure of 15 kilo Pascal and surroundings at 20 degree centigrade find the actual work and irreversible work between the inlet and exit. So, this is a very classical situation related to analysis of steam turbine. I will first draw a schematic of the situation in the board.

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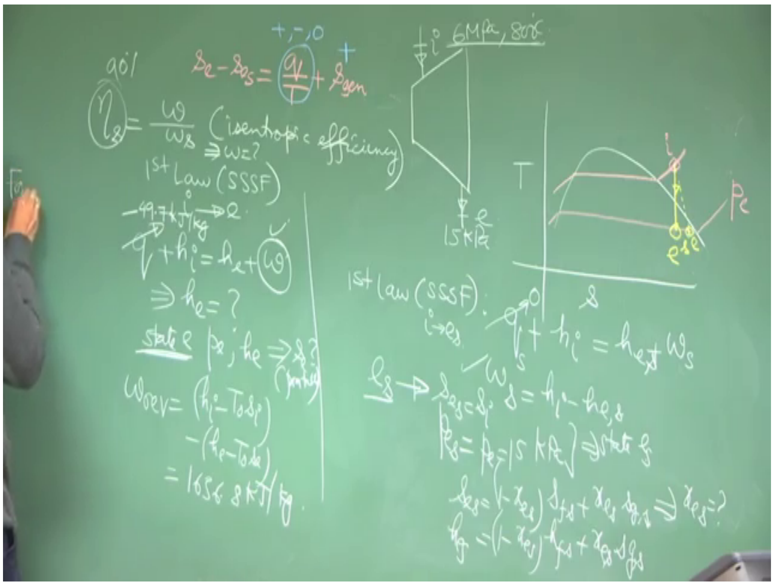

So, there is a steam turbine it has an inlet state i and the exit state e. The inlet state is 6 MPa, 800 degree centigrade. So, if you draw this in a T-s diagram, sometimes there is a temptation of drawing it in enthalpy entropy diagram hs diagram, the reason is that for 1st law of s calculations you require enthalpy, it will not really require temperature. So, if there is a diagram that directly enthalpy versus entropy then that is very convenient that in industrial application perspective is also known as Mollier chart or Mollier diagram ah.

Here we are more concerned about the fundamentals of thermodynamics, so, we will not get into the use of Mollier chart, but we will I am just telling that as a passing note because you may be requiring the hs chart for solving problems when you are participating in more applied thermodynamics courses this is the fundamental thermodynamics course.

So, you have the liquid vapour doom. The turbine is grossly specified by the following. So, in one you have a pressure that at which the steam enters the turbine this is say given by p i and the pressure at which the steam exits from the turbine. Now, by isentropic efficiency we want to compare the actual work done by the turbine vis-a-vis the reversible adiabatic work that is if the state e would have been such that from i to e it would have been a reversible adiabatic process or an isentropic process then what would be the work?

So, if would have been a reversible adiabatic process let us call this as e s this is not the actual state e, but this is the reversible adiabatic hypothetical state e. So, e s the actual process will take the point somewhere here. Now, the question is where is the guarantee that this point e will be in the right side of e s or it could also be in the left side of e s? ok. So, let us look into that more careful.

So, between i to e s there is no; so, you can decompose change of state from i to e as from i to e s and then from e s to e, just break it into 2 parts from i to e s there is no change in entropy, because it is a reversible adiabatic process from e s to e you can write s e minus s e s is equal to some q by T plus entropy generation this is what you can write. So, the question is that this is always positive, right. This could be plus, minus or 0.

So, that the net effect could be that this one is plus; when it is trivially plus it is trivially plus that this is the case when the turbine is adiabatic because if the turbine is adiabatic this is 0, then entropy generation is always positive, so, e goes to the right side. This is what most commonly happens in industrial practice because for all practical purposes the turbine can be treated adiabatic in most of the circumstances.

However, there is no guarantee to that. You could have this Q plus, minus or 0. So, the net s e minus s e s could be plus, minus or 0. So, technically this e could be in a right of e s it could even coincide with s and it could be in the left of this that must be conceptually understood. So, the very fact that we have in most of the practical cases e to the right side of e s should not develop a prejudice in our mind that e will always be in the right of e s. It depends on the nature of heat transfer across the turbine, that is what it is governed by because other than heat transfer the entropy generation part that is trivially positive part ok.

So, now, coming back to this problem let us see what is defined what is given. State e is 15 kPa which is same as state e s. There is no difference in pressure between e and e s. So, this is 15 kPa. So, now if you apply the 1st law for per unit mass flow rate across the turbine; so, you have Q plus h i say 1st law I apply for i to e s. In that case the reversible adiabatic Q s is 0 because it is adiabatic. So, I am completing the expression. So, I am writing this as W s; W s corresponds to reversible adiabatic per unit work or isentropic work.

So, isentropic work will necessarily be h i minus h e s this is h e s. So, how do you know what is the state e s? Very simple. The state e s be defined by 2 properties one s e s equal to s i and s i is known from steam table at this data you find out what is s i and p e s is equal to what? P e s is equal to 15 kPa.

