Basics of Mechanical Engineering-3

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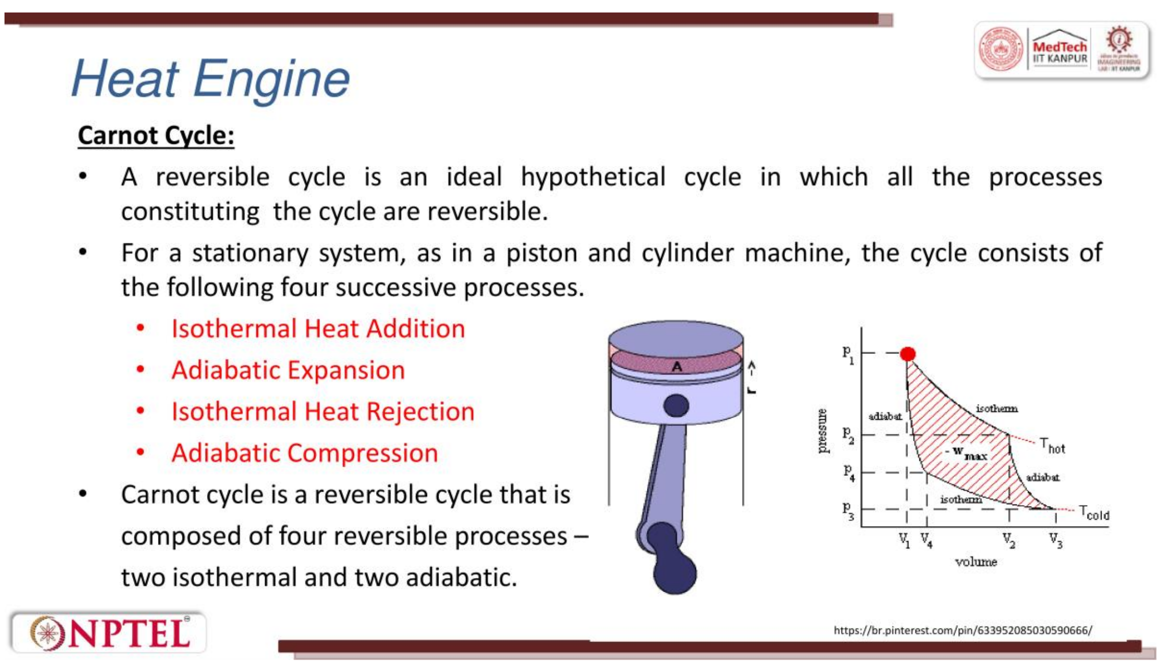
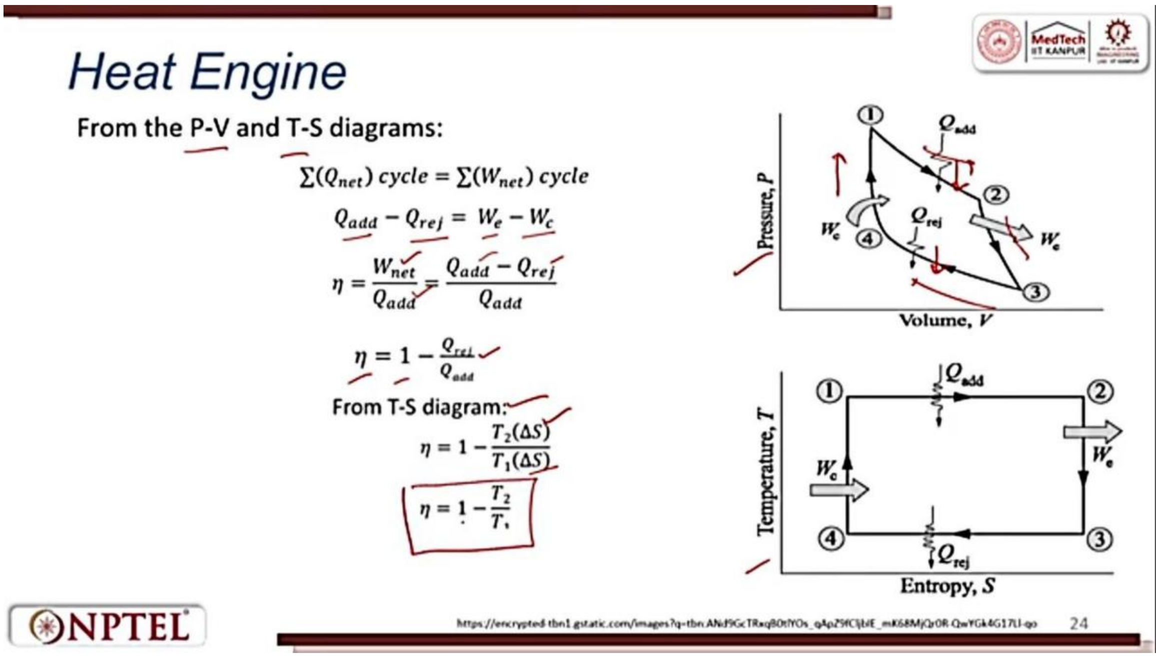
Week 03

Lecture 12: Tutorial 2 Heat Engine and Pump, Entropy, Exergy

Welcome to the second tutorial of the course. We discussed the First Law of Thermodynamics and a basic introduction to thermodynamics in the first tutorial. This tutorial will focus mainly on the Second Law of Thermodynamics. We discussed heat engines and heat pumps. We discussed the coefficient of performance. Some problem statements on this will be very interesting. This lecture will focus on heat engines, heat pumps, entropy, and exergy.



To revise the heat engine concept, regarding the Carnot cycle, a reversible cycle is an ideal hypothetical cycle in which all the processes constituting the cycle are reversible. For a stationary system, as in a piston and cylinder machine, the cycle consists of four successive processes: isothermal heat addition, adiabatic expansion, isothermal heat rejection, and adiabatic compression. These processes are given here. You have gone through this in the lecture series in week 2. The Carnot cycle is a reversible cycle composed of four reversible processes: two isothermal and two adiabatic.



Further discussing heat engines, we saw in the PV and TS diagrams—that is, pressure-volume and temperature-entropy diagrams—the addition and rejection of heat. Because of this, many changes occur between states 1 to 2, 2 to 3, 3 to 4, and 4 to 1. This has already been discussed.

