Lecture 5

The Second Law of Thermodynamics

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Note:-

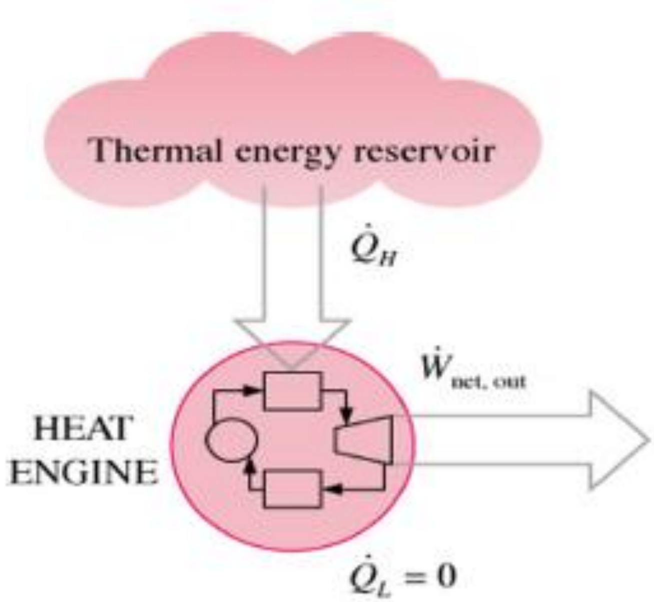
- The ***first law*** places *no restriction on the direction of a process and* does not ensure whether the process will actually occur or not.

- **The *second Law* of Thermodynamics can answer on:**
  - ✓Identifies the direction of processes;
  - ✓Asserts that energy has quality as well as quantity;
  - ✓Optimal performance of the process or cycle;
  - ✓Determines the theoretical limits for the performance of commonly used engineering systems.

The second law of thermodynamic statements:

1- Kelvin-Plank Statement:-

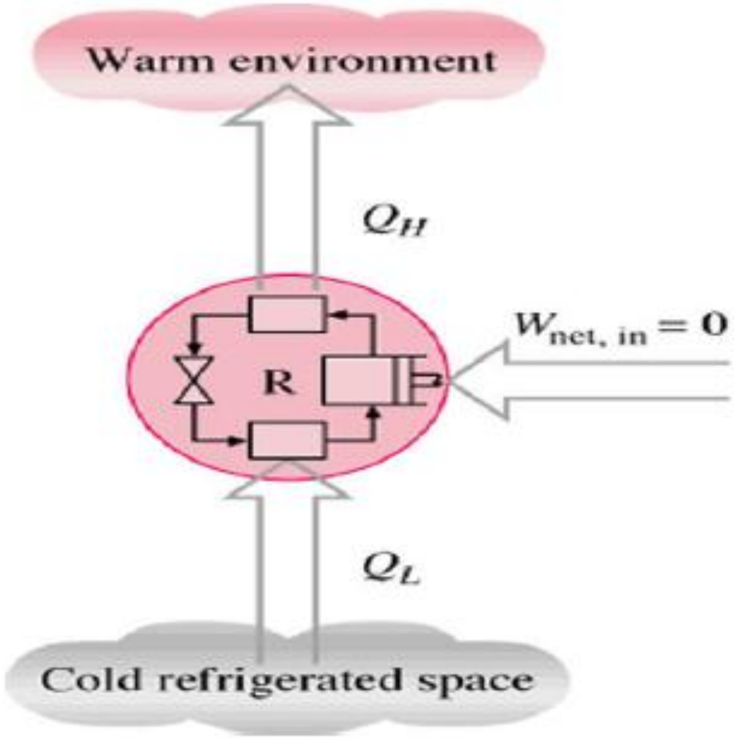
It is *impossible* for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.



$$\eta_{th} \neq 100\ \%$$

2- Classius Statement:-

It is *impossible* to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower temperature body to a higher-temperature body.



