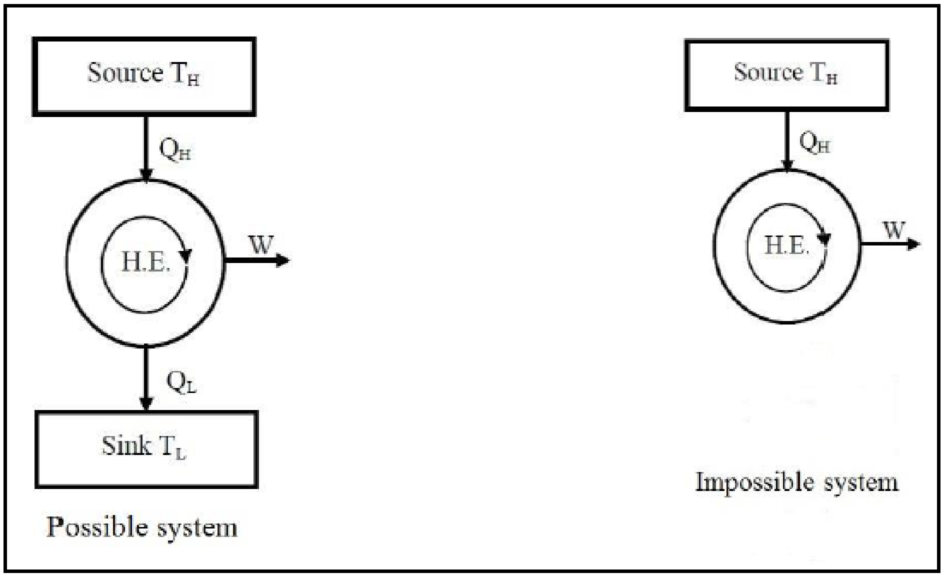
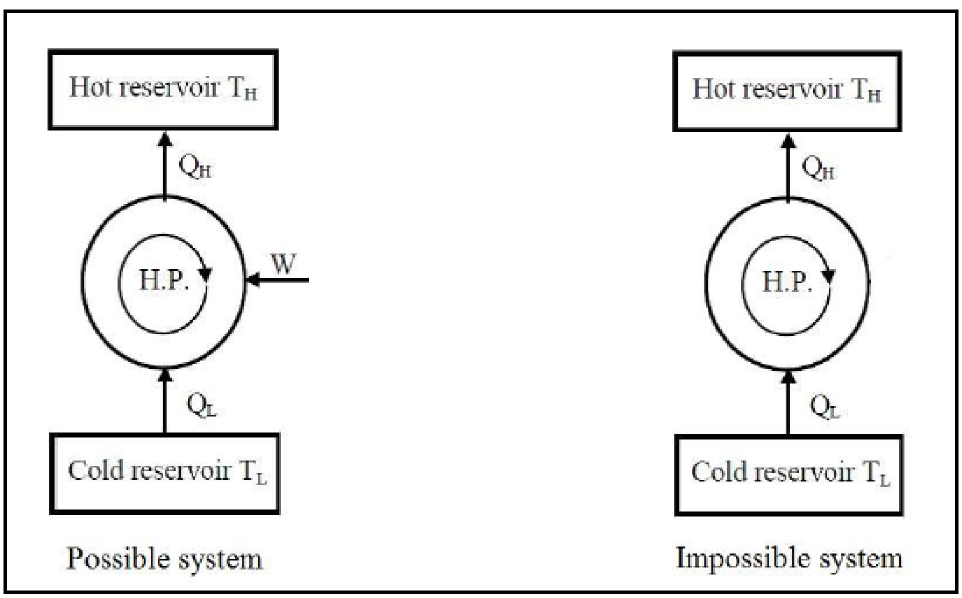
STATEMENTS OF THE SECOND LAW OF THERMODYNAMICS

1. Kelvin-Planck statement: no process is possible whose sole effect is the removal of heat from a single thermal reservoir at a uniform temperature and the performance of an equal amount of work.



