Republic of Iraq
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THERMODYNAMIC I

FIRST STAGE

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7. 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 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 Reservoir

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

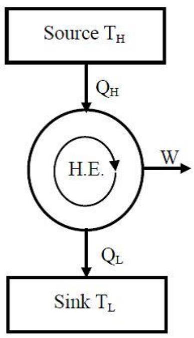
It is defined as the system operating in a complete cycle and developing a net work from a supply of heat. The second law implies a source of heat and sink of heat are both necessary. Let the heat supplied from the source be Q_H, let the heat rejected to the sink be Q_L and let the net work done by the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

$$\sum dQ = \sum dW \qquad \dots\dots\dots\dots\dots\dots\dots (7.1)$$

$$Q_H - Q_L = W \qquad \dots\dots\dots\dots\dots\dots\dots (7.2)$$

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

$$Q_H > W \qquad \dots\dots\dots\dots\dots\dots\dots (7.3)$$



$T_H>T_L$

Heat Engine

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

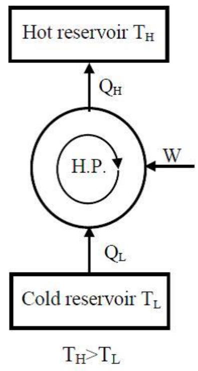
$$\eta = \frac{W}{Q_H} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H} \qquad \dots\dots\dots\dots\dots\dots\dots (7.4)$$

The thermal efficiency of a heat engine is always less than 100%.

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.

Heat Pump and Refrigerator

It is the inverse of heat engine. Work is done on the system. The net work done on the system equals the net heat rejected by the system. In the heat pump an amount of heat Q_L is supplied from cold reservoir and amount of heat Q_H is rejected to the hot reservoir. According to the first law of thermodynamics:



Heat Pump

$$\sum dQ = \sum dW \qquad \dots\dots\dots\dots\dots\dots\dots (7.5)$$

$$Q_H - Q_L = W$$

$$Q_H = Q_L + W \qquad \dots\dots\dots\dots\dots\dots\dots (7.6)$$

Therefore, in order to transfer heat from a cold reservoir to a hot reservoir a work must be done.

$$W > 0 \qquad \dots\dots\dots\dots\dots\dots\dots (7.7)$$

As heat a pump is not a work producing machine and also its objective is to maintain a body at higher temperature, so its performance can't be defined using efficiency as in the case of heat engines. Performance of a heat pump is quantified through a parameter called coefficient of performance $(C.O.P)$. Coefficient of performance is defined by the ratio of desired effect and net work done for getting the desired effect.

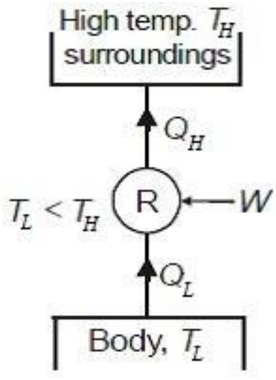
$$C.O.P. = \frac{\text{Desired effect}}{\text{Net work done}} \qquad \dots\dots\dots\dots\dots\dots\dots (7.8)$$

$$C.O.P. = \frac{Q_H}{W} \qquad \dots\dots\dots\dots\dots\dots\dots (7.9)$$

$$W = Q_H - Q_L \qquad \dots\dots\dots\dots\dots\dots\dots (7.10)$$

$$C.O.P. = \frac{Q_H}{Q_H - Q_L} \qquad \dots\dots\dots\dots\dots\dots\dots (7.11)$$

A **Refrigerator** is a device similar to a heat pump but with reverse objective. It maintains a body at a temperature lower than that of the surroundings while operating in a cycle.



Refrigerator

Refrigerator also performs a non-spontaneous process of extracting heat from low temperature body for maintaining it cool, therefore external work W is to be done for realizing it. The block diagram shows how refrigerator extracts heat Q_L for maintaining body at low temperature T_L at the expense of work W and rejects heat to high temperature surroundings.

