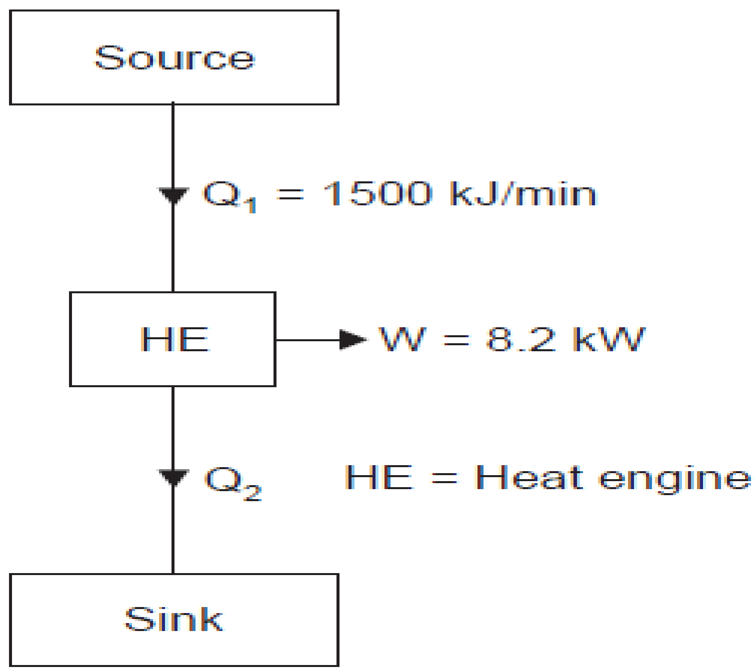
AERO ENGINEERING THERMODYNAMICS

Dr. A. Muthuram
Assistant Professor,
SRM Institute of Science and Technology.

Unit-2 : SECOND LAW OF THERMODYNAMICS

- Limitations of the first law of Thermodynamics - Introduction to heat reservoirs, sources and sinks. Heat Engine, Refrigerator and Heat pump. Thermal efficiency of heat engines, COP - Second law of Thermodynamics - Kelvin-Planck statement, Clausius statement and their equivalence. Reversible and irreversible processes- causes of irreversibility. Carnot Theorem and corollary. Absolute Thermodynamic Temperature scale. Carnot cycle and its performance.

- *A heat engine receives heat at the rate of 1500 kJ/min and gives an output of 8.2 kW. Determine :*
- (*i*) *The thermal efficiency ; (ii) The rate of heat rejection*



Solution. Heat received by the heat engine,

$$Q_1 = 1500 \text{ kJ/min}$$

$$= \frac{1500}{60} = 25 \text{ kJ/s}$$

Work output, $W = 8.2 \text{ kW} = 8.2 \text{ kJ/s}$.