2. Clausius statement: no process is possible whose sole effect is the removal of heat from a reservoir at a lower temperature and the absorption of equal amount of heat by a reservoir at a higher temperature.



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CARNOT CYCLE

Carnot cycle is a reversible thermodynamic cycle comprising of four reversible processes. The concept of this cycle provided basics upon which the second law of thermodynamics was stated by Clausius and others. Thermodynamic processes constituting Carnot cycle are:

1. Reversible isothermal expansion process in which heat is added (Q_{add}).
2. Reversible adiabatic (isentropic) expansion process (W_{exp}).
3. Reversible isothermal compression process in which heat is rejected (Q_{rej}).
4. Reversible adiabatic (isentropic) compression process (W_{comp}).

Carnot cycle is shown on the (P-V) diagram between states (1, 2, 3, 4) and 1. A reciprocating piston-cylinder assembly is also shown in Figure (4).

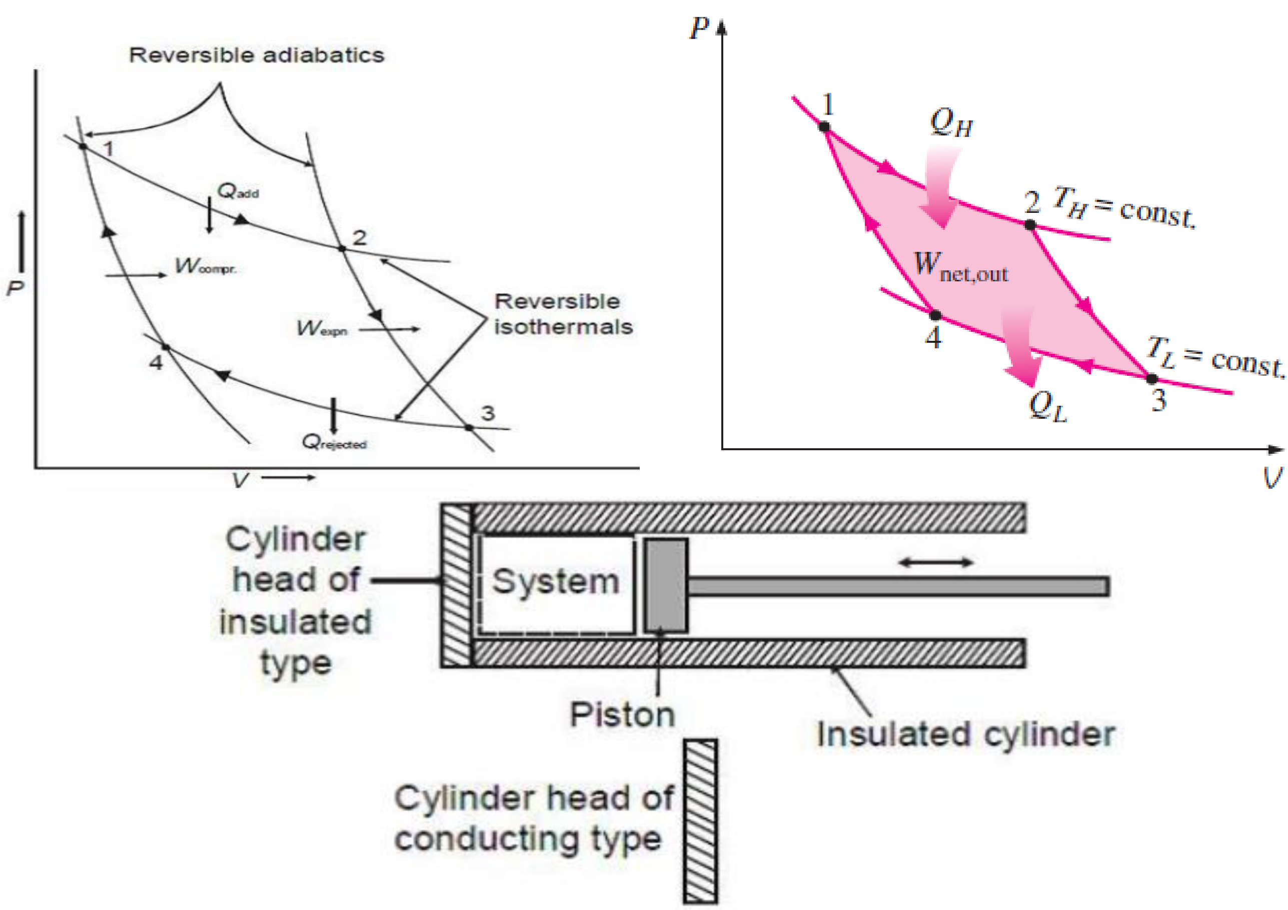

Figure (4) *P-V* diagram of the Carnot cycle.

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Process (1–2) is a reversible isothermal expansion process in which heat is transferred to the system isothermally. In the piston cylinder arrangement heat (Q_{add}) can be transferred to the gas from a constant temperature source (T_1) through a cylinder head of conductor type.

Process (2–3) is a reversible adiabatic expansion process which may be held inside the cylinder with cylinder head being replaced by insulating type so that the complete arrangement is insulated, and adiabatic expansion is carried out. During adiabatic expansion the work (W_{exp}) is available and ($Q_{2-3} = 0$).

Process (3–4) is a reversible isothermal compression process in which heat is rejected from the system. The cylinder head of insulating type may be replaced by a conducting type as in process (1–2) and heat (Q_{rej}) is extracted out isothermally.

$$\eta_C = \frac{\text{Net work}}{\text{Heat supplied}}$$

$$\text{Net work} = W_{exp} - W_{comp}$$

$$\text{Heat supplied} = Q_{add}$$

Substituting gives:

$$\eta_C = \frac{W_{\text{exp}} - W_{\text{comp}}}{Q_{\text{add}}}$$