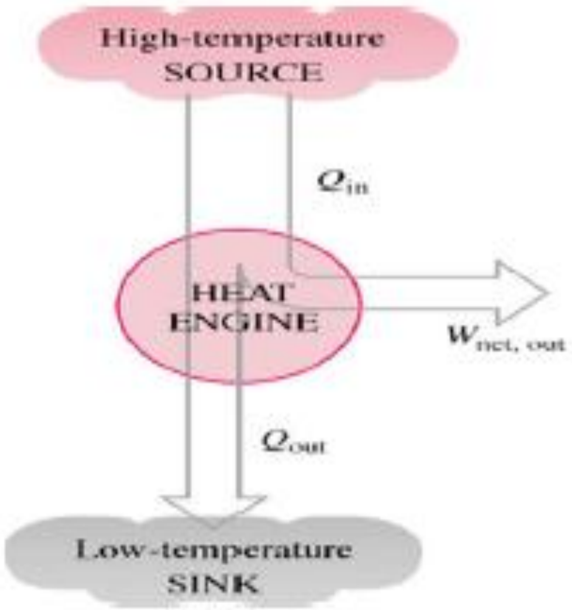
❖ Heat Engine:

It is a device that operates in a thermodynamic cycle produces work as a result of heat transfer from high temperature body to low temperature body.

Or a device to convert Heat to Work

❑ The characteristics of heat engines:

1. Receive heat from a high-temperature source (solar energy, oil furnace, nuclear reactor, etc.).
2. Convert part of this heat to work, e.g. a rotating shaft.
3. Reject the remaining waste heat to a low-temperature sink (the atmosphere, rivers, etc.).
4. Operate on a thermodynamic cycle.

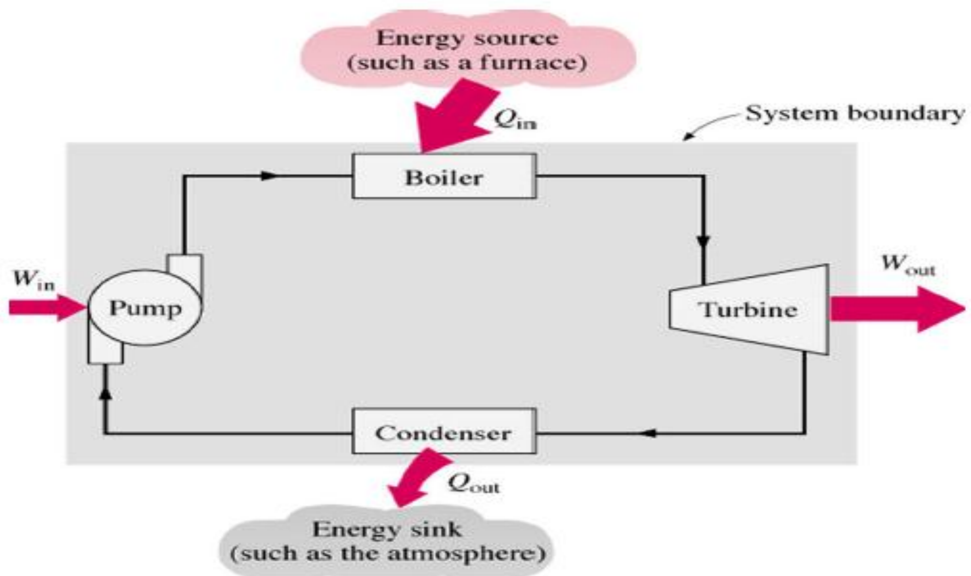


❑Thermal Efficiency

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{Q_L}{Q_H}$$

- The work-producing device that best fits into definition of heat engine is ***the steam power plant,*** which is ***an external combustion engine***. That is, the combustion take place outside the engine.

- Each unit is a steady-state open system.
- The combination system is a closed one, *i.e.* $\Delta E = \Delta U = 0$.



- Overall Energy Balance:

$$W_{in} + Q_{in} = W_{out} + Q_{out}$$

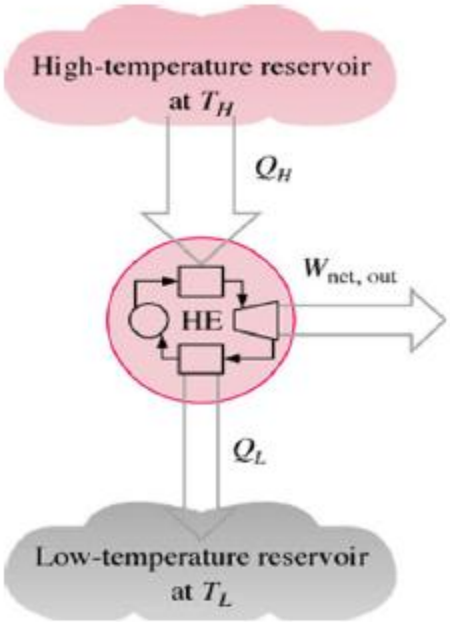
❑ ***Thermal Efficiency***

$$\text{Themal efficiency} = \frac{\text{Net work ouput}}{\text{Total heat input}}$$