Performance of refrigerator is also quantified by coefficient of performance, which could be defined as:

$$(C.O.P.)_{ref.} = \frac{\text{Desired effect}}{\text{Net work}} = \frac{Q_L}{W} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7.12)$$

$$W = Q_H - Q_L \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7.13)$$

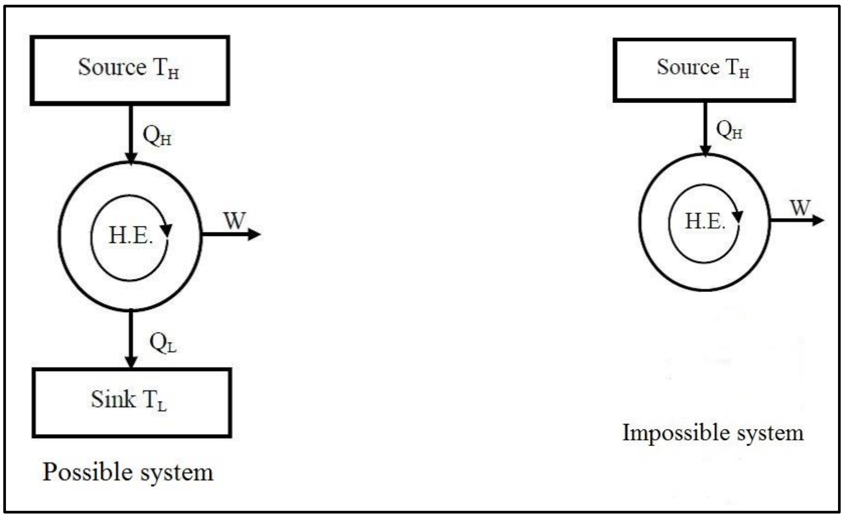
$$(C.O.P.)_{ref.} = \frac{Q_L}{Q_H - Q_L} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7.14)$$

$(C.O.P.)$ values of a heat pump and a refrigerator can be interrelated as:

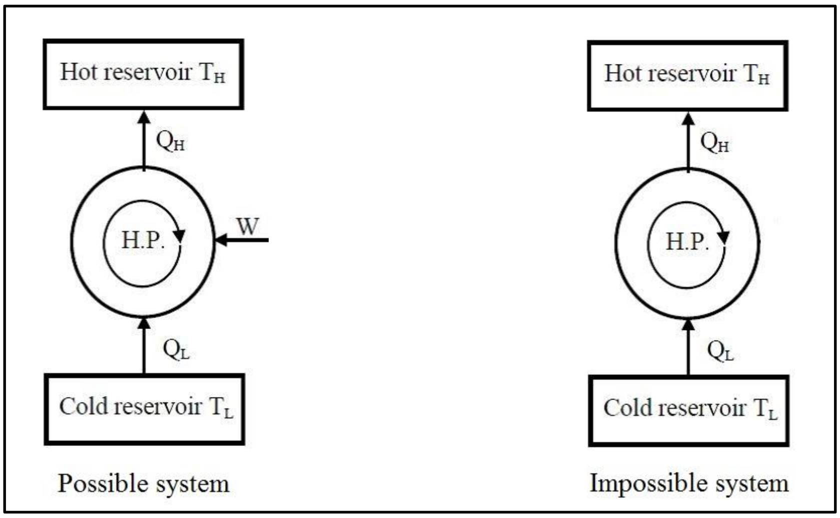
$$(C.O.P.)_{HP} = (C.O.P.)_{ref.} + 1 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7.15)$$

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.



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}).

