THE SECOND LAW OF THERMODYNAMICS

It can be started that, according to the first law of thermodynamics, **when a system undergoes a complete cycle then the net heat supplied is equal to the net work done**. This is based on the conservation of energy principle, which follows from observation of natural events. The second law came up as embodiment of real happenings while retaining the basic nature of the first law of thermodynamics. Feasibility of process, direction of process and grades of energy such as low and high are the potential answers provided by the 2nd law. The second law of thermodynamics is capable of indicating the maximum possible efficiencies of heat engines, coefficient of performance of heat pumps and refrigerators, defining a temperature scale independent of physical properties etc.

The first law places no restriction on the direction of a process, but satisfying the first law does not ensure that the process can actually occur. This inadequacy of the first law to identify whether a process can take place is remedied by introducing another general principle, the second law of thermodynamics.

The use of the second law of thermodynamics is not limited to identifying the direction of processes, however. The second law also asserts that energy has quality as well as quantity. The first law is concerned with the quantity of energy and the transformations of energy from one form to another with no regard to its quality. Preserving the quality of energy is a major concern to engineers, and the second law provides the necessary means to determine the quality as well as the degree of degradation of energy during a process. Higher-temperature energy can be converted to work, and thus it has a higher quality than the same amount of energy at a lower temperature. The second law of thermodynamics is also used in determining the theoretical limits for the performance of commonly used engineering systems, such as heat engines and refrigerators, as well as predicting the degree of completion of chemical reactions.

The Second Law of thermodynamics, which is also a natural law, indicates that, although the net heat supplied in a cycle is equal to the net work done, **the gross heat supplied must be greater than the net work done**; some heat must always be rejected by the system. This law can be understood by considering the heat pump and heat engine.

THERMAL ENERGY RESERVOIRS

A thermal reservoir is defined as a sufficiently large system in stable equilibrium to which and from which a finite amount of heat can be transferred without any change in its temperature.

Heat source is a high temperature reservoir such as: boiler, furnace, combustion chamber, nuclear reactor, the sun, etc.

Heat sink: is a low temperature reservoir such as: condenser, atmospheric air, river water, ocean, etc.

HEAT ENGINE

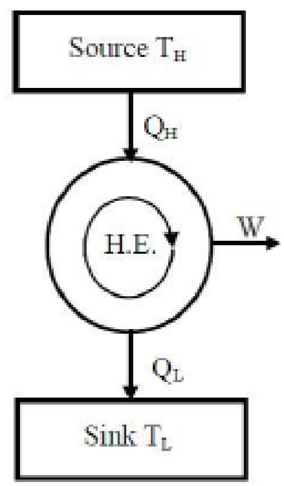
It is defined as the system operating in a complete cycle and developing a network from a supply of heat. The second law implies a source of heat and sink of heat are both necessary. Let the heat supplied from the source be (Q_H), let the heat rejected to the sink be (Q_L) and let the net work done by the engine be (W). apply the first law of thermodynamics:

$$\Sigma\, dQ = \Sigma\, dW$$

$$Q_H - Q_L = W$$

According to the second law the gross heat supplied must be greater than the network.

$$Q_H > W$$



$T_H > T_L$

Heat Engine

It can be seen that a temperature difference is always required for heat to flow; therefore, the source must be at higher temperature than the sink.

The thermal efficiency is defined as the ratio of the net work done during the cycle to gross heat supplied during the cycle.

$$\eta = \frac{W_{net,out}}{Q_H} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

$$W_{net,out} = Q_H - Q_L$$

Where:
Q_H: magnitude of heat transfer between the cyclic device and the hightemperature medium at temperature (T_H).
Q_L: magnitude of heat transfer between the cyclic device and the lowtemperature medium at temperature (T_L).
The thermal efficiency of a heat engine is always less than 100%.

Example (1): Heat is transferred to a heat engine from a furnace at a rate of (80 MW). If the rate of waste heat rejection to a nearby river is (50 MW), determine the net power output and the thermal efficiency for this heat engine.

Solution:

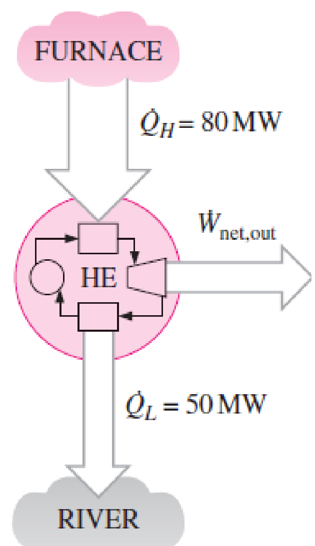
The net power output of this heat engine is

$$W_{net,out} = Q_H - Q_L = 80 - 50 = 30\ MW$$

Then the thermal efficiency is easily determined to be

$$\eta = \frac{W_{net,out}}{Q_H} = \frac{30}{80}$$

$$\eta = 0.375 = 37.5\ \%$$



REFRIGERATORS AND HEAT PUMPS

Refrigerators, like heat engines, are cyclic devices. The working fluid used in the refrigeration cycle is called a refrigerant. The most frequently used refrigeration cycle is the vapor-compression refrigeration cycle, which involves four mains

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components: a compressor, a condenser, an expansion valve, and an evaporator, as shown in Figure (1).