That is the net cycle. Heat is equal to the net cycle work. That is,

$$\sum(Q_{net})\ cycle = \sum(W_{net})\ cycle$$

$$Q_{add} - Q_{rej} = W_e - W_c$$

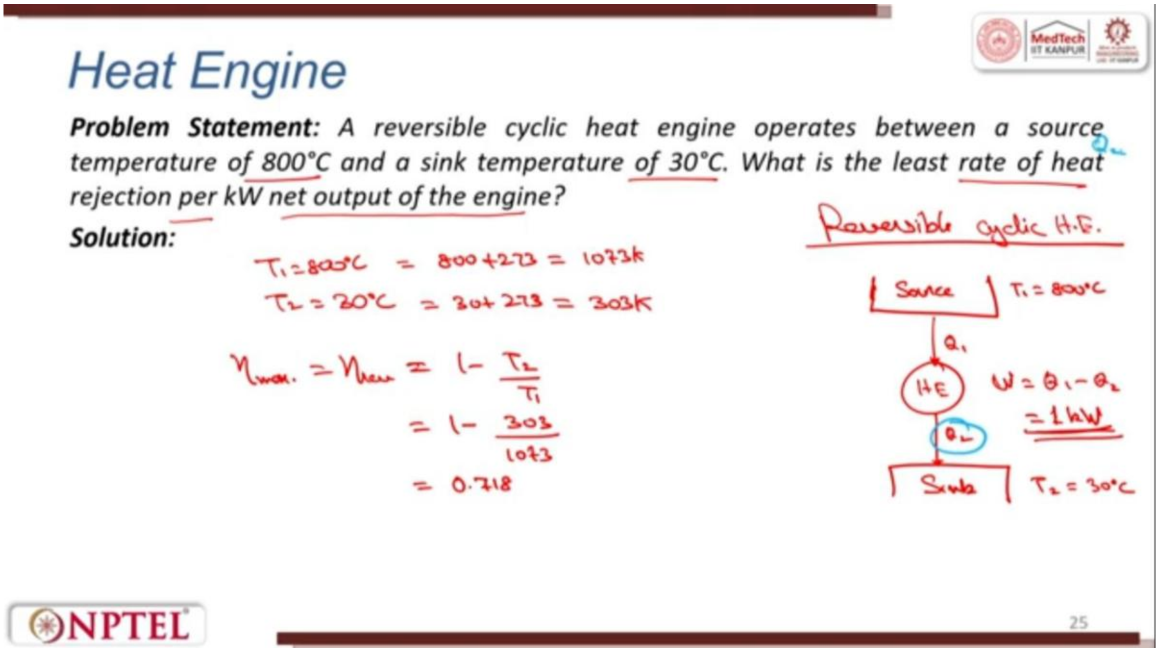
$$\eta = \frac{W_{net}}{Q_{add}} = \frac{Q_{add} - Q_{rej}}{Q_{add}}$$

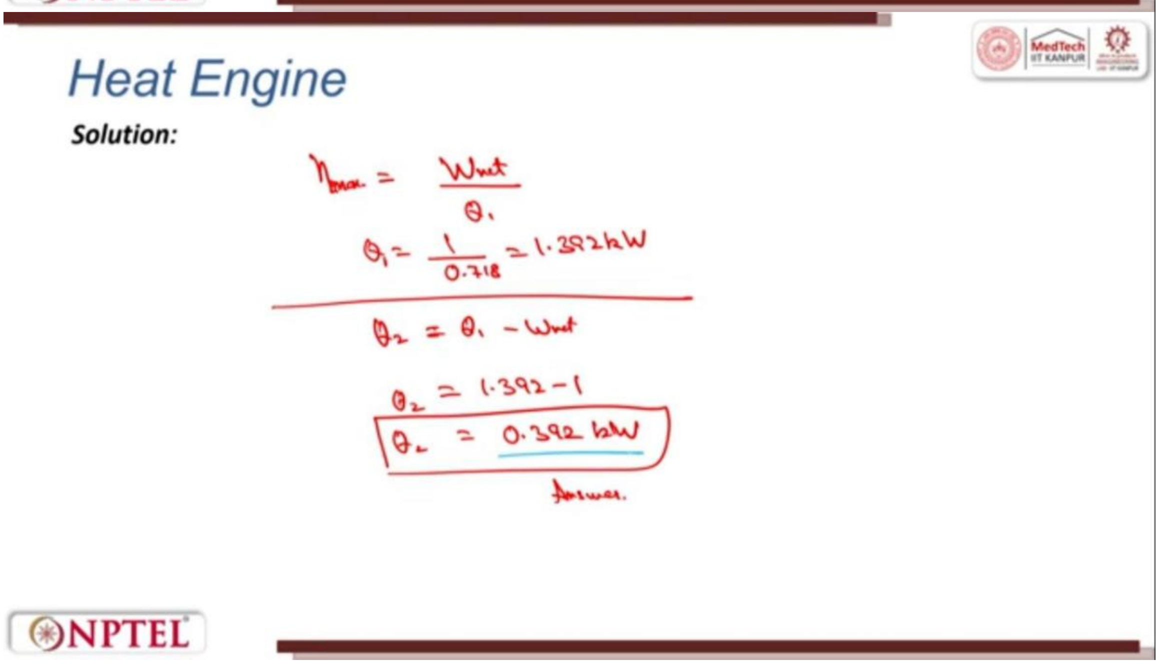
$$\eta = 1 - \frac{Q_{rej}}{Q_{add}}$$

From T-S diagram:

$$\eta = 1 - \frac{T_2(\Delta S)}{T_1(\Delta S)}$$

$$\eta = 1 - \frac{T_2}{T_1}$$





Let me see a problem on this to find the efficiency. A reversible cyclic heat engine operates between a source temperature of 800 degrees centigrade and a sink temperature of 30 degrees centigrade. What is the least rate of heat rejection per kilowatt net output of the engine? That is, they are asking for the least rate.

I need to find the efficiency, and I will try to find the value of Q2 because Q1 is almost given. That is, I will find the maximum efficiency first. Then, I will try to find the least rate of heat rejection per kilowatt of the net output of the engine. I will just quickly draw this engine here. What is the least rate of heat rejection per kilowatt net output of the engine? That is they are asking the least rate.

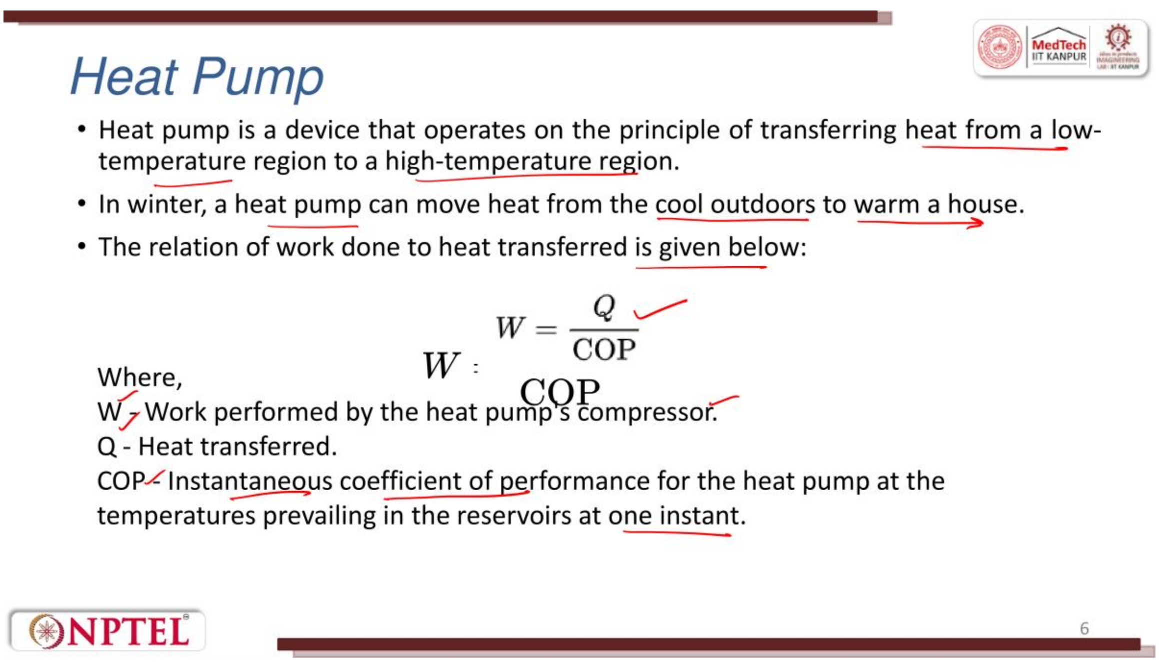
I need to find the efficiency and I will try to find the value of Q2 because Q1 is there given almost. That is I will find the maximum efficiency first. Then I will try to find the least rate of heat rejection per kilowatt of the net output of the engine. I will just quickly draw this engine here. So, it is a reversible engine where we have the hot that is source, we would say This is source. It is the hot body where the temperature is equal to 800 degree centigrade.