(*i*) Thermal efficiency, $\eta_{th} = \dfrac{W}{Q_1}$

$$= \frac{8.2}{25} = 0.328 = 32.8\%$$

Hence, **thermal efficiency = 32.8%.** **(Ans.)**

(*ii*) Rate of heat rejection,

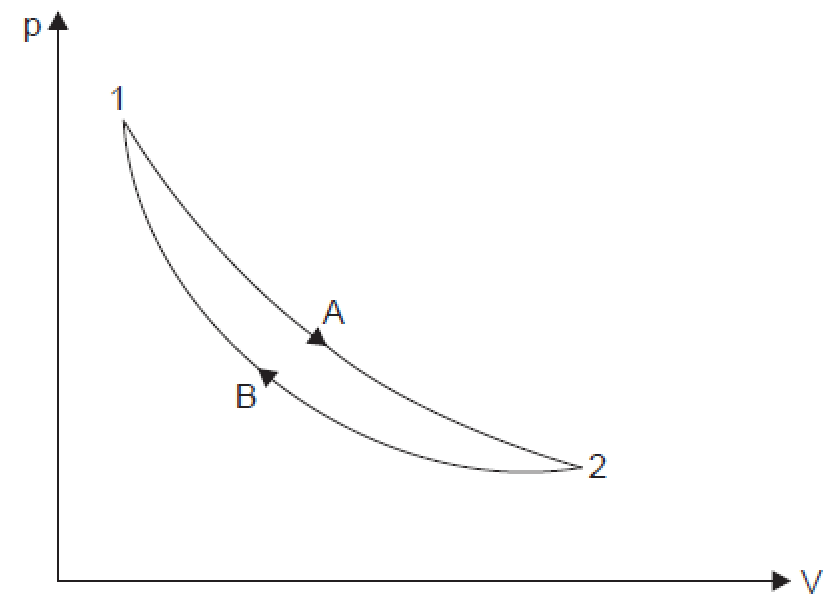
$$Q_2 = Q_1 - W = 25 - 8.2$$

$$= 16.8 \text{ kJ/s}$$

Hence, **the rate of heat rejection = 16.8 kJ/s.**

(Ans.)

- *During a process a system receives 30 kJ of heat from a reservoir and does 60 kJ of work. Is it possible to reach initial state by an adiabatic process ?*
- **Solution.**
- Heat received by the system = 30 kJ
- Work done = 60 kJ



Process 1-2 : By first law of thermodynamics,

$$Q_{1-2} = (U_2 - U_1) + W_{1-2}$$

$$30 = (U_2 - U_1) + 60 \qquad \therefore \qquad (U_2 - U_1) = -30 \text{ kJ}.$$

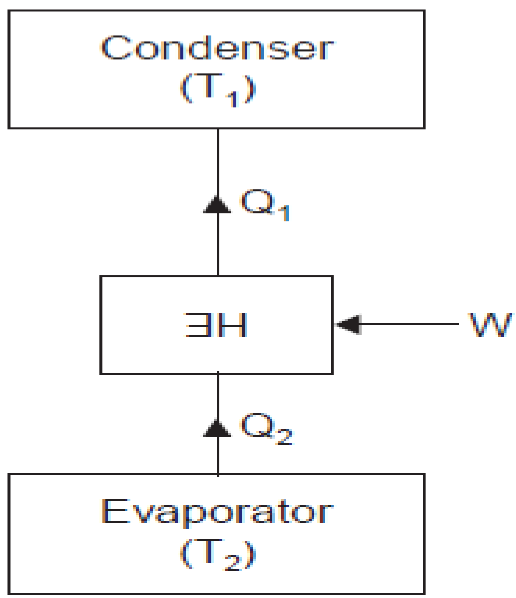
Process 2-1 : By first law of thermodynamics,

$$Q_{2-1} = (U_1 - U_2) + W_{2-1}$$

$$\therefore \qquad 0 = 30 + W_{2-1} \qquad \therefore \qquad W_{2-1} = -30 \text{ kJ}.$$

Thus 30 kJ work has to be done *on the system* to restore it to original state, by adiabatic process.

- *Find the co-efficient of performance and heat transfer rate in the condenser of a refrigerator in kJ/h which has a refrigeration capacity of 12000 kJ/h when power input is 0.75 kW.*



Refrigeration capacity, $Q_2 = 12000$ kJ/h

Power input, $W = 0.75$ kW ($= 0.75 \times 60 \times 60$ kJ/h)

Co-efficient of performance, C.O.P. :

Heat transfer rate :

$$(\text{C.O.P.})_{refrigerator} = \frac{\text{Heat absorbed at lower temperature}}{\text{Work input}}$$

$$\therefore \qquad \text{C.O.P.} = \frac{Q_2}{W} = \frac{12000}{0.75 \times 60 \times 60} = 4.44$$