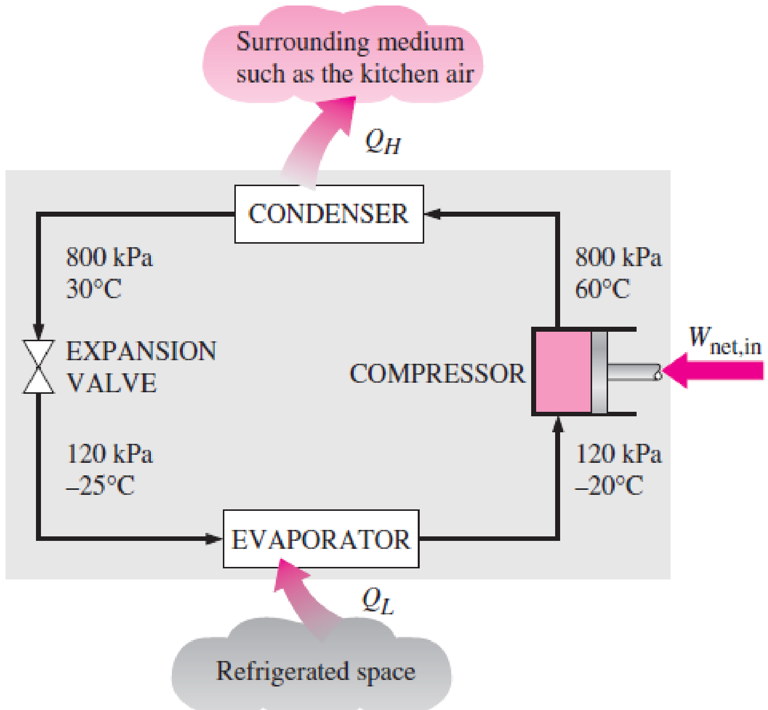

Figure (1) Basic components of a refrigeration system and typical operating conditions.

A refrigerator is shown schematically in Figure (2). Here (Q_L) is the magnitude of the heat removed from the refrigerated space at temperature (T_L), (Q_H) is the magnitude of the heat rejected to the warm environment at temperature (T_H), and ($W_{net,in}$) is the network input to the refrigerator. (Q_L) and (Q_H) represent magnitudes and thus are positive quantities.

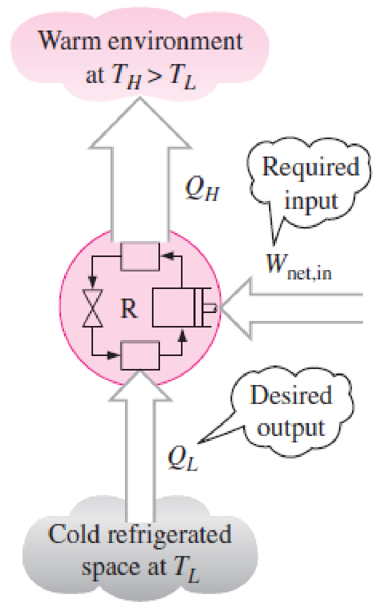

Figure (2) The objective of a refrigerator is to remove Q_L from the cooled space.

The efficiency of a refrigerator is expressed in terms of the coefficient of performance (COP), denoted by (COP_R). the COP of a refrigerator can be expressed as:

$$COP_R = \frac{Desired\ output}{REquired\ input} = \frac{Q_L}{W_{net,in}}$$

$$W_{net,in} = Q_H - Q_L$$

$$COP_R = \frac{Q_L}{QH - QL} = \frac{1}{\frac{Q_H}{Q_L} - 1}$$

Notice that the value of (COP_R) can be greater than unity.

Heat Pumps:

Another device that transfers heat from a low temperature medium to a high temperature one is the heat pump, shown schematically in Figure (3).