And we have the cold body that is sink where the temperature is 30 degree centigrade. In which we have a heat engine in between that is Q1 enters here to the heat engine and Q2 goes out of the heat engine. So W = Q1 - Q2 = 1 kilowatt. This means Q1 = 1/0.718 = 1.392 kilowatts.

Now, Q2 = Q1 minus W_{net}

Q2 = 1.392 – 1 = 0.392 kilowatts.

This is our answer.

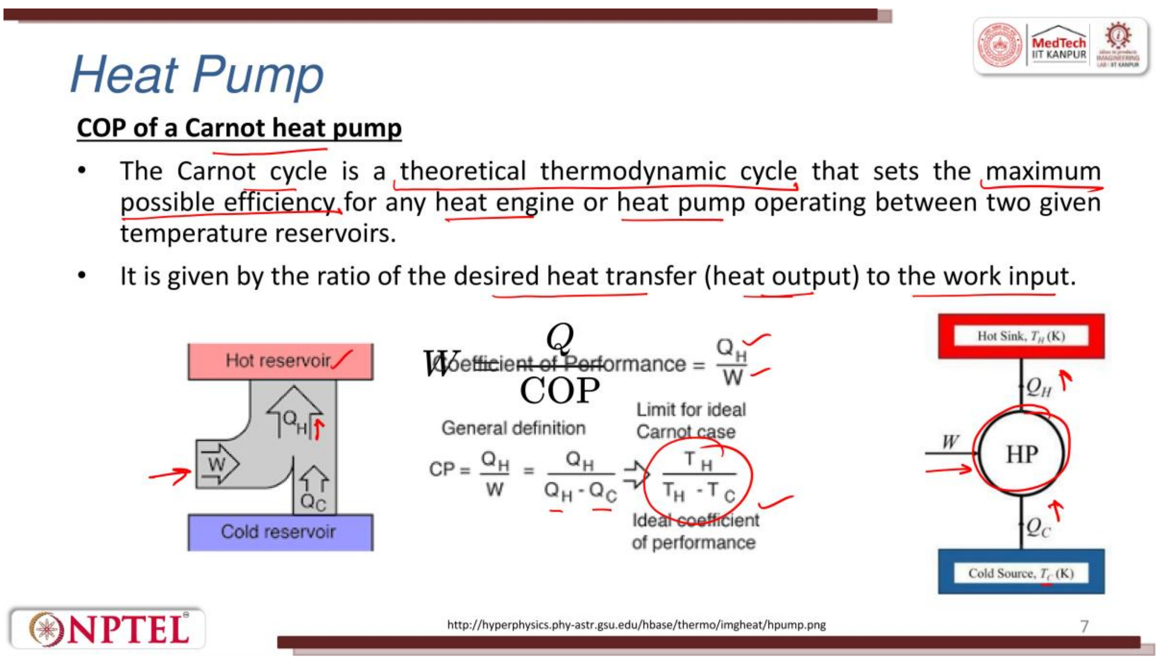


Now, let us recall the concept of a heat pump. A heat pump is a device that transfers heat from a cooler body to a hotter body. For example, your refrigerator. For example, from outside, the heat is transferred inside in winters. So, a heat pump is a device that operates on the principle of transferring heat from a low-temperature region to a high-temperature region. In winter, a heat pump can move heat from the cool outdoors to warm a house. So, work is to be done over it.

Some mechanical energy is to be put into it so that heat transfers from the lower temperature region to a higher temperature region. The relation of work done to heat transferred is given below.

$$W = \frac{Q}{\text{COP}}$$

The work performed by the heat pump's compressor is W. Q is the heat transferred. And, COP is the coefficient of performance, which is instantaneous, at a specific instant. For example, at the temperatures prevailing in the reservoir at a specific instant, this is COP, the coefficient of performance.

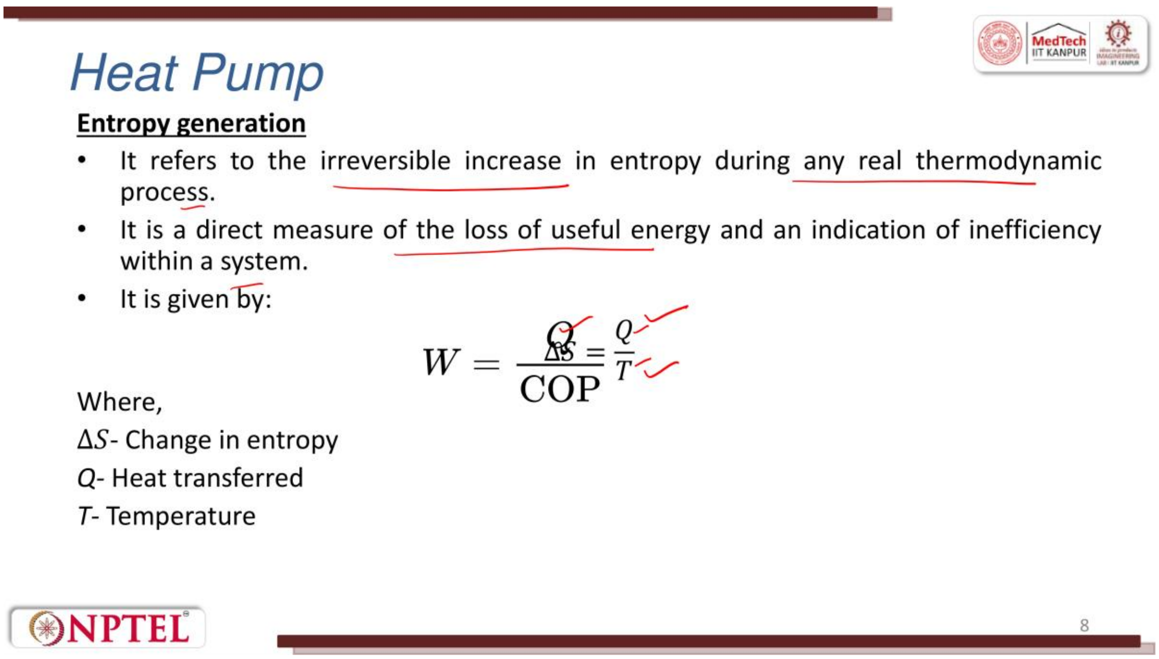


To understand the heat pump further, we can connect it to the Carnot heat pump. The Carnot cycle is a practical thermodynamic cycle that sets the maximum possible efficiency for any system, whether it is a heat engine or a heat pump, operating between two given temperature reservoirs. It is given by the ratio of the desired heat transfer, that is, the heat output to the work input. You see, some work is done from outside.