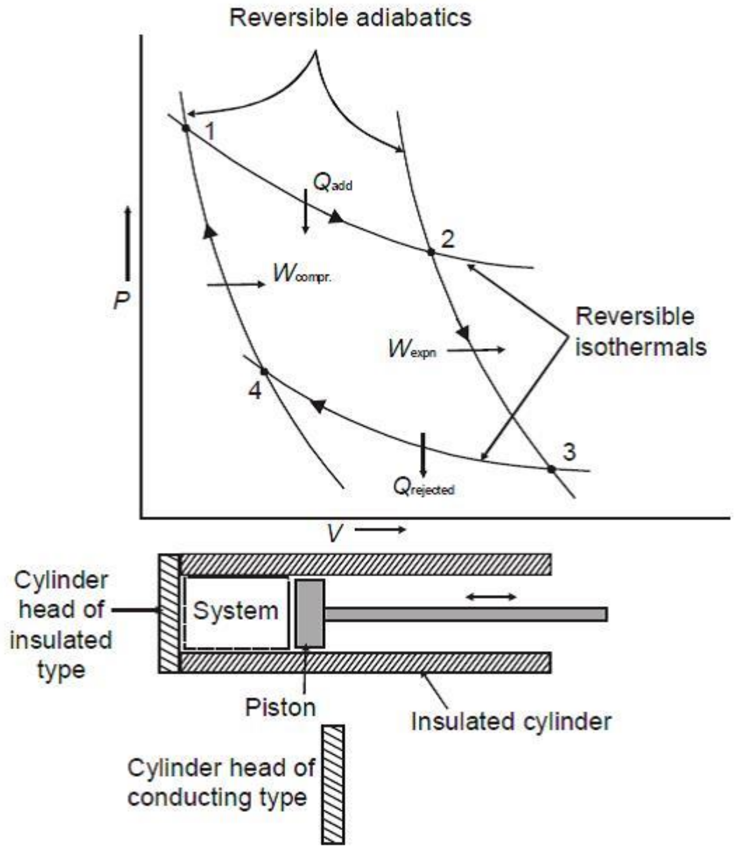
Carnot cycle is shown on the (P-V) diagram between states 1, 2, 3, 4 and 1. A reciprocating piston-cylinder assembly is also shown below.

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.

Process (4–1) is a reversible adiabatic compression process with work requirement for compression. In the piston-cylinder arrangement the cylinder head of conducting type as used in process (3–4) is replaced by an insulating type, so that the whole arrangement becomes insulated and adiabatic compression may be realized.



The efficiency of the Carnot cycle can be given as:

$$\eta_{Carnot} = \frac{\text{Net work}}{\text{Heat supplied}}$$

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

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

Substituting gives:

$$\eta_{Carnot} = \frac{W_{exp} - W_{comp}}{Q_{add}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7.16)$$

For a cycle: $\sum_{cycle} W = \sum_{cycle} Q$

So we can say that: $W_{net} = Q_{add} - Q_{rej}$

Hence:

$$\eta_{Carnot} = 1 - \frac{Q_{rej}}{Q_{add}} \qquad \dots\dots\dots\dots\dots\dots\dots (7.17)$$

As the heat addition takes place at high temperature, while heat rejection takes place at low temperature, so writing these heat interactions as Q_{High}, Q_{Low} we get:

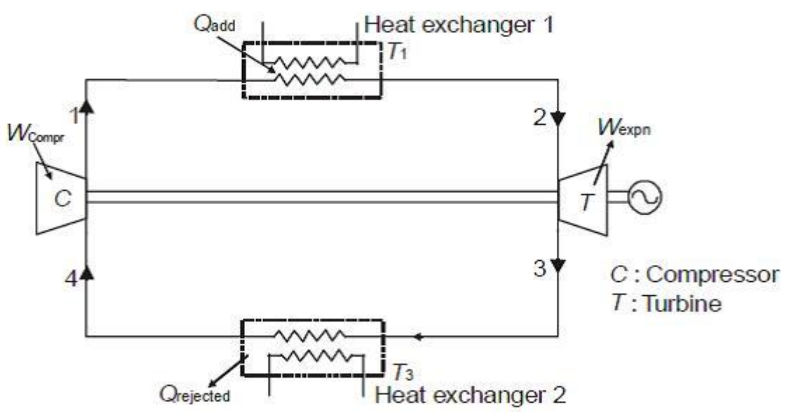
$$\eta_{Carnot} = 1 - \frac{Q_{Low}}{Q_{High}} \qquad \dots\dots\dots\dots\dots\dots\dots (7.18)$$