The measure of performance of a heat pump is also expressed in terms of the coefficient of performance (COP_{HP}), defined as:

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$$COP_{HP} = \frac{Desired\ output}{REquired\ input} = \frac{Q_H}{W_{net,in}}$$

$$W_{net,in} = Q_H - Q_L$$

$$COP_{HP} = \frac{Q_H}{QH - QL} = \frac{1}{1 - \frac{Q_L}{Q_H}}$$

(COP) values of a heat pump and a refrigerator can be interrelated as:

$$COP_{HP} = COP_R + 1$$

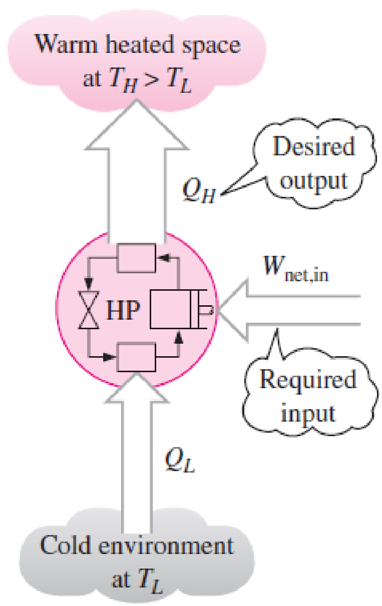


Figure (3) The objective of a heat pump is to supply heat Q_H into the warmer space.

Example (2): The food compartment of a refrigerator, is maintained at (4 °C) by removing heat from it at a rate of (360 kJ/min). If the required power input to the refrigerator is (2 kW), determine (*a*) the coefficient of performance of the refrigerator and (*b*) the heat rejection to the room that houses the refrigerator.

Solution:

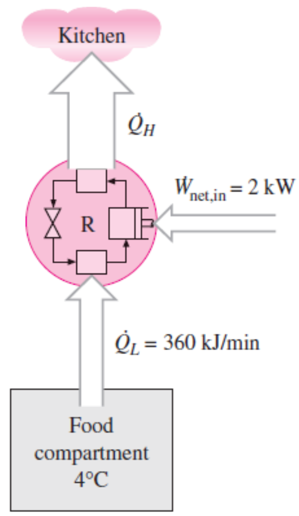
$$Q_L = \frac{360\ KJ/min}{60} = 6\ KJ/s = 6\ KW$$

$$COP_R = \frac{Q_L}{W_{net,in}} = \frac{6}{2} = 3$$

$$W_{net,in} = Q_H - Q_L$$

$$2 = Q_H - 6$$

$$Q_H = 8\ KW$$



Example (3): A heat pump is used to meet the heating requirements of a house and maintain it at (20 °C). On a day when the outdoor air temperature drops to (- 2 °C), the house is estimated to lose heat at a rate of (80,000 kJ/h). If the heat pump under these conditions has a COP of (2.5), determine (*a*) the power consumed by the heat pump and (*b*) the rate at which heat is absorbed from the cold outdoor air.

Solution:

$$Q_H = \frac{80000\ KJ/hr}{3600} = 22.2\ KJ/s = 22.2\ KW$$

$$COP_{HP} = \frac{Q_H}{W_{net,in}} \Rightarrow 2.5 = \frac{22.2}{W_{net,in}}$$

$$W_{net,in} = 8.9\ KW$$

$$\dot{W}_{net,in} = \dot{Q}_H - \dot{Q}_L$$

$$8.9 * 3600 = 80000 - \dot{Q}_L$$

$$\dot{Q}_L = 48000\ KJ/hr$$

HOMEWORK

1- A (600 MW) steam power plant, which is cooled by a nearby river, has a thermal efficiency of 40 percent. Determine the rate of heat transfer to the river water. Ans. 900 MW.

2- A steam power plant receives heat from a furnace at a rate of (280 GJ/h). Heat losses to the surrounding air from the steam as it passes through the pipes and other components are estimated to be about (8 GJ/h). If the waste heat is transtransferred to the cooling water at a rate of (145 GJ/h), determine (*a*) net power output and (*b*) the thermal efficiency of this power plant.

Ans. (a) 35.3 MW, (b) 45.4 %

3- A household refrigerator with a COP of (1.2) removes heat from the refrigerated space at a rate of (60 kJ/min). Determine (*a*) the electric power consumed by the refrigerator and (*b*) the rate of heat transfer to the kitchen air.

Ans. (a) 0.83 kW, (b) 110 kJ/min

4- An air conditioner removes heat steadily from a house at a rate of (750 kJ/min) while drawing electric power at a rate of (6 kW). Determine (*a*) the COP of this air conditioner and (*b*) the rate of heat transfer to the outside air.

Ans. (a) 2.08, (b) 1110 kJ/min.

5- Determine the COP of a refrigerator that removes heat from the food compartment at a rate of (5040 kJ/h) for each kW of power it consumes. Also, determine the rate of heat rejection to the outside air. Ans. 1.4, 8640 KJ/hr.

6- Determine the COP of a heat pump that supplies energy to a house at a rate of (8000 kJ/h) for each kW of electric power it draws. Also, determine the rate of energy absorption from the outdoor air.

Ans. 2.22, 4400 kJ/h.

7- A heat pump is used to maintain a house at a constant temperature of (23 °C). The house is losing heat to the outside air through the walls and the windows at a rate of (60,000 kJ/h) while the energy generated within the house from people, lights, and appliances amounts to (4000 kJ/h). For a COP of (2.5), determine the required power input to the heat pump.

Ans. 6.22 kW.

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