From the cold reservoir, heat is transferred to the hot reservoir. This is the heat pump in between, where work is an input. From the cooler body to the hotter body, the temperature is there. So, this is temperature cool, temperature hot. Where the coefficient of performance = Q_H/W.

That is the general definition.

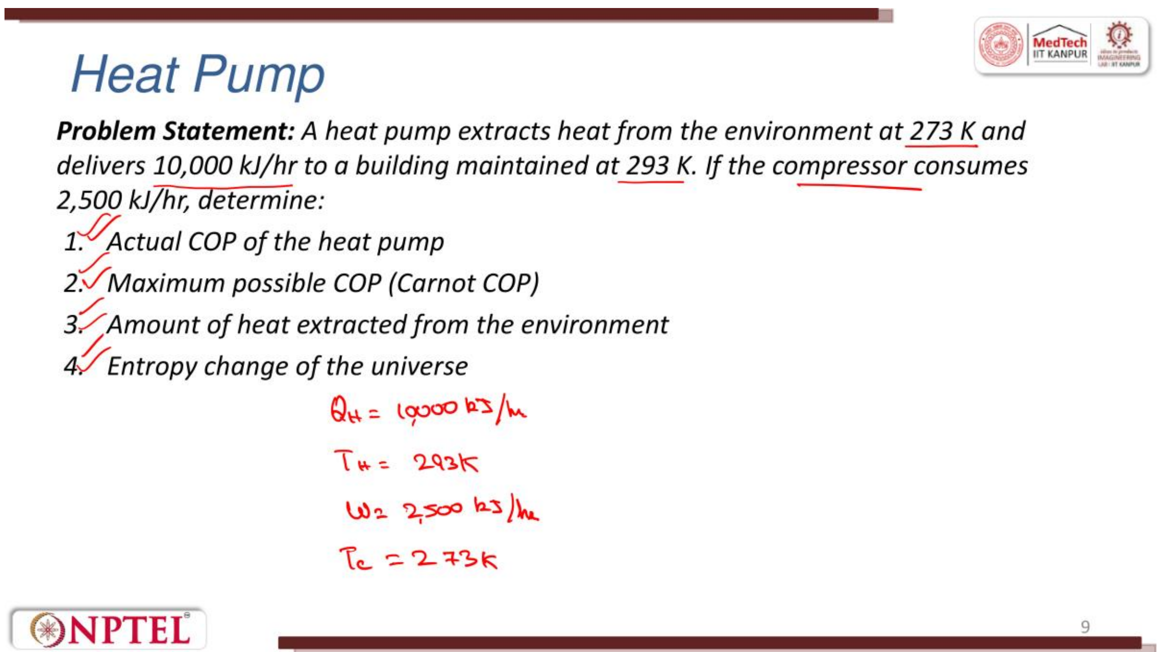
$$CP = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_C} \Rightarrow \left(\frac{T_H}{T_H - T_C} \right)$$

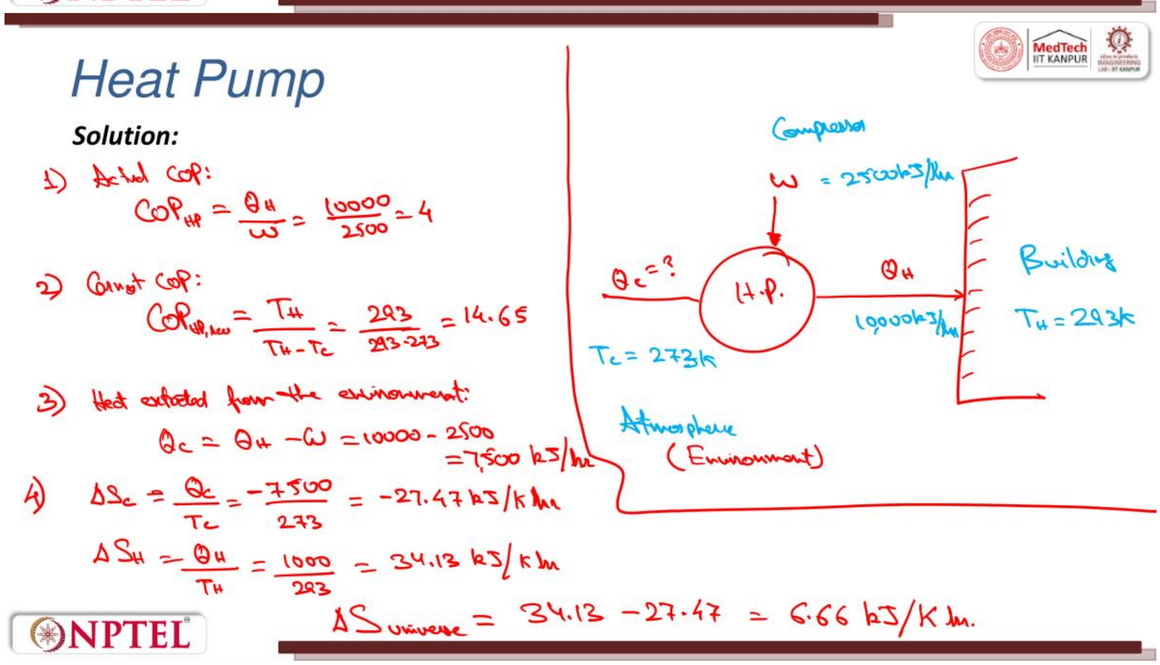


Now, in this, entropy generation is also present. It refers to the irreversible increase in entropy during any real thermodynamic process. It is a direct measure of the loss of useful energy and an indication of inefficiency within a system.

$$dS = Q/T.$$

Q is the heat transferred, and T is the temperature.