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

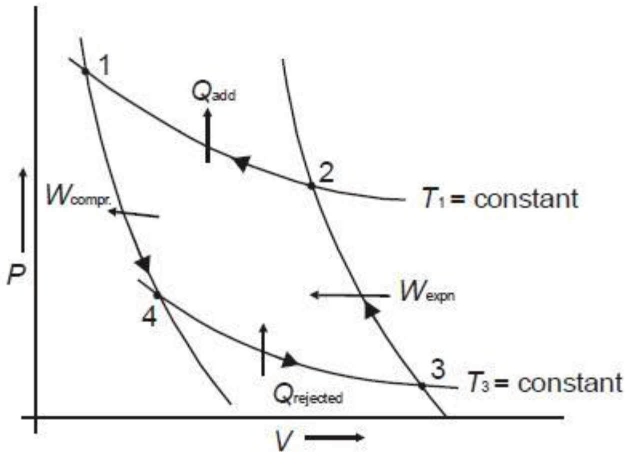
1. Frequent change of cylinder head i.e. of insulating type and diathermic type for adiabatic and isothermal processes is very difficult.
2. Isothermal heat addition and isothermal heat rejection are practically very difficult to be realized.
3. Reversible adiabatic expansion and compression are not 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 achieved 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 below.



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:

$$\eta_{thermal} = 1 - \frac{Q_L}{Q_H} = 1 - f(T_H, T_L) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7.19)$$

There are many functional relations that could be chosen to satisfy the relation given in equation (7.19). For simplicity, the thermodynamic scale is defined as:

$$\frac{Q_H}{Q_L} = \frac{T_H}{T_L} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7.20)$$

Substituting this definition into equation (7.19), results in the following relation between the thermal efficiency of a Carnot cycle and the absolute temperatures of the two reservoirs:

$$\eta_{thermal} = 1 - \frac{T_L}{T_H} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7.21)$$

Example (7.1): A heat engine produces net power output of 30 MW and the rate of waste heat rejected to a nearby river is 50 MW. Determine the heat transferred to the heat engine from the furnace and its thermal efficiency.

Solution:

The river is the cold sink of the heat engine, while the furnace is the heat source.

$$W_{net} = Q_H - Q_L \rightarrow Q_H = W_{net} + Q_L = 30 + 50$$

$\boldsymbol{Q_H} = \mathbf{80\ kW}$ **Ans.**

The thermal efficiency of the heat engine is:

$$\eta_{th} = \frac{W_{net}}{Q_H} = \frac{30}{80}$$

$\boldsymbol{\eta_{th} = 37.5\%}$ **Ans.**

Example (7.2): Food freezer in a refrigerator is maintained at 4°C by removing its heat at a rate of 360 kJ/min. If the required power input to the refrigerator is 2 kW. Determine the coefficient of performance and the rate of heat rejection to the room containing the refrigerator.

Solution:

The room represents the high-temperature reservoir, while the freezer represents the low temperature reservoir to the refrigerator. The coefficient of performance of the refrigerator is:

$$(C.O.P.)_{ref.} = \frac{\text{Desired effect}}{\text{Net work}} = \frac{Q_L}{W_{net}} = \frac{360}{60 \times 2}$$

$\boldsymbol{(C.O.P.)_{ref.} = 3}$ **Ans.**

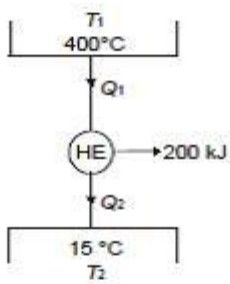
The rate of heat rejection to the room:

$$Q_H = Q_L + W_{net} = \frac{360}{60} + 2$$

$\boldsymbol{Q_H} = \mathbf{8\ kW}$ **Ans.**

Example (7.3): Determine the heat to be supplied to a Carnot engine operating between 400°C and 15°C and producing 200 kJ of work.