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}}$$ *where* $$W_{net,out} = W_{out} - W_{in} = Q_{in} - Q_{out}$$ *So that:* $$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}}$$

$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

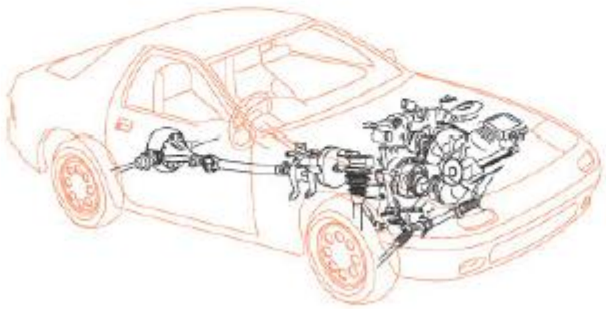
where
$\boldsymbol{Q_H}$ = magnitude of heat transfer between the cyclic device and the high-temperature medium at temperature $\boldsymbol{T_H}$.
$\boldsymbol{Q_L}$ = magnitude of heat transfer between the cyclic device and the low-temperature medium at temperature $\boldsymbol{T_L}$.

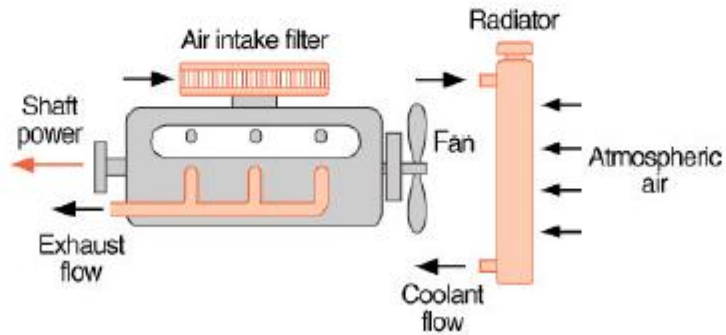


- ➢ The thermal efficiency is
- ✓ only about 25% for automobile engines!
- ✓ 40% for diesel engines and large gas-turbine plants

Example Energy Rejection of an Engine

An automobile engine produces 100 kW on the output shaft with a thermal efficiency of 30 %. The fuel it burns gives 35000 kJ/kg as energy release. Find the total rate of energy rejected to the ambient and the rate of fuel consumption in kg/s.





From the definition of heat engine:

$$\dot{W} = \eta_{eng}\dot{Q}_H$$

$$\dot{Q}_H = \dot{W} / \eta_{eng} = 100 / 0.30 = 333 \text{ kW}$$

The energy equation for overall engine gives:

$$\dot{Q}_L = \dot{Q}_H - \dot{W} = \dot{Q}_H - \eta\dot{Q}_H$$

$$\dot{Q}_L = (1 - 0.3)\dot{Q}_H = 233 \text{ kW}$$

From the energy release in the burning we have

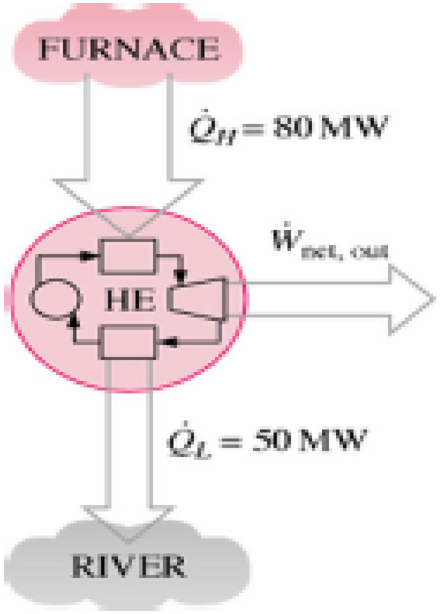
$$\dot{Q}_H = \dot{m}q_H$$

$$\dot{m} = \frac{Q_H}{q_H} = \frac{333 \text{ kW}}{35,000 \text{ kJ/kg}} = 0.0095 \text{ kg/s}$$

Example Thermal Efficiency of a Heat Engine

Heat is transferred to a heat engine from a furnace at a rate of 80 MW. If the rate of waste heat rejection is 50 MW, determine the net power and the thermal efficiency for this heat engine.