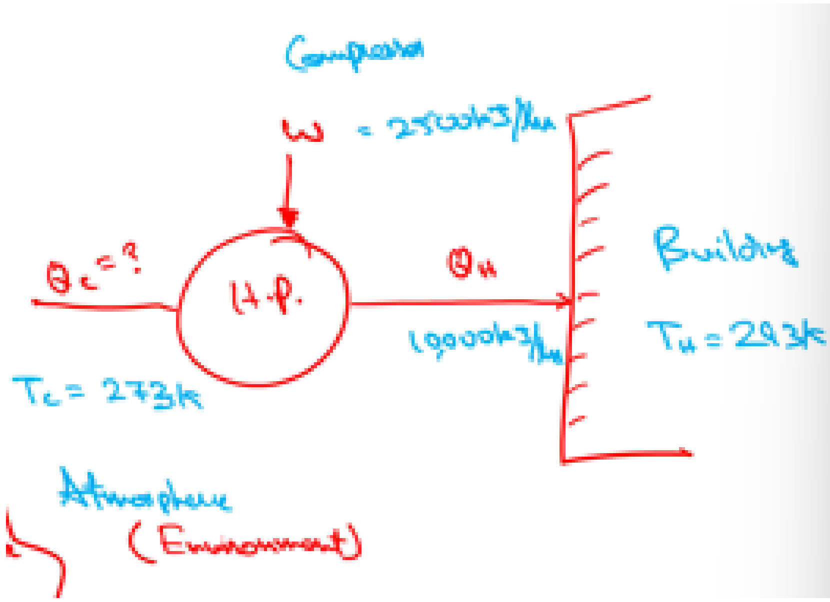




Now, let us see a problem statement here. A heat pump extracts heat from the environment at 273 Kelvin and delivers 10,000 kJ/hr to a building maintained at 293 Kelvin. If the compressor consumes 2,500 kJ/hr, determine: the actual COP of the heat pump, the maximum possible coefficient of performance (that is, the Carnot COP), the amount of heat extracted from the environment, and the entropy change of the universe. So, in this, we have been given the rate of heat transfer QH as 10,000 kJ/hr. And we have the temperatures: the hotter temperature is 293 Kelvin, and the cooler temperature Tc = 273 Kelvin.

Now, the compressor also consumes 2500 kJ/hr. What is this? When we talk about the compressor, that is the mechanical energy being induced into it. W = 2500 kJ/hr.

Let me quickly draw a heat pump system here.



1) Actual COP :

   $COP_{HP} = QH/W = 10000/2500 = 4$

2) Carnot COP:

   $COP_{HP} = \frac{Th}{Tg-TC} = \frac{293}{293-273} = 14.65$

3) Heat extracted from the environment:

   $Qc = QH - W = 10000 - 2500 = 7500$ kJ/hr

4) $dS_C = QC/TC = -7500/273 = -27.47$ kJ/hr

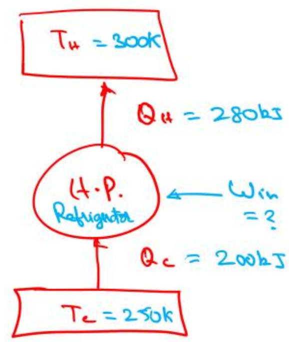
   $dS_H = QH/TH = 10000/293 = 34.13$ kJ/hr

   $dS_{universe} = 34.13 - 27.47 = 6.66$ kJ/hr

Heat Pump

Problem Statement: *A refrigerator extracts heat from a cold room at 250 K and rejects it to a room at 300 K. During each cycle, the refrigerator removes 200 kJ of heat from the cold room and rejects 280 kJ to the hot room.*

1. *Calculate the actual work input*
2. *Determine the COP of the refrigerator*
3. *Compare with the reversible COP*
4. *Determine the entropy generation per cycle*



Heat Pump

Solution: 1) Work input

$$W = Q_H - Q_C = 280 - 200 = 80\,kJ$$

2) COP of the refrigerator

$$COP = \frac{Q_C}{W} = \frac{200}{80} = 2.5$$

3) COP reversible

$$COP_{rev.} = \frac{T_C}{T_H - T_C} = \frac{250}{300-250} = 5$$

4)

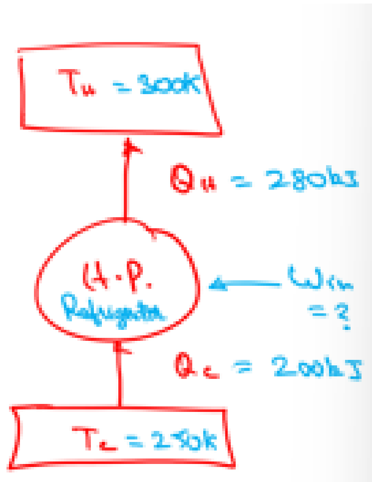
$$\Delta S_{cold} = -\frac{Q_C}{T_C} = \frac{200}{250} = -0.8\,kJ/K$$

$$\Delta S_{hot} = \frac{Q_H}{T_H} = \frac{280}{300} = 0.933\,kJ/K$$

$$\Delta S_{universe} = 0.933 - 0.8 = 0.133\,kJ/K$$

Let me see another problem regarding the refrigerator. A refrigerator extracts heat from a cold room at 250 Kelvin and rejects it to a room at 300 Kelvin. During each cycle, the refrigerator removes 200 kilojoules of heat from the cold room and rejects 280 kilojoules to the hot room.

Just to draw the heat pump once again here.



1) Work input:

   W = QH – QC = 280 – 200 = 80 kJ

2) COP of the refrigerator

   COP = QC/W = 200/80 = 2.5

3) COP Reversible:

   $COP_{rev.} = \frac{TC}{TH - TC} = \frac{250}{300-250} = 5$

4) dS_{cold} = - QC/TC = 200/250 = - 0.8 kJ/K

   dS_{hot} = QH/TH = 280/200 = 0.933 kJ/K

   $dS_{universe}$ = 0.933 – 0.8 = 0.133 kJ/K

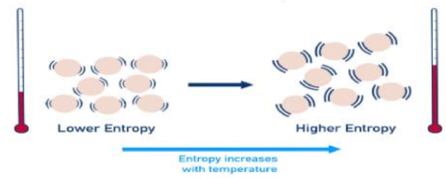
Now, I have discussed heat engines and heat pumps. I will now try to talk about entropy and exergy in a little more detail.

Entropy

- **Entropy** is a central concept in the Second Law of Thermodynamics and serves as a quantitative measure of **disorder**, **randomness**, or **energy unavailability** in a system.
- In simple terms, entropy indicates the degree of spreading or dispersal of energy. When energy is transformed—such as heat flowing from a hot body to a cold one—not all of it remains available to do useful work, and this loss is reflected by an increase in entropy.

$$W = \frac{Q}{\mathrm{COP}}$$

- In a **reversible process**, the total entropy change of the system and surroundings is zero, while in **irreversible processes**, which dominate the real world, the total entropy always increases.



Let us see or recall the concept of entropy. Entropy is a central concept in the second law of thermodynamics and serves as a quantitative measure of disorder, randomness, and energy unavailability in a system. In simple terms, entropy indicates the degree of spreading or dispersal of energy when energy is transformed, such as heat flowing from a hot body to a cold one. Not all of it remains available for useful work. There is heat rejection as well.

That is, the loss is reflected by an increase in entropy. In a reversible process, the total entropy change of the system and surroundings is zero, while in an irreversible process, which dominates the real world, the total entropy always increases. This was just a recall.