Solution:



$$\frac{Q_1}{Q_2} = \frac{T_1}{T_2} \rightarrow \frac{Q_1}{Q_2} = \frac{673}{288} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$W = Q_1 - Q_2 \rightarrow 200 = Q_1 - Q_2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

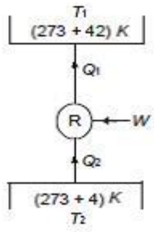
Solving (1) and (2) we get:

$Q_1 = 349.6$ kJ, $Q_2 = 149.6$ kJ

Heat to be supplied $= \mathbf{349.6}$ kJ **Ans.**

Example (7.4): 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:



$$\frac{Q_1}{Q_2} = \frac{T_1}{T_2} \rightarrow \frac{Q_1}{2} = \frac{315}{277} \rightarrow Q_1 = 2.274 \text{ kW}$$

$W = Q_1 - Q_2 = 2.274 - 2$

$\boldsymbol{W = 0.274}$ **kW** **Ans.**

Exercises

Problem (7.1): A household refrigerator with a C.O.P. of 1.2 removes heat from the refrigerated space at a rate of 60 kJ/min. Determine the electric power consumed by the refrigerator and the rate of heat transferred to the kitchen air.

Ans. (0.83 kW, 1.83 kW)

Problem (7.2): 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 the C.O.P. of this air conditioner and the rate of heat transfer to the outside air.

Ans. (2.08, 18.5 kW)

Problem (7.3): A Carnot heat engine operates between a source at 1300 K and a sink at 300 K. If the heat engine is supplied with heat at a rate of 800 kJ/min, determine the thermal efficiency and the power output of this heat engine.

Ans. (77%, 10.23 kW)

Problem (7.4): A Carnot heat engine receives 650 kJ of heat form a source of unknown temperature and rejects 250 kJ of it to a sink at 24°C. Determine the temperature of the source and the thermal efficiency of the heat engine.

Ans. (499.2°C, 61.5%)

Problem (7.5): A Carnot refrigerator operates in a room in which the temperature is 22°C and consumes 2 kW of power when operating. If the food compartment of the refrigerator is to be maintained at 3°C, determine the rate of heat removal from the food compartment.

Ans. (29 kW)

Problem (7.6): A refrigerator is to remove heat from the cooled space at a rate of 300 kJ/min to maintain its temperature at –8°C. If the air surrounding the refrigerator is at 25°C, determine the minimum power input required for this refrigerator.

Ans. (0.623 kW)

Problem (7.7): An air conditioning system operating on the reversed Carnot cycle is required to transfer heat from a house at a rate of 750 kJ/min to maintain its temperature at 24°C. If the outdoor air temperature is 35°C, determine the power required to operate this air conditioning system.

Ans. (0.46 kW)

Problem (7.8): A Carnot refrigerator operates in a room in which the temperature is 25°C. The refrigerator consumes 500 kW of power when operating and has a C.O.P. of 4.5.

Determine the rate of heat removal for the refrigerated space and the temperature of the refrigerated space.

Ans. (2250 kW, –29.2°C)

Problem (7.9): In a winter season when the outside temperature is –1°C, the inside of a house is to be maintained at 25°C. Estimate the minimum power required to run the heat pump of maintaining the temperature. Assume heating load as 125 MJ/h.

Ans. (3.02 kW)

Problem (7.10): A reversible heat engine operates between two reservoirs at 827°C and 27°C. The engine drives a Carnot refrigerator maintaining –13°C and rejecting heat to a reservoir at 27°C. Heat input to the engine is 2000 kJ and the net work available is 300 kJ. How much heat is transferred to the refrigerant and total heat rejected to the reservoir at 27°C?

Ans. (7504.58 kJ, 9204.68 kJ)