Homework #5

MEMS 0051 - Introduction to Thermodynamics

Assigned February 16$^{\text{th}}$, 2019
Due: February 22$^{\text{nd}}$, 2019

Problem #1

A gasoline engine produces 15 hp using 40 kW of heat transfer from burning fuel. What is its thermal efficiency, and how much power is rejected to the ambient surroundings

$$\dot{W} = 15 \text{ [hp]} = 11.1855 \text{ [kW]}$$

$$\dot{Q}_h = 40 \text{ [kW]}$$

$$\eta_{th} = 100\%\Big(\frac{\dot{W}}{\dot{Q}_h}\Big) = 100\%\Big(\frac{11.1855 \text{ [kW]}}{40 \text{ [kW]}}\Big) \implies$$

$$\eta_{th} = \boxed{27.964\%}$$

$$\dot{Q}_l = \dot{Q}_h - \dot{W} = 40 \text{ [kW]} - 11.1855 \text{ [kW]} \implies$$

$$\dot{Q}_l = \boxed{28.815 \text{ [kW]}}$$

Problem #2

A window air-conditioner unit is placed on a laboratory bench and tested in cooling mode using 750 [W] of electric power with a COP of 1.75. What is the cooling power capacity, and what is the net effect on the laboratory?

$$\dot{W}_{in} = 750 \text{ [W]} \quad \beta = 1.75$$

$$\beta = \frac{\dot{Q}_l}{\dot{W}_{in}} \implies \dot{Q}_l = (1.75)(750 \text{ [W]}) =$$

Cooling capacity:

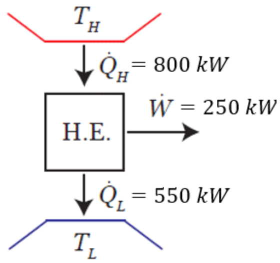
$$\dot{Q}_l = \boxed{1,312.5 \text{ [W]}}$$

The net effect on the laboratory:
750 [W] of energy must be extracted from the laboratory in the form of electricity
or some other energy to remove heat from the room at a rate of 1,312.5 [W].

Problem #3

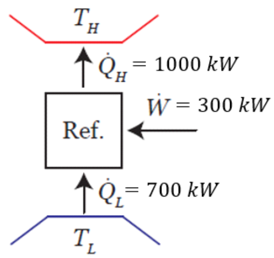
For each of the following devices, draw a schematic that labels and quantifies all of the energy flows ($\dot{W}$,$\dot{Q}_H$, $\dot{Q}_L$) between two thermal reservoirs (T_H,T_L). Then calculate the correct metric of performance (η, β, or β') for each device.

a) A heat engine that converts 800 [kW] of heat into 250 [kW] of power.



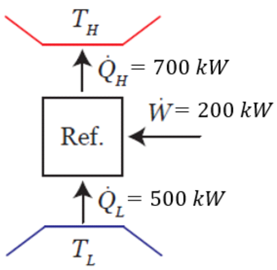
$$\eta = \frac{\dot{W}}{\dot{Q}_H} = \frac{250\,[\text{kW}]}{800\,[\text{kW}]} = 0.3125$$

b) A refrigerator with a power input of 300 [kW] that rejects 1000 [kW] of heat to the environment.



$$\beta = \frac{\dot{Q}_L}{\dot{W}} = \frac{700\,[\text{kW}]}{300\,[\text{kW}]} = 2.33$$

c) A heat pump that takes in 500 [kW] of heat and outputs 700 [kW] of heat.



$$\beta' = \frac{\dot{Q}_H}{\dot{W}} = \frac{700\,[\text{kW}]}{200\,[\text{kW}]} = 3.5$$

Problem #4

Consider a heat engine and heat pump connected as shown in Fig. 1. Assume $T_{H1} = T_{H2} > T_{amb}$. For each case, determine if the setup satisfies the first law and/or violates the second law. (*Note:* Be sure to indicate which postulate(s), if applicable, are violated by the second law)

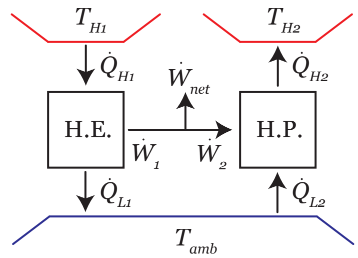


Figure 1: Schematic for Problem #4.