Entropy

- The third law of thermodynamics states that the entropy of a perfect crystal at absolute zero temperature (0 Kelvin) is zero. Therefore, the absolute entropy at any temperature T is calculated by integrating the heat capacity at constant pressure.

$$S(T) = \int_0^T \frac{C_p}{T}\, dT$$

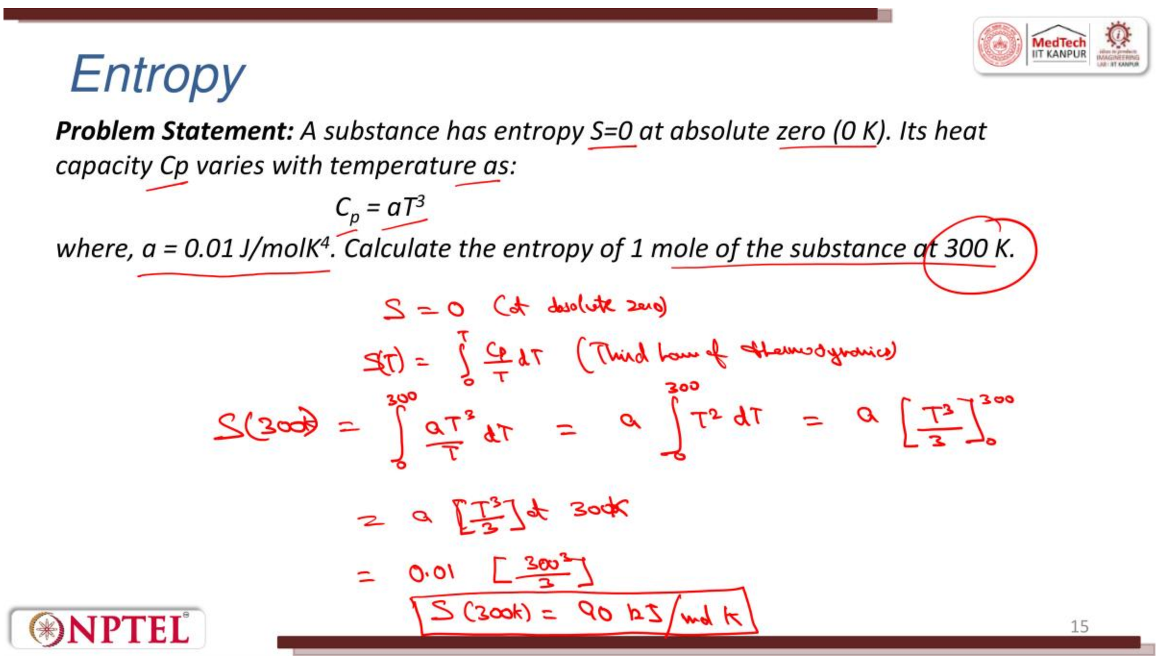
$$W = \frac{Q}{\mathrm{COP}}$$

- *S(T)* - Absolute entropy at temperature
- C_p - Heat capacity at constant pressure
- The integral represents the summation of heat capacity changes as the temperature increases from 0 K to T.

Just to recall, how do we calculate the entropy?

$$S(T) = \int_0^T \frac{C_p}{T}\, dT$$

That is, Cp is the heat capacity at constant pressure. S(T) here, that is being calculated, is the absolute entropy. The third law of thermodynamics states that the entropy of a perfect crystal at absolute zero temperature (0 Kelvin) is zero. So, therefore, the absolute entropy is integrated from 0 to T, where T is the temperature at which it is being determined.



Let me try to see this problem.

S (T) = $\int_0^T \frac{Cp}{T} dT$ (Third law of thermodynamics)

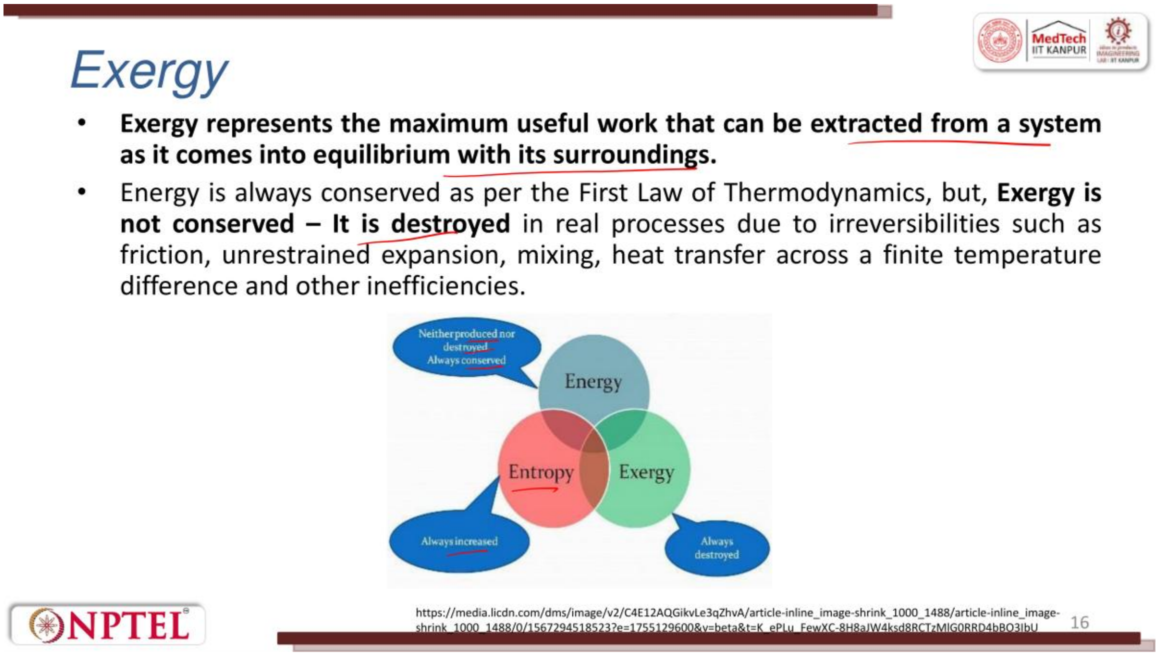
S (300) = $\int_0^{300} \frac{aT^3}{T} dT$ = a $\int_0^{300} T^2\, dT = a\ \left[\frac{T^3}{3}\right]_0^{300}$

a $a\ \left[\frac{T^3}{3}\right]$ at 300 K

0.01 [300^3/3]