So, s e s is equal to s i and p e s is equal to 15 kPa this will give you what is state s it will be in 2 phase region typically. So, you can find out the quality by setting s e s equal to 1 minus x e s into s f s plus x e s into s g s where s f and s g are s f and s g at 15 kPa, ok. So, once you calculate this what is a s e s then you can calculate what is h e s also by using this interpolation formula for enthalpy. So, h e s is equal to 1 minus x e s into h f s plus x e s into h g s ok.

So, to summarise by this calculation you know what is reversible adiabatic work? What is the actual work? For actual work we have to use the 1st law between the states i to e. Now, this turbine is a special turbine where heat transfer is not neglected. So, Q is there plus h i is equal to h e plus W, right. This Q is given. This Q is it has a heat loss of 49.7 kilo Joule per kg.

So, this will tell you and what is the exit state? The exit state is governed by what is the actual work. Now, you know that the actual work by the isentropic or reversible adiabatic what this is defined as the isentropic efficiency. This the definition, please make a note of this. I will talk about the definition of isentropic efficiency of a work absorbing device also after I complete his problem. This is the definition of isentropic efficiency of a work producing device, but the actual work is less than the reversible adiabatic work.

So, then because you know what is W s by substituting in this formula, and isentropic efficiency is given as 90 percent; so, from this you know what is W. You substitute that where, once you substitute that W here you get what is h e. So, what is asked is what is the reversible work between the inlet and exit? So, to understand what is a reversible work between the inlet and the exit you need to also know the entropy of the exit, not just enthalpy. So, you have to specify state e. How is state e is specified? It is specified by p e and h e ok. So, from here you can get what is s e from table.

So, what is the reversible work? H i minus T 0 s i minus h e T minus T 0 s e ok. This is the expression that we have derived, this is a reversible work per unit mass because of change in state from i to e. So, if you know these values T 0 is given T 0 is 20 degree centigrade that is 293.15 Kelvin. So, this will be 1636.8 kilo Joule per kg. I just want to make a final note before concluding the solution of this problem.

The final note is that this definition of isentropic efficiency is true for a work producing device only. For a work absorbing device like a compressor the reversible adiabatic work is the minimum work not the maximum. So, for isentropic efficiency of compressor it will be the reversible adiabatic work input in the top, in the numerator divided by the actual work input which I mean both are in terms of magnitude at the bottom.

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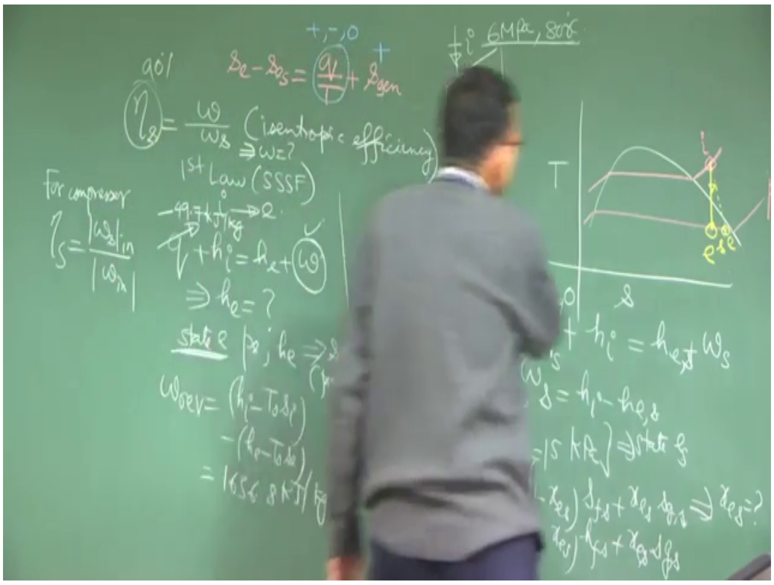

So, for compressor let me spell it out mode of work input by mode of reversible adiabatic work. The spirit of reversing the expression is the efficiency is always have an imagination it cannot be more than 100 percent, but it is always a comparison between reversible adiabatic with the actual case; which one will be there at the numerator and denominator depends on which one is more than which one is less. So, let us solve another problem 8.3.