Hence **C.O.P. = 4.44. (Ans.)**

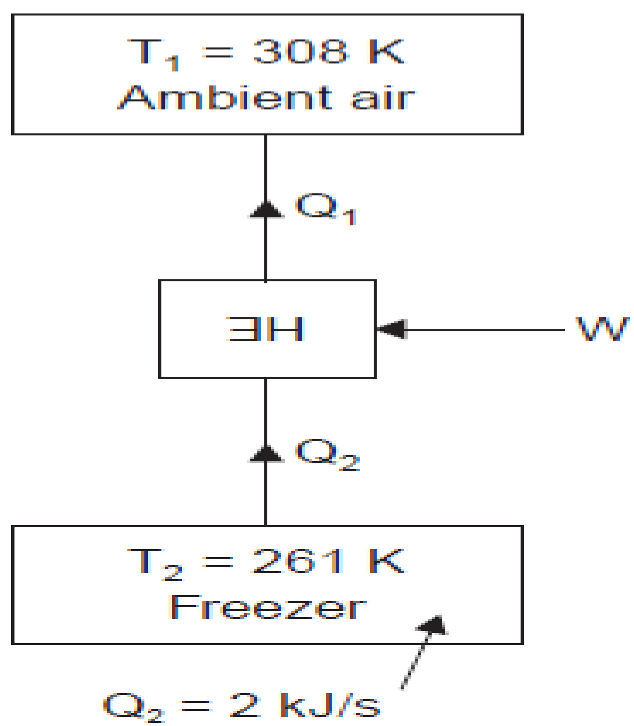
Hence transfer rate in condenser $= Q_1$

According to the first law

$$Q_1 = Q_2 + W = 12000 + 0.75 \times 60 \times 60 = 14700 \text{ kJ/h}$$

Hence, **heat transfer rate = 14700 kJ/h. (Ans.)**

- *A domestic food refrigerator maintains a temperature of − 12°C. The ambient air temperature is 35°C. If heat leaks into the freezer at the continuous rate of 2 kJ/s determine the least power necessary to pump this heat out continuously.*



Solution. Freezer temperature,

$$T_2 = -12 + 273 = 261 \text{ K}$$

Ambient air temperature,

$$T_1 = 35 + 273 = 308 \text{ K}$$

Rate of heat leakage into the freezer = 2 kJ/s

Least power required to pump the heat :

The refrigerator cycle removes heat from the freezer at the same rate at which heat leaks into it (Fig. 5.12).

For minimum power requirement

$$\frac{Q_2}{T_2} = \frac{Q_1}{T_1}$$

$$\therefore \qquad Q_1 = \frac{Q_2}{T_2} \times T_1 = \frac{2}{261} \times 308 = 2.36 \text{ kJ/s}$$

$$\therefore \qquad W = Q_1 - Q_2$$

$$= 2.36 - 2 = 0.36 \text{ kJ/s} = 0.36 \text{ kW}$$

Hence, *least power required to pump the heat continuously*

= 0.36 kW. (Ans.)

- *A house requires 2 × 10^5 kJ/h for heating in winter. Heat pump is used to absorb heat from cold air outside in winter and send heat to the house. Work required to operate the heat pump is 3 × 10^4 kJ/h. Determine :*
- (*i) Heat abstracted from outside ;*
- (*ii) Co-efficient of performance.*

Solution. (*i*) Heat requirement of the house, Q_1 (or heat rejected)

$$= 2 \times 10^5 \text{ kJ/h}$$

Work required to operate the heat pump,

$$W = 3 \times 10^4 \text{ kJ/h}$$

Now, $$Q_1 = W + Q_2$$

where Q_2 is the heat abstracted from outside.