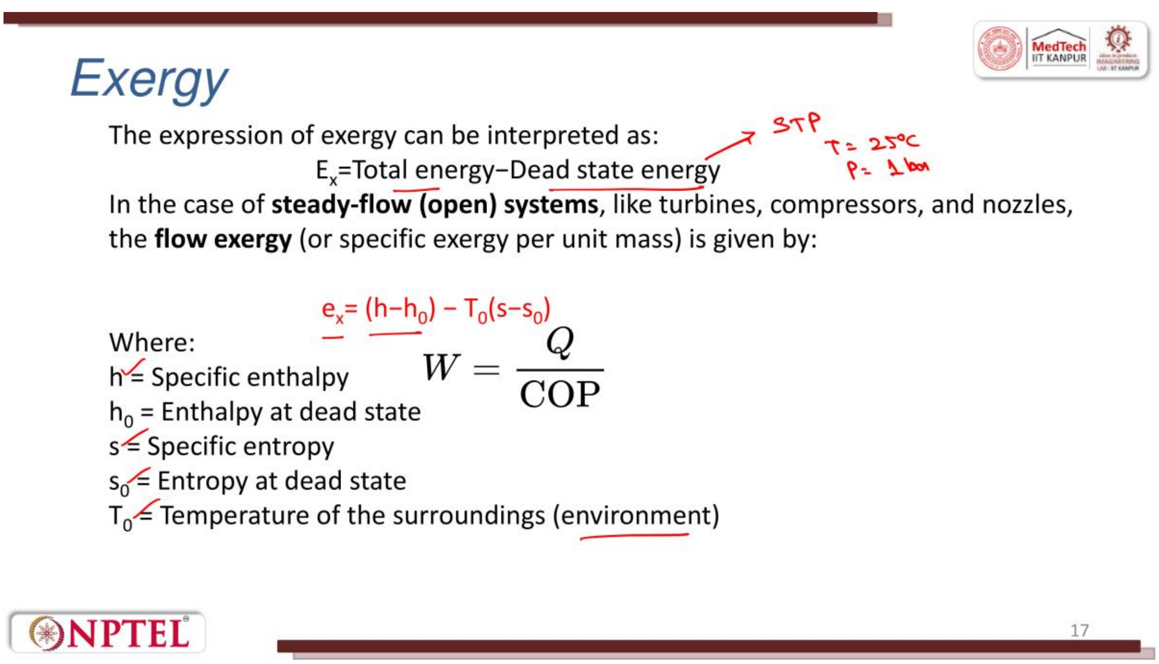
S (300K) = 90 kJ/ mol K

This was a simple problem on entropy.



So, just to recall the concept of exergy as well, exergy represents the maximum useful work that can be extracted from a system as it comes into equilibrium with its surroundings. Energy is always conserved by the first law of thermodynamics, but exergy is not conserved as it is destroyed. And you have seen this in the lecture series as well. Exergy, energy.

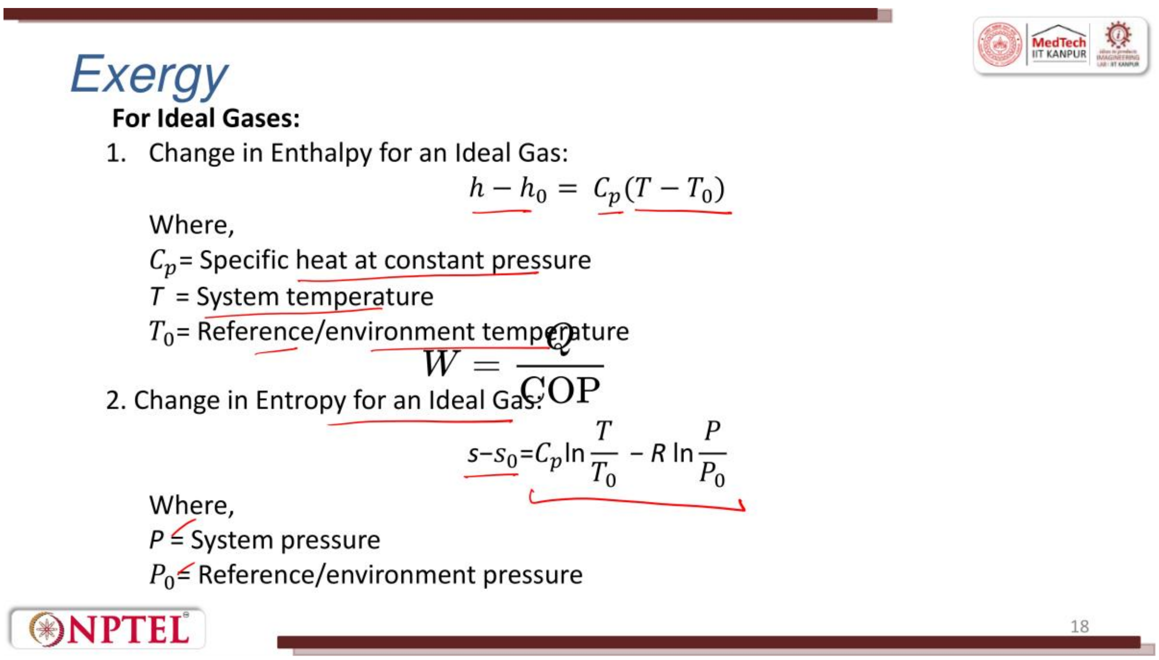
And entropy—they all come together. Entropy always increases. Energy can neither be produced nor destroyed. It is always conserved. But exergy is something that is always destroyed. Not going into the concepts in detail.



I'll just try to see how we calculate exergy. The total energy minus dead state energy is the exergy. Dead state means we are talking about standard temperature and pressure. That is, temperature as 25 degrees centigrade and pressure as 1 bar.

That is the dead state. In the case of steady flow, that is, open systems like turbines, compressors, and nozzles, the flow exergy or specific exergy per unit mass is given by $e_x = (h - h_0) - T_0(s - s_0)$ H is the specific enthalpy. h0 is the enthalpy at a dead state.

S is the specific entropy. And S0 is the entropy at a dead state. T0 is the temperature of the surroundings. That is the environment when we are talking about a dead state. Let me try to see.