For a cycle

$$\sum_{\text{cycle}} W = \sum_{\text{cycle}} Q$$

So, we can say that:

$$W_{net} = Q_{add} - Q_{rej}$$

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

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

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As the heat addition takes place at high temperature, while heat rejection takes place at low temperature, so writing these heat interactions as (Q_H), (Q_L) we get:

$$\eta_C = 1 - \frac{Q_L}{Q_H}$$

were

Q_H: is heat transferred to the heat engine from a high-temperature reservoir at (T_H).

Q_L: is heat rejected to a low-temperature reservoir at (T_L).

The piston-cylinder arrangement shown and discussed for realizing Carnot cycle is not practically feasible as:

1. Frequent change of cylinder head i.e. of insulating type and diathermic type for adiabatic and isothermal processes is very difficult.

2. Isothermal heat addition and isothermal heat rejection are practically very difficult to be realized.

3. Reversible adiabatic expansion and compression are not possible.

4. Even if near reversible isothermal heat addition and rejection is to be achieved then time duration for heat interaction should be very large i.e. infinitesimal heat interaction occurring at dead slow speed. Near reversible adiabatic processes can be chieved by making them to occur fast. In a piston-cylinder reciprocating engine arrangement such speed fluctuation in a single cycle is not possible.

Carnot heat engine arrangement is also shown with turbine, compressor and heat exchangers for adiabatic and isothermal processes. Fluid is compressed in compressor adiabatically, heated in heat exchanger at temperature (T_1), expanded in turbine adiabatically, cooled in heat exchanger at temperature (T_3) and sent to compressor for compression. Here also following practical difficulties are confronted:

1. Reversible isothermal heat addition and rejection are not possible.

2. Reversible adiabatic expansion and compression are not possible.

Carnot cycle can also operate reversibly as all processes constituting it are of reversible type. Reversed Carnot cycle is shown in Figure (5).