$\therefore$ $$2 \times 10^5 = 3 \times 10^4 + Q_2$$

Thus $$Q_2 = 2 \times 10^5 - 3 \times 10^4$$

$$= 200000 - 30000 = 170000 \text{ kJ/h}$$

Hence, **heat abstracted from outside = 170000 kJ/h. (Ans.)**

(*ii*) $$(\text{C.O.P.})_{heat\ pump} = \frac{Q_1}{Q_1 - Q_2}$$

$$= \frac{2 \times 10^5}{2 \times 10^5 - 170000} = 6.66$$

Hence, **co-efficient of performance = 6.66. (Ans.)**

Note. If the heat requirements of the house were the same but this amount of heat had to be abstracted from the house and rejected out, *i.e., cooling of the house in summer*, we have

$$(\text{C.O.P.})_{refrigerator} = \frac{Q_2}{Q_1 - Q_2} = \frac{Q_2}{W}$$

$$= \frac{170000}{3 \times 10^4} = 5.66$$

Thus the same device has two values of C.O.P. depending upon the objective.

- *What is the highest possible theoretical efficiency of a heat engine operating with a hot reservoir of furnace gases at 2100°C when the cooling water available is at 15°C ?*

Solution. Temperature of furnace gases, $T_1 = 2100 + 273 = 2373$ K

Temperature of cooling water, $T_2 = 15 + 273 = 288$ K

Now,
$$\eta_{max} \left(= \eta_{carnot}\right) = 1 - \frac{T_2}{T_1} = 1 - \frac{288}{2373} = 0.878 \text{ or } 87.8\%. \quad \text{(Ans.)}$$

- *A Carnot cycle operates between source and sink temperatures of 250°C and – 15°C. If the system receives 90 kJ from the source, find :*
- (*i) Efficiency of the system ; (ii) The net work transfer ;*
- (*iii) Heat rejected to sink*

Solution. Temperature of source, $T_1 = 250 + 273 = 523$ K

Temperature of sink, $T_2 = -15 + 273 = 258$ K

Heat received by the system, $Q_1 = 90$ kJ

(*i*)
$$\eta_{carnot} = 1 - \frac{T_2}{T_1} = 1 - \frac{258}{523} = 0.506 = \mathbf{50.6\%.} \quad \textbf{(Ans.)}$$

(*ii*) **The net work transfer,** $W = \eta_{carnot} \times Q_1$ $\left[\because \ \eta_{carnot} = \frac{W}{Q_1}\right]$

$= 0.506 \times 90 = \mathbf{45.54\ kJ.}$ **(Ans.)**

(*iii*) **Heat rejected to the sink,** $Q_2 = Q_1 - W$ $[\because \ W = Q_1 - Q_2]$

$= 90 - 45.54 = \mathbf{44.46\ kJ.}$ **(Ans.)**

- *An inventor claims that his engine has the following specifications :*
- *Temperature limits ...... 750°C and 25°C*
- *Power developed ...... 75 kW*
- *Fuel burned per hour ...... 3.9 kg*
- *Heating value of the fuel ...... 74500 kJ/kg*
- *State whether his claim is valid or not.*

Solution. Temperature of source, $T_1 = 750 + 273 = 1023$ K

Temperature of sink, $T_2 = 25 + 273 = 298$ K

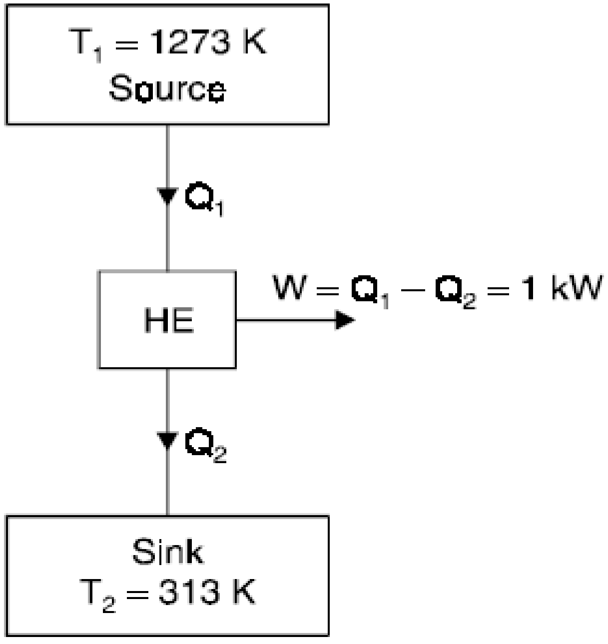
We know that the thermal efficiency of Carnot cycle is the maximum between the specified temperature limits.