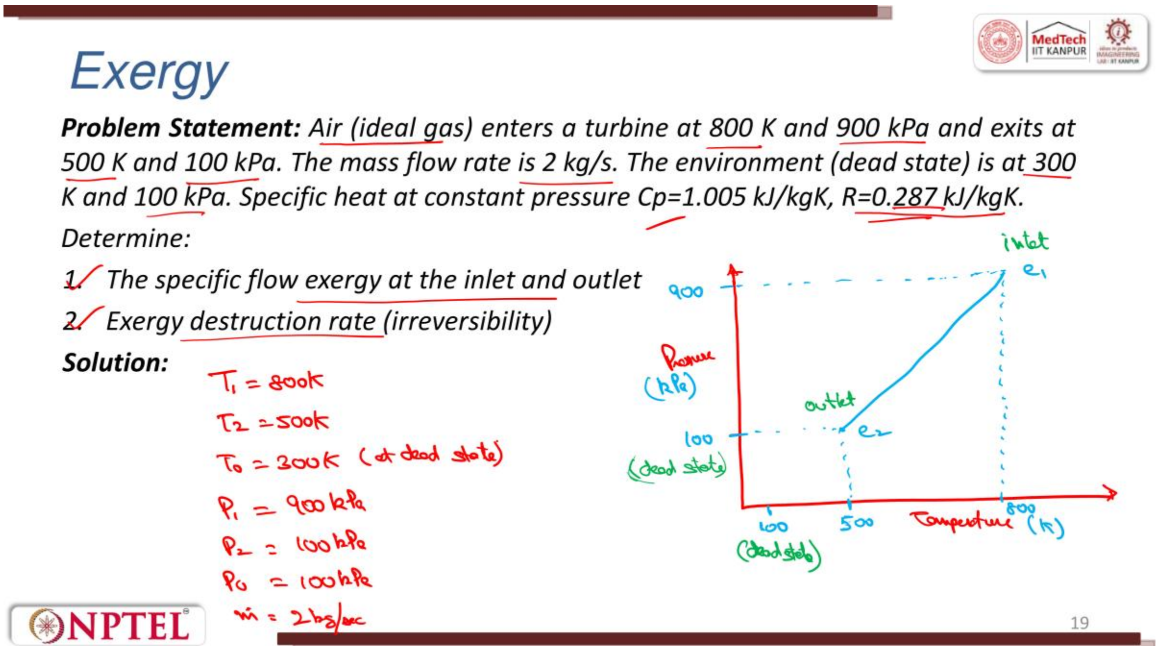


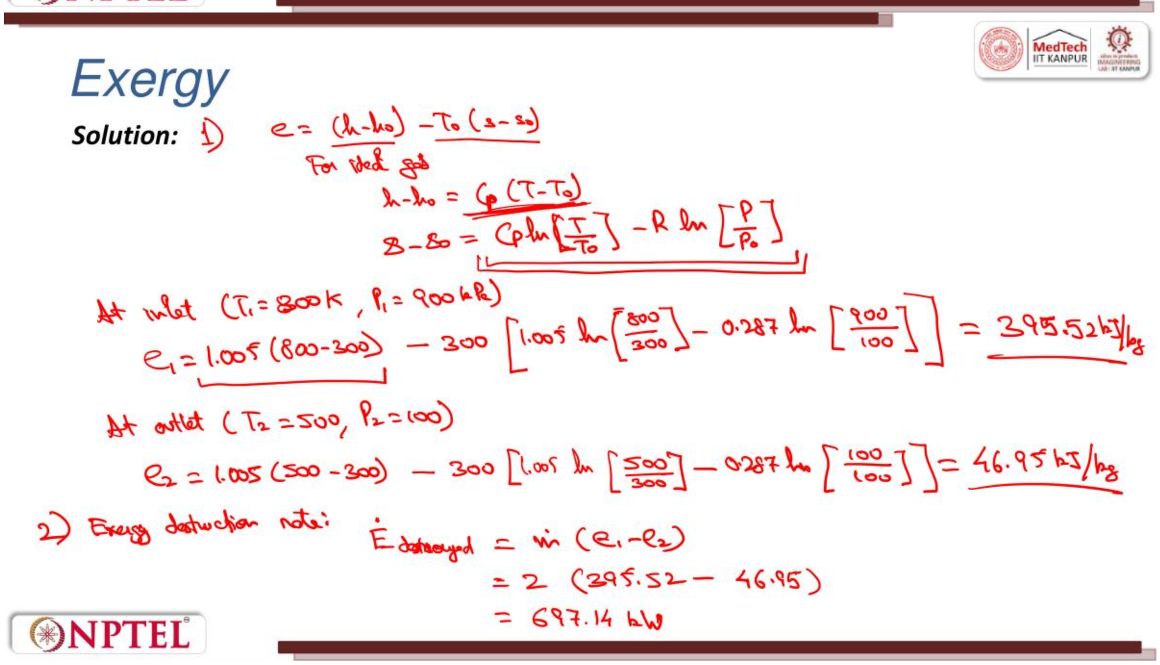
For an ideal gas, $h - h_0 = C_p(T - T_0)$ Cp is the specific heat at constant pressure. T is the system temperature. T0 is the reference temperature.

That is, in general, the environmental temperature. And the change in entropy, that is,

$$s - s_0 = C_p \ln \frac{T}{T_0} - R \ln \frac{P}{P_0}$$

Where P and P0 are the system pressure and the reference environmental pressure.





Let us see a problem on exergy. Here, an ideal gas enters a turbine at 800 Kelvin and 900 kilopascals.

It exits at 500 Kelvin and 100 kilopascals. The mass flow rate is 2 kg per second. The environment, that is, the dead state, is at 300 Kelvin and 100 kilopascals. The specific heat at constant pressure, that is, CP, is 1.005 kilojoules per kg Kelvin.

And the value of R is also given here as 0.287 kg. That is, kilojoules per kilogram Kelvin. Determine the specific flow of exergy at the inlet and outlet. Exergy destruction rate, that is, irreversibility. So, we have been given here the temperature T_1 as 800 Kelvin and T_2 as 500 Kelvin.

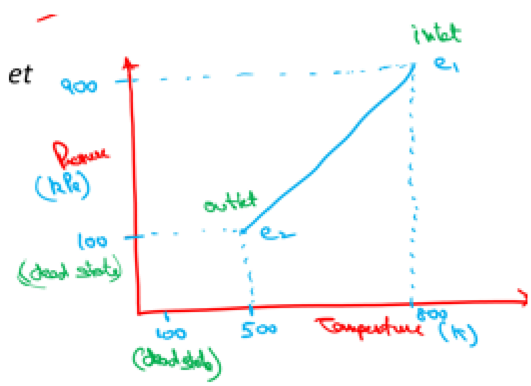
And, T_0 is 300 Kelvin, which is STP, that is at dead state. Pressure P_1 is 900 kilopascal. P_2 is 100 kilopascal. And P_0 is 100 kilopascal, again. Also, we have been given the value of CPR, and m dot is also given as 2 kg per second.

Now, just to try to draw the exergy of a system—though exergy is not generally drawn—I will still try to draw the pressure and temperature. At the pressure of 100 kilopascal. This is 100 kilopascal. And the temperature is 500 Kelvin. We will put here as 500.

This is temperature in Kelvin. This is 500 Kelvin, and we have 800 Kelvin somewhere. We have 100 Kelvin as well, somewhere here. Here, we have a point from which it starts. That is exergy.

That is being destroyed. And from 100 kilopascal pressure, it goes to 900 kilopascal pressure. 900 and 800. Here, we can find a point that comes here at 800. This is where it goes. So, this is e1 and e2. This is where we have the inlet, and this is the outlet. And here, we have the dead state at 100.

Here also, the pressure dead state is 100 kilopascal. At 100 Kelvin also, we have the dead state. Now, the first part that is asked in the question is the specific flow exergy at the inlet and outlet.



1) $e = (h - h_0) - T_0 (s - s_0)$

For ideal gas,

$h - h_0 = C_p (T - T_0)$

$s - s0 = Cp \ In\ [T/T0] - R\ In\ [P/P0]$

At inlet (T1 = 800 K, P1 = 900 kPa)

$e1 = 1.005\ (800 - 300) - 300\ [1.005\ In\ [800/300] - 0.287\ In\ [900/100]]$

$= 395.52$ kJ/kg

At outlet (T2 = 500, P2 = 100)

$e2 = 1.005\ (500 - 300) - 300\ [1.005\ In\ [500/300] - 0.287\ In\ [100/100]]$

$= 46.95$ kJ/kg

2) Exergy destruction rate:

$E^{\circ}_{destroyed} = m^{\circ}\ (e1 - e2)$

$= 2\ (395.52 - 46.95)$

$= 697.14$ kW

This was one more problem in exergy. With this, I'm closing my tutorial on the first two weeks of the course. I will come up with more tutorials in the coming sessions. And also, I will try to talk about the virtual laboratory demonstration on thermodynamics. Then, we'll close the thermodynamics.

We'll move to fluid mechanics. Thank you.