Solution:



$$\dot{Q}_H = 80MW \qquad \dot{Q}_L = 50MW$$

$$\dot{W}_{net,out} = \dot{Q}_H - \dot{Q}_L = 80 - 50 = 30MW$$

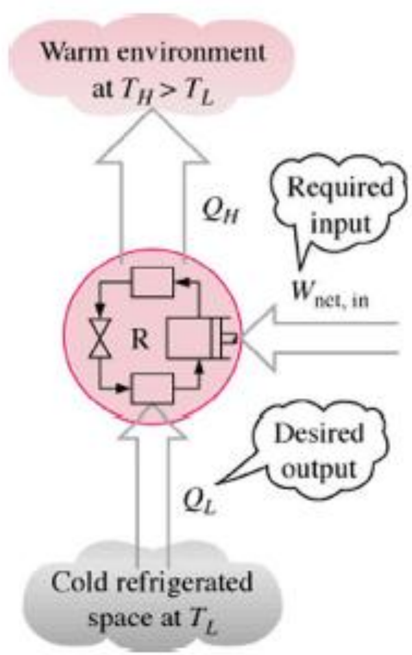
$$\eta_{th} = \frac{\dot{W}_{net,out}}{\dot{Q}_{in}} = \frac{30MW}{80MW} = 37.5\%$$

❖ Refrigerators and Heat Pump:

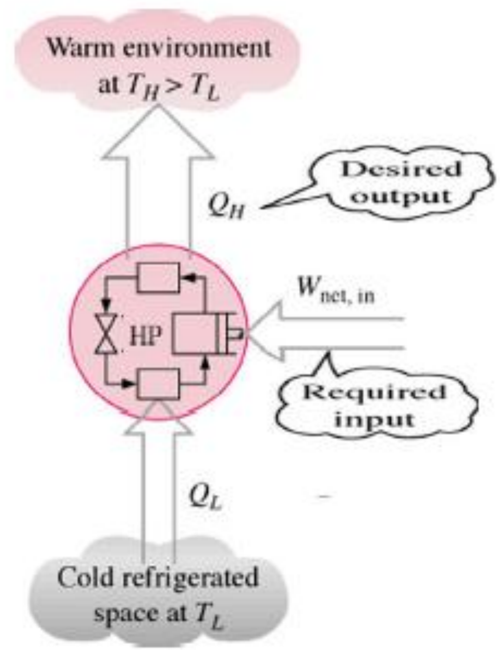
It is a device that operates in a thermodynamic cycle receives work to transfer heat from low temperature body to high temperature body.

Refrigerator: it is a device that removes heat from a low temperature medium (called Cooling Load).

Heat Pump: it is a device that transfers heat to a high temperature medium (called Heating Load).



Refrigerator



Heat Pump

Coefficient of Performance (COP):

- For refrigerator:

$$COP|_R = \frac{Required\ Input}{Desired\ Output} = \frac{Q_L}{W_{net}} = \frac{Q_L}{Q_H - Q_L}$$

- For heat pump:

$$COP|_{H.P} = \frac{Desired\ Output}{Required\ Input} = \frac{Q_H}{W_{net}} = \frac{Q_H}{Q_H - Q_L}$$

Note:

➢The *COP* of a heat pump is always greater than unity. At a fixed value of Q_L and Q_H:

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

$$COP|_R + 1 = \frac{Q_L}{Q_H - Q_L} + \frac{Q_H - Q_L}{Q_H - Q_L} = \frac{Q_L + Q_H - Q_L}{Q_H - Q_L} = \frac{Q_H}{Q_H - Q_L} = COP|_{HP}$$