Now,
$$\eta_{carnot} = 1 - \frac{T_2}{T_1} = 1 - \frac{298}{1023} = 0.7086 \quad \text{or} \quad 70.86\%$$

The actual thermal efficiency claimed,

$$\eta_{thermal} = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{75 \times 1000 \times 60 \times 60}{3.9 \times 74500 \times 1000} = 0.9292 \quad \text{or} \quad 92.92\%.$$

- *A cyclic heat engine operates between a source temperature of 1000°C and a sink temperature of 40°C. Find the least rate of heat rejection per kW net output of the engine ?*



Solution. Temperature of source,

$$T_1 = 1000 + 273 = 1273 \text{ K}$$

Temperature of sink,

$$T_2 = 40 + 273 = 313 \text{ K}$$

Least rate of heat rejection per kW net output :

For a reversible heat engine, the rate of heat rejection will be minimum (Fig. 5.13)

$$\eta_{max} = \eta_{rev.} = 1 - \frac{T_2}{T_1}$$

$$= 1 - \frac{313}{1273} = 0.754$$

Now $$\frac{W_{net}}{Q_1} = \eta_{max} = 0.754$$

$\therefore$ $$Q_1 = \frac{W_{net}}{0.754} = \frac{1}{0.754} = 1.326 \text{ kW}$$

Now $$Q_2 = Q_1 - W_{net} = 1.326 - 1 = 0.326 \text{ kW}$$

Hence, **the least rate of heat rejection = 0.326 kW. (Ans.)**

- *A fish freezing plant requires 40 tons of refrigeration. The freezing temperature is –35°C while the ambient temperature is 30°C. If the performance of the plant is 20% of the theoretical reversed Carnot cycle working within the same temperature limits, calculate the power required.*
- *Given : 1 ton of refrigeration = 210 kJ/min.*

Solution. Cooling required = 40 tons = 40 × 210

= 8400 kJ/min

Ambient temperature, $T_1 = 30 + 273 = 303$ K

Freezing temperature, $T_2 = -35 + 273 = 238$ K

Performance of plant = 20% of the theoretical reversed Carnot cycle

$$(\text{C.O.P.})_{refrigerator} = \frac{T_2}{T_1 - T_2} = \frac{238}{303 - 238} = 3.66$$

$\therefore$ Actual C.O.P = 0.20 × 3.66 = 0.732

Now work needed to produce cooling of 40 tons is calculated as follows :

$$(\text{C.O.P.})_{actual} = \frac{\text{Cooling reqd.}}{\text{Work needed}}$$

$$0.732 = \frac{8400}{W} \quad \text{or} \quad W = \frac{8400}{0.732} \text{ kJ/min} = 191.25 \text{ kJ/s} = 191.25 \text{ kW}$$

Hence, **power required = 191.25 kW. (Ans.)**

- *Source 1 can supply energy at the rate of 12000 kJ/min at 320°C. A second source 2 can supply energy at the rate of 120000 kJ/min at 70°C. Which source (1 or 2) would you choose to supply energy to an ideal reversible heat engine that is to produce large amount of power if the temperature of the surroundings is 35°C ?*

Solution. Source 1 :

Rate of supply of energy = 12000 kJ/min

Temperature, $T_1 = 320 + 273 = 593$ K.