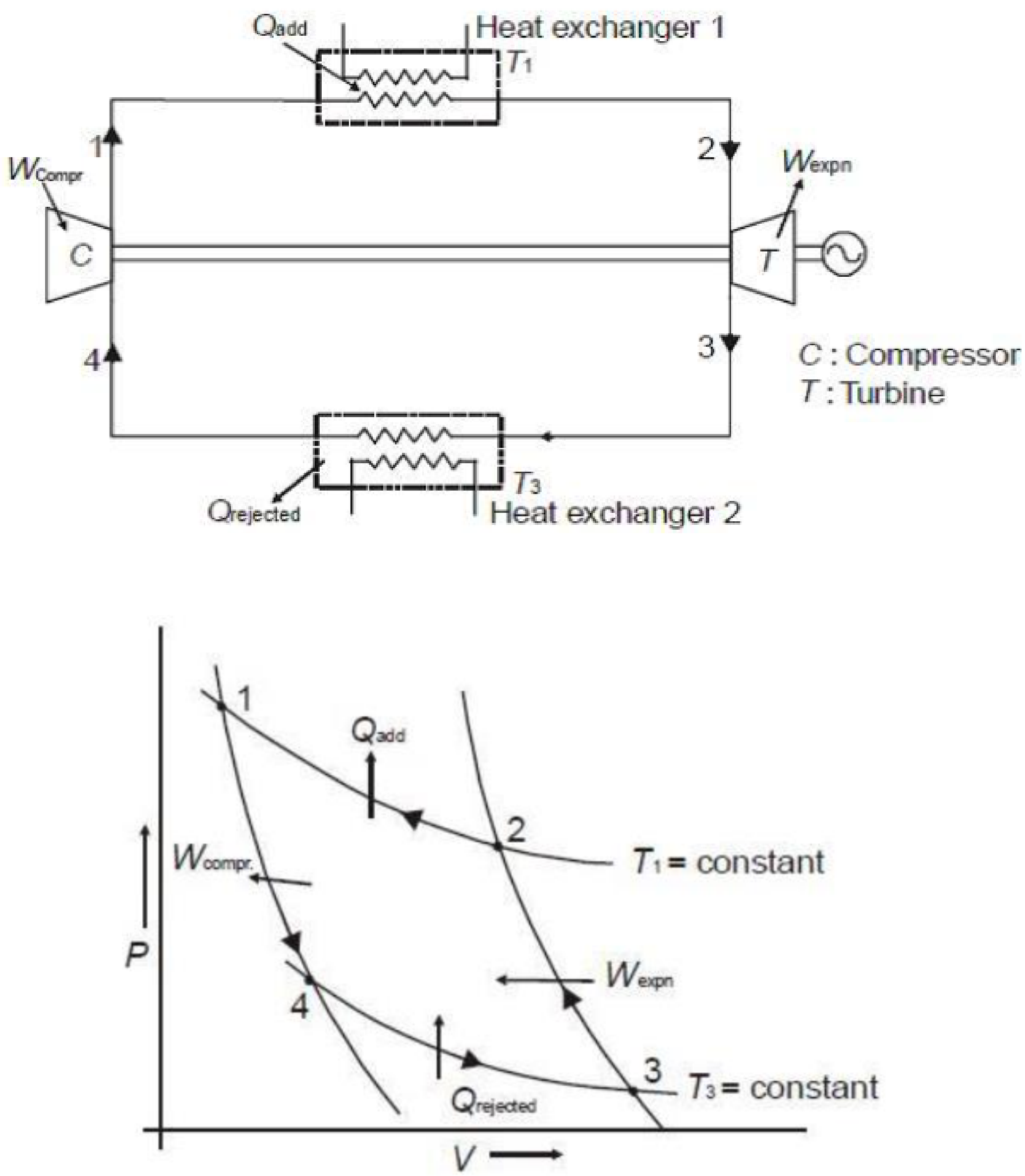

Figure (5) Carnot refrigeration cycle

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Heat engine cycle in reversed form as shown above is used as an ideal cycle for refrigeration and called "Carnot refrigeration cycle".