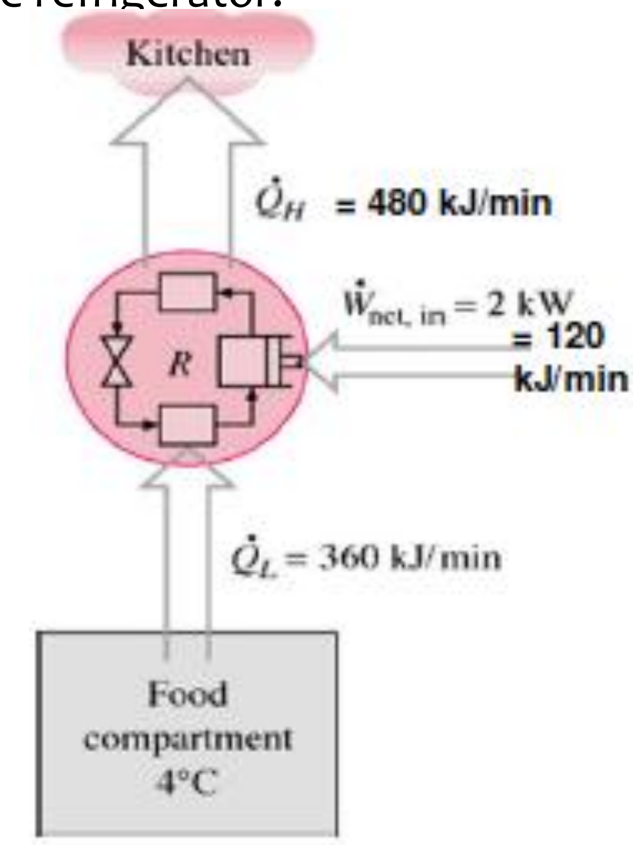
Example Heat Rejection by a Refrigerator

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 powered input to the refrigerator is 2 kW, determine

a) The *COP of the refrigerator.*

b) The rate of heat rejection to the room that houses the refrigerator.

Solution:



a)

$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{net,in}} = \frac{360 kJ/min}{2kW}\left(\frac{1kW}{60kJ/min}\right) = 3$$

b)

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

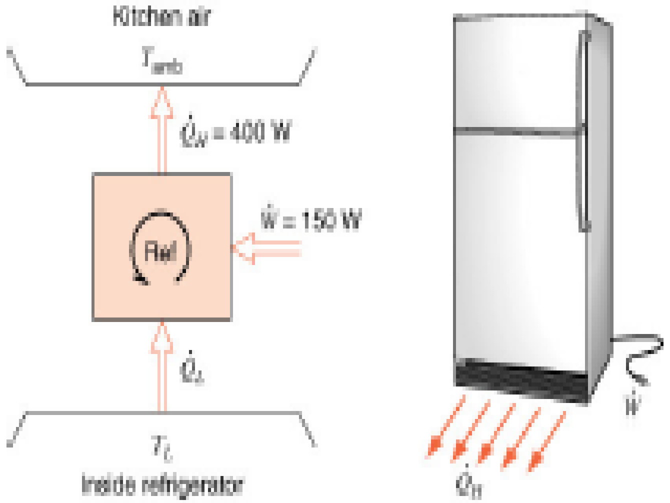
$$\dot{Q}_H = 360\ kJ/min + (2kW)\left(\frac{60kJ/min}{1kW}\right)$$

$$\dot{Q}_H = 480\ kJ/min$$

Example Coefficient of Performance of a Refrigerator

The refrigerator in a kitchen receives an electrical input power of 150 W to derive the system, and it rejects 400 W to the kitchen air. Find a) the rate of energy taken out of the cold space and b) the coefficient of performance of the refrigerator.

Solution



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

$$\dot{Q}_L = 400 - 150 = 250W$$

b) $$COP_R = \frac{\dot{Q}_L}{\dot{W}_{net,in}} = \frac{250}{150} = 1.67$$

➢That is 1.67 kJ of heat is recovered from the refrigerated space for each kJ of work supplied

Example Heating a House by a Heat Pump

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 loose 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 adsorbed from the cold outdoor air.

Solution

a) The power consumed by the heat pump is

$$\dot{W}_{net,in} = \frac{\dot{Q}_H}{COP_{HP}}$$

$$\dot{W}_{net,in} = \frac{80{,}000 \text{ kJ/h}}{2.5} = 32{,}000 \text{ kJ/h} (\text{or } 8.9\text{kW})$$

b) The rate of heat transfer from outdoor is

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

$$\dot{Q}_L = (80{,}000 - 32{,}000)\text{kJ/h} = 48{,}000\text{kJ/h}$$