Source 2 :

Rate of supply of energy = 120000 kJ/min

Temperature, $T_1 = 70 + 273 = 343$ K

Temperature of the surroundings, $T_2 = 35°C + 273 = 308$ K

Let the Carnot engine be working in the two cases with the two source temperatures and the single sink temperature. The efficiency of the cycle will be given by :

$$\eta_1 = 1 - \frac{T_2}{T_1} = 1 - \frac{308}{593} = 0.4806 \quad \text{or} \quad 48.06\%$$

$$\eta_2 = 1 - \frac{T_2}{T_1} = 1 - \frac{308}{343} = 0.102 \quad \text{or} \quad 10.2\%$$

$\therefore$ The work delivered in the two cases is given by

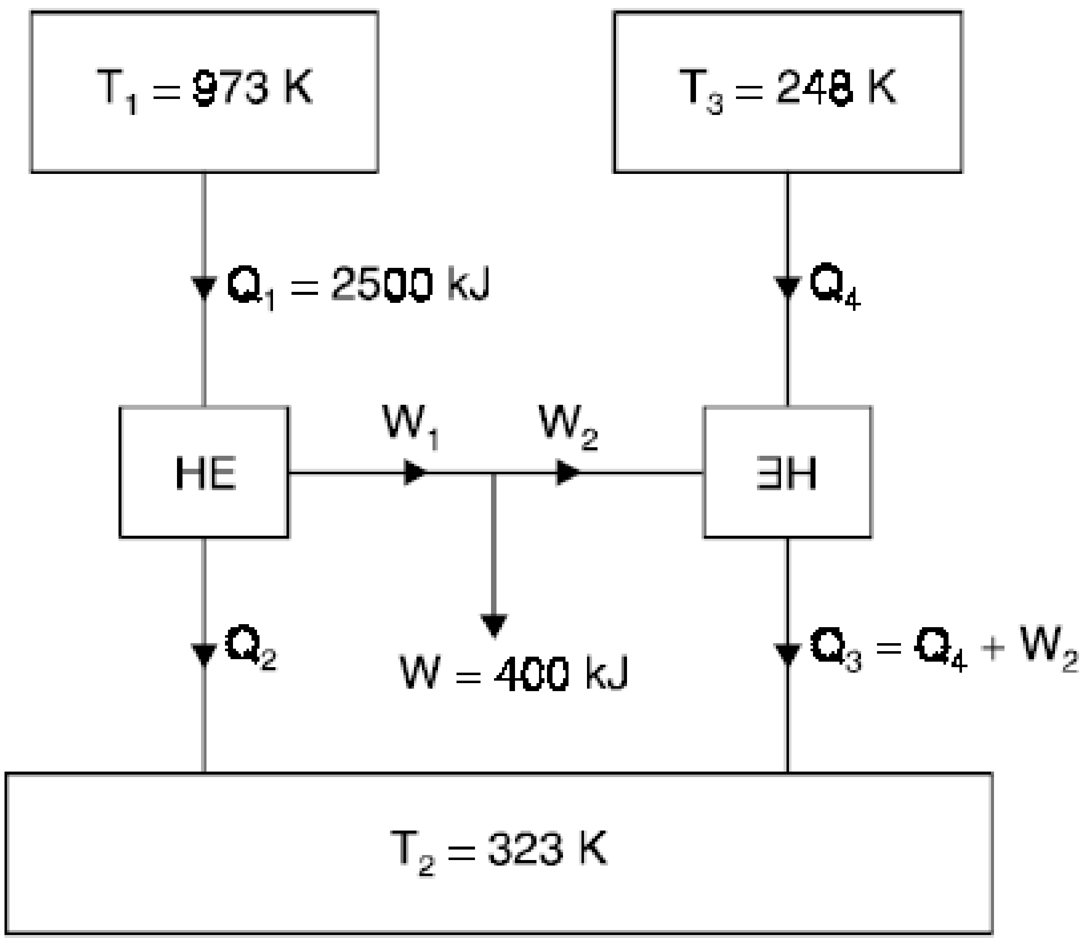
$$W_1 = 12000 \times 0.4806 = 5767.2 \text{ kJ/min}$$

and $$W_2 = 120000 \times 0.102 = 12240 \text{ kJ/min.}$$

Thus, choose **source 2**. **(Ans.)**

Note. The source 2 is selected even though *efficiency* in this case is *lower*, because the *criterion for selection is the larger output.*