THERMODYNAMIC TEMPERATURE SCALE

The zeroth law of thermodynamics provides a basis for temperature measurement, but that a temperature scale must be defined in terms of a particular thermometer substance and device. A temperature scale that is independent of any particular substance, which might be called an absolute temperature scale, would be most desirable. In the preceding paragraph we noted that the efficiency of a Carnot cycle is independent of the working substance and depends only on the reservoir temperatures. **This fact provides the basis for such an absolute temperature scale called the thermodynamic scale. Since the efficiency of a Carnot cycle is a function only of the temperature, it follows that**:

$$\eta_{\text{thermal}} = 1 - \frac{Q_L}{Q_H} = 1 - f(T_H, T_L)$$

There are many functional relations that could be chosen to satisfy the relation given in the above equation. For simplicity, the thermodynamic scale is defined as:

$$\frac{Q_H}{Q_L} = \frac{T_H}{T_L}$$

Substituting this definition into the above equation, results in the following relation between the thermal efficiency of a Carnot cycle and the absolute temperatures of the two reservoirs:

$$\eta_{\text{thermal}} = 1 - \frac{T_L}{T_H}$$

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Example (1): Determine the heat to be supplied to a Carnot engine operating between (400 °C) and (15 °C) and producing (200 kJ) of work.

Solution:

$$\frac{Q_H}{Q_L} = \frac{T_H}{T_L}$$

$$\frac{Q_H}{Q_L} = \frac{(400+273)}{(15+273)} \Rightarrow Q_H = 2.34\, Q_L \qquad (1)$$

$$W_{net} = Q_H - Q_L \Rightarrow 200 = Q_H - Q_L \qquad (2)$$

Substitute Eq. (1) into Eq. (2)

$$200 = 2.34\, Q_L - Q_L$$

$Q_L = 149.25\ KJ$ Substitute in Eq. (1)

$$Q_H = 2.34 * 149.25 = 349.25\ KJ$$

The heat to be supplied is

$$Q_H = 349.25\ KJ$$

Example (2): A refrigerator operates on reversed Carnot cycle. Determine the power required to drive the refrigerator between the temperatures of (42 °C) and (4 °C), if heat at the rate of (2 kW) is extracted from the low temperature region.

Solution:

$$\frac{Q_H}{Q_L} = \frac{T_H}{T_L}$$

$$\frac{Q_H}{2} = \frac{(42+273)}{(4+273)} \Rightarrow Q_H = 2.274\ KW$$

$$W = Q_H - Q_L \Rightarrow W = 2.274 - 2$$

$$W = 0.274\ KW$$

Example (3): A heat engine operates between a source at (550 °C) and a sink at (25 °C). If heat is supplied to the heat engine at a steady rate of (1200 kJ/min), determine the maximum power output of this heat engine.

Solution:

$$\eta_{\text{th},C} = 1 - \frac{T_L}{T_H}$$

$$\eta_{max} = \eta_{\text{th},C} = 1 - \frac{(25+273)}{(550+273)} = 0.638 = 63.8\%$$

$$W_{net,out} = \eta_{\text{th},C}\ Q_H$$

$$W_{net,out} = 0.638 * \frac{1200}{60} = 12.76\ KW$$

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HOMEWORK

1- A Carnot heat engine operates between a source at (1000 K) and a sink at (300 K). If the heat engine is supplied with heat at a rate of (800 kJ/min), determine (*a*) the thermal efficiency and (*b*) the power output of this heat engine.

Ans. (a) 70 %, (b) 9.33 kW

2- A Carnot heat engine receives (650 kJ) of heat from a source of unknown temperature and rejects (250 kJ) of it to a sink at (24 °C). Determine (*a*) the temperature of the source and (*b*) the thermal efficiency of the heat engine.

Ans. (a) 772.2 K, (b) 61.5 %

3- An innovative way of power generation involves the utilization of geothermal energy the energy of hot water that exists naturally underground as the heat source. If a supply of hot water at (140 °C) is discovered at a location where the environmental temperature is (20 °C), determine the maximum thermal efficiency a geothermal power plant built at that location can have.

Ans. 29.1 %

4- A Carnot heat engine receives (500 kJ) of heat per cycle from a high-temperature source at (652 °C) and rejects heat to a low-temperature sink at (30 °C). Determine (*a*) the thermal efficiency of this Carnot engine and (*b*) the amount of heat rejected to the sink per cycle.

Ans. (a) 67.2 %, (b) 164 kJ

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