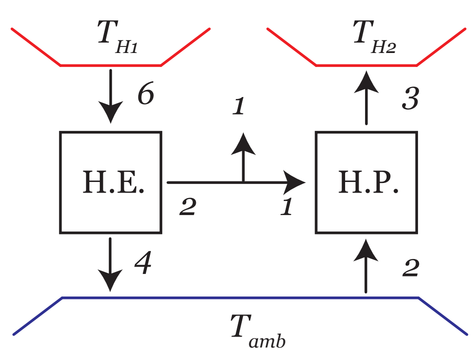
	$\dot{Q}_{H1}$	$\dot{Q}_{L1}$	$\dot{W}_1$	$\dot{Q}_{H2}$	$\dot{Q}_{L2}$	$\dot{W}_2$
Case 1	6	4	2	3	2	1
Case 2	6	4	2	5	4	1
Case 3	3	2	1	4	3	1

To determine if the system adheres to the first and second law of thermodynamics, it must be shown that the system- its components and the whole system- abides by the principals and postulates that define said laws. For the sake of this problem, we will us units of [J] to represent the numbers.
(*Note: units of power or energy do not matter as long as they are the same for all components*)

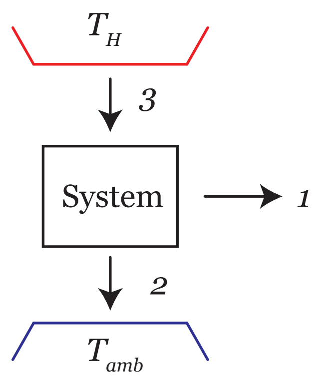
First Law of Thermodynamics: Conservation of energy in a system.
Second Law of Thermodynamics:

1. Kelvin-Planck Statement: All energy transferred from a high temperature reservoir can not turn into output work.
2. Clasius Statement: Heat can not transfer from a cold temperature reservoir without external work applied.

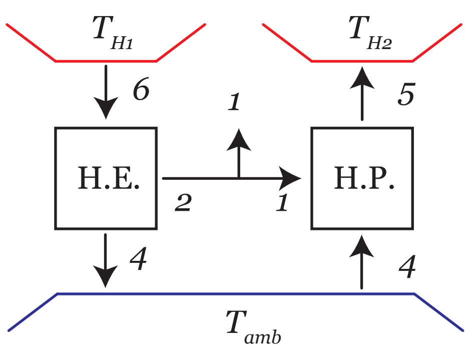
Case 1:



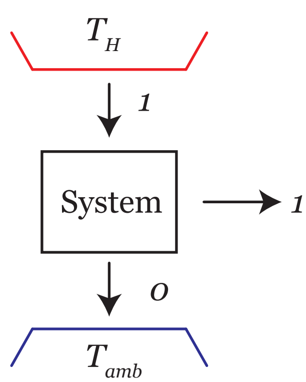
Heat Engine (H.E): The heat engine takes in 6 [J] of energy from the hot temperature reservoir, rejects 4 [J] into the cold temperature reservoir and produces 2 [J] work. Here, the first law and the Kelvin-Planck postulate of the second law is satisfied.
Heat Pump (H.P): The heat pump takes in 2 [J] of energy from the cold temperature reservoir, rejects 3 [J] into the hot temperature reservoir and uses 1 [J] of work to do this. Here, the first law and the Clausius postulate of the second law is satisfied.
System: The whole system takes in a net 3 [J] of energy from the hot temperature reservoir, rejects a net 2 [J] into the cold temperature reservoir and produces 1 [J] of net work. Here, the first law and the Kelvin-Planck postulate of the second law is satisfied



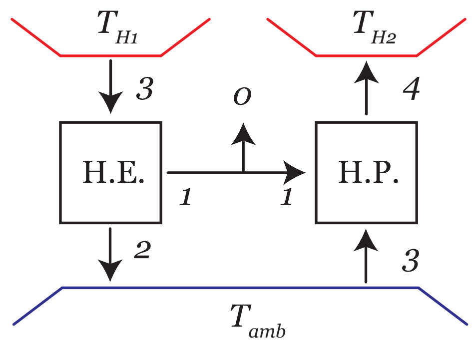
Case 2:



Heat Engine (H.E): The heat engine takes in 6 [J] of energy from the hot temperature reservoir, rejects 4 [J] into the cold temperature reservoir and produces 2 [J] work. Here, the first law and the Kelvin-Planck postulate of the second law is satisfied.
Heat Pump (H.P): The heat pump takes in 4 [J] of energy from the cold temperature reservoir, rejects 5 [J] into the hot temperature reservoir and uses 1 [J] of work to do this. Here, the first law and the Clausius postulate of the second law is satisfied.
System: The whole system takes in a net 1 [J] of energy from the hot temperature reservoir, rejects 0 [J] into the cold temperature reservoir and produces 1 [J] of net work. Here, the first law is satisfied, but the Kelvin-Planck postulate of the second law is violated.



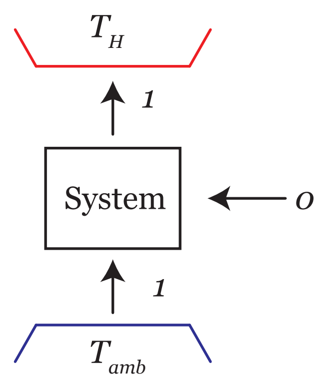
Case 3:



Heat Engine (H.E): The heat engine takes in 3 [J] of energy from the hot temperature reservoir, rejects 2 [J] into the cold temperature reservoir and produces 1 [J] work. Here, the first law and the Kelvin-Planck postulate of the second law is satisfied.

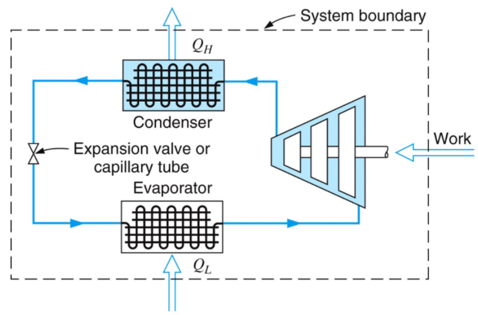
Heat Pump (H.P): The heat pump takes in 3 [J] of energy from the cold temperature reservoir, rejects 4 [J] into the hot temperature reservoir and uses 1 [J] of work to do this. Here, the first law and the Clausius postulate of the second law is satisfied.

System: The whole system takes in a net 1 [J] of energy from the cold temperature reservoir and rejects 1 [J] into the cold temperature reservoir. While it may appear that no work was applied to perform the operation, keep in mind that 1 [J] of work was taken from the heat engine within the system to perform this operation. In other words, the system is powering itself and not producing any net work for other use. Therefore, it can be said that the Clausius postulate is still satisfied along with the first law of thermodynamics.



Problem #5

Consider the refrigeration cycle shown below, where a refrigerant cycles through a compressor, an evaporator, an expansion valve, and a condenser. The compressor requires an electrical input, the evaporator removes heat from the inside of the refrigerator, and the condenser rejects heat to the air in the room.



a) What are some sources of irreversibility in this cycle? List at least two.
   i) Heat transfer - there must be a finite temperature difference at the evaporator and the compressor in order for heat to be transferred into and out of the system. This results in irreversibility at both locations of heat transfer.
   ii) Compression & expansion - the compression and expansion of the refrigerant (across the compressor and the expansion valve, respectively) results in irreversible losses.
   iii) Friction - anytime you have a liquid flowing through pipes, there are frictional losses at the inner pipe walls, resulting in irreversibility.

b) What are some modifications you could make to this system to make it more reversible? Describe at least two modifications.
   i) Reduce temperature drops for heat transfer - make the temperature differences smaller between the condenser and the environment and between the inside of the refrigerator and the evaporator. This will result in slower heat transfers, but will reduce irreversibility.
   ii) Reduce the refrigerant flow-rate - flowing the refrigerant more slowly through the system will result in reduced friction and compression/expansion losses. However, it will also reduce the rate at which heat can be removed from the refrigerator.