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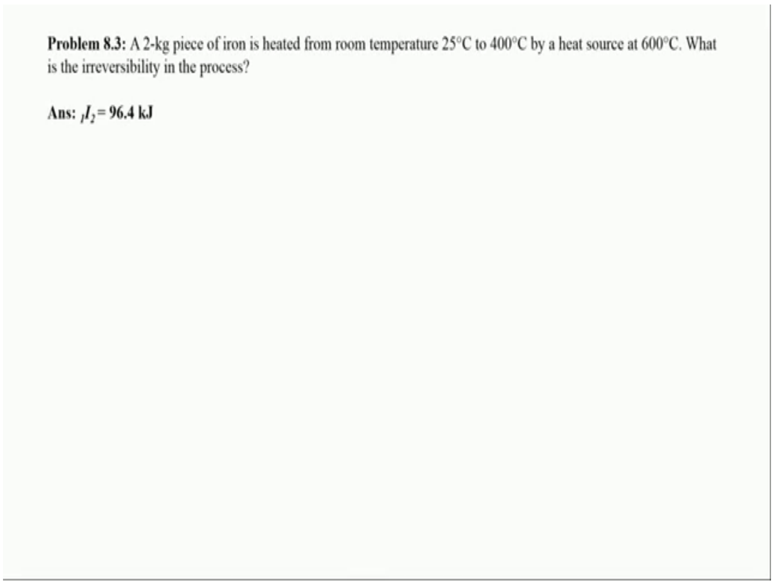

**Problem 8.3:** A 2-kg piece of iron is heated from room temperature 25°C to 400°C by a heat source at 600°C. What is the irreversibility in the process?

**Ans:** $_1I_2 = 96.4$ **kJ**

So, problem 8.3; a 2-kg piece of iron is heated from room temperature 25 degree centigrade to 400 degree centigrade by a heat source at 600 degree centigrade. What is the irreversibility in the process? So, this is a very straight forward typical problem, but let us work it out.

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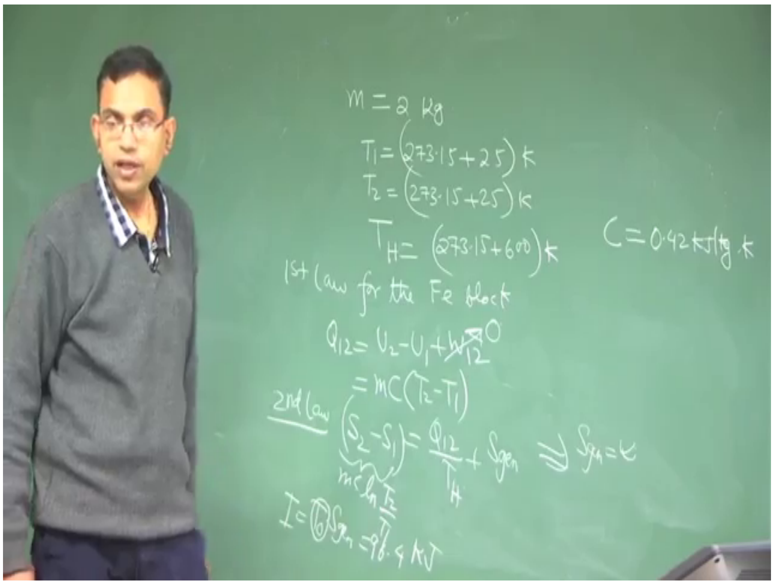

So, you have a mass of 2 kg of iron. Your T 1 is 273.15 plus 25 Kelvin T 2 is 273.15 plus 25 Kelvin and the temperature of the ambient is 273.15 plus 600. So, for knowing the reversibility you need to know what is the entropy generation. To know the entropy generation you have to know what is the heat transfer? To know the heat transfer you have to apply the 1st law. So, we will start with the 1st law for the copper block or iron block Q 12 is equal to U 2 minus U 1 plus W 12; copper block does not do any work.

So, the heat transfer is simply and U 2 minus U 1 for a solid object like cooper is m C into T 2 minus T 1. The specific heat of copper C is 0.42 kilo Joule per kg Kelvin. This data is required for solving your problem. So, you get what is Q 12. Then you apply the 2nd law S 2 minus S 1 is equal to Q 12 by T 0 plus entropy generation ok.

So, in this case we have to clearly see whether. So, this here we have to make a decision. What is the decision? The decision is that is this ambient temperature or is this the heat source temperature different from the ambient temperature, right. So, here it appears that it is not ambient temperature it is the heat source temperature at 600 degree centigrade. So, the irreversibility that you calculate the reference temperature is always important.

You could calculate irreversibility by taking the heat source of the reference temperature, but that is called as immediate surrounding. Normal tradition is to calculate irreversibility with respect to the actual ambient temperature as the reference temperature.

So, if we do not choose this to be the ambient temperature, it is not clear in this problem statement that this is not ambient temperature. So, in that case the heat transfer is taking place with this thermal resolver are not T 0, right. So, the entropy generation this will appear in the heat transfer term and S 2 minus S 1 is mC ln T 2 by T 1. So, this in this expression everything known accept entropy generation which is found out.

The irreversibility is simply T 0 into entropy generation. Here you have to make a decision that what is this T 0, right. Normally, this is called as exergy reference temperature which is the ambient temperature. So, in this problem the intuition is that the ambient temperature is 25 degree centigrade and not the 600 degree centigrade, right. So, then if you put that as T 0, so, this will give you the irreversibility and the irreversibility in this case is 96.4 kilo Joule ok.

So, let us stop here for the timing being. We will continue with more problem solving in the next lecture.