- *A reversible heat engine operates between two reservoirs at temperatures 700°C and 50°C. The engine drives a reversible refrigerator which operates between reservoirs at temperatures of 50°C and – 25°C. The heat transfer to the engine is 2500 kJ and the net work output of the combined engine refrigerator plant is 400 kJ.*
- (*i) Determine the heat transfer to the refrigerant and the net heat transfer to the reservoir at 50°C ;*
- (*ii) Reconsider (i) given that the efficiency of the heat engine and the C.O.P. of the refrigerator are each 45 per cent of their maximum possible values.*



$T_1 = 973$ K
$T_3 = 248$ K
$Q_1 = 2500$ kJ
Q_4
HE
W_1
W_2
ƎH
Q_2
$W = 400$ kJ
$Q_3 = Q_4 + W_2$
$T_2 = 323$ K

Temperature, $T_1 = 700 + 273 = 973$ K

Temperature, $T_2 = 50 + 273 = 323$ K

Temperature, $T_3 = -25 + 273 = 248$ K

The heat transfer to the heat engine, $Q_1 = 2500$ kJ

The network output of the combined engine refrigerator plant,

$$W = W_1 - W_2 = 400 \text{ kJ.}$$

(*i*) Maximum efficiency of the heat engine cycle is given by

$$\eta_{max} = 1 - \frac{T_2}{T_1} = 1 - \frac{323}{973} = 0.668$$

Again,
$$\frac{W_1}{Q_1} = 0.668$$

$\therefore$
$$W_1 = 0.668 \times 2500 = 1670 \text{ kJ}$$

$$(\text{C.O.P.})_{max} = \frac{T_3}{T_2 - T_3} = \frac{248}{323 - 248} = 3.306$$

Also,
$$\text{C.O.P.} = \frac{Q_4}{W_2} = 3.306$$

Since, $$W_1 - W_2 = W = 400 \text{ kJ}$$

$$W_2 = W_1 - W = 1670 - 400 = 1270 \text{ kJ}$$

$\therefore$ $$Q_4 = 3.306 \times 1270 = 4198.6 \text{ kJ}$$

$$Q_3 = Q_4 + W_2 = 4198.6 + 1270 = 5468.6 \text{ kJ}$$

$$Q_2 = Q_1 - W_1 = 2500 - 1670 = 830 \text{ kJ.}$$

Heat rejection to the 50°C reservoir

$$= Q_2 + Q_3 = 830 + 5468.6 = \mathbf{6298.6 \text{ kJ.}} \quad \textbf{(Ans.)}$$

(*ii*) Efficiency of actual heat engine cycle,

$$\eta = 0.45\ \eta_{max} = 0.45 \times 0.668 = 0.3$$

$\therefore$ $$W_1 = \eta \times Q_1 = 0.3 \times 2500 = 750 \text{ kJ}$$

$\therefore$ $$W_2 = 750 - 400 = 350 \text{ kJ}$$

C.O.P. of the actual refrigerator cycle,

$$\text{C.O.P.} = \frac{Q_4}{W_2} = 0.45 \times 3.306 = 1.48$$

$\therefore$ $$Q_4 = 350 \times 1.48 = \mathbf{518 \text{ kJ.}} \quad \textbf{(Ans.)}$$

$$Q_3 = 518 + 350 = 868 \text{ kJ}$$

$$Q_2 = 2500 - 750 = 1750 \text{ kJ}$$

Heat rejected to 50°C reservoir

$$= Q_2 + Q_3 = 1750 + 868 = \mathbf{2618 \text{ kJ.}} \quad \textbf{(Ans.)}$$