## EXAMPLE 4.1

(*i*) The capacity of a refrigeration system is specified to be 12 tons. What is then the cooling rate of the machine ?

(*ii*) 250 litres of drinking water is required per hour at 10°C. Would the use of 1.5 ton refrigerating system be justified if the available water is at 30°C ?

(*iii*) A refrigerating machine takes 1.25 kW and produces 25 kg/hr of ice at 0°C from water available at 30°C. Determine refrigerating effect, tonnage and coefficient of performance of machine. Take

Specific heat of water = 4.18 kJ/kg K

Enthalpy of solidification of water from and at 0°C = 335 kJ/kg

**Solution:** (*i*) 1 ton of refrigeration $\equiv 3.5$ kJ/s

$\therefore$ Cooling rate of machine $= 12 \times 3.5 = 42$ kJ/s

(*ii*) Refrigeration effect required for cooling the water

$$= mc_p \Delta T = 250 \times 4.18 \times (30\text{-}10) = 20900 \text{ kJ/hr}$$

1 ton of refrigeration $\equiv 3.5$ kJ/s $= 12600$ kJ/hr

$$\therefore \quad \text{Tonnage required} = \frac{20900}{12600} = 1.658$$

As such, the use of 1.5 ton machine will not serve the purpose.

(*iii*) Refrigeration effect

$$\equiv \text{removal of heat from water at 30°C to convert into ice at 0°C}$$

$$= m[c_{pw} \Delta T + L] = 25[4.18(30\text{-}0) + 335] = 11510 \text{ kJ/hr}$$

1 ton of refrigeration $\equiv 3.5$ kJ/s $= 12600$ kJ/hr

$$\therefore \quad \text{Tonnage required} = \frac{11510}{12600} = 0.913$$

$$COP = \frac{\text{refrigerating effect}}{\text{work input}}$$

$$= \frac{11510/3600}{1.25} = 2.558$$

## EXAMPLE 4.2

**A metal beaker contains water initially at room temperature and the water is cooled by gradually adding ice water to it. When the water temperature reaches 13°C, the moisture from room air begins to condense on the beaker. Make calculations for the specific humidity and parts by mass of water vapour in the room air. Take:**

**room air temperature = 22°C and barometric pressure = 1.01325 bar**

**Solution :** From steam tables, the partial pressure of water vapour at *dpt* of 12.5°C

$$p_v = 1500 \text{ N/m}^2$$

partial pressure of dry air

$$p_a = 101325 - 1500 = 99825 \text{ N/m}^2$$

(*a*) Specific humidity or humidity ratio,

$$\omega = \frac{m_v}{m_a} = 0.622\frac{p_v}{p_a} = 0.622 \times \frac{1500}{99825} = \mathbf{0.009346} \text{ kg/kg of dry air}$$

(*b*) Parts of mass of water vapour,

$$\frac{m_v}{m} = \frac{\omega}{1+\omega} = \frac{0.009346}{1+0.00934} = \mathbf{0.00926} \text{ kg/kg of mixture}$$

## EXAMPLE 4.3

**The air supplied to an air-conditioned room is noted to be at temperature 20°C and specific humidity 0.0085. Corresponding to these conditions, detetrmine the partial pressure of vapour, relative humdiity and dew point temperature.**

**Take barometric or total pressure = 1.0132 bar**

**Solution :** Specific humidity

$$\omega = 0.622\frac{p_v}{p_a} = 0.622\frac{p_v}{p_t - p_v}$$

Thus : $$0.0085 = 0.622\frac{p_v}{1.0132 - p_v}$$

∴ Partial pressure of vapour

$$p_v = \frac{1.0132 \times 0.0085}{0.622 + 0.0085} = \mathbf{0.01366} \text{ bar}$$

(*b*) The relative humidity is defined as $\phi = p_v/p_{vs}$ . From steam tables, the saturation vapour pressure at 20°C = 0.0234 bar.

Then: $$\phi = \frac{0.01366}{0.0234} = 0.5837 \quad \text{or} \quad \mathbf{58.38\%}$$

(*c*) The dew point temperature is the saturation temperature of water at a pressure of 0.01366 bar

DPT (from steam tables by interpolation)

$$= 11 + (12-11) \times \frac{(0.01366 - 0.01312)}{0.01401 - 0.01312} = 11 + 0.607 = \mathbf{11.607°C}$$

**Example 2.2.** *A machine working on a Carnot cycle operates between 305 K and 260 K. Determine the C.O.P. when it is operated as: 1. a refrigerating machine; 2. a heat pump; and 3. a heat engine.*

**Solution.** Given : $T_2 = 305$ K ; $T_1 = 260$ K

**1.** ***C.O.P. of a refrigerating machine***

We know that C.O.P. of a refrigerating machine,

$$(\text{C.O.P.})_R = \frac{T_1}{T_2 - T_1} = \frac{260}{305 - 260} = 5.78 \textbf{ Ans.}$$

**2.** ***C.O.P. of a heat pump***

*We know that C.O.P. of a heat pump,

$$(\text{C.O.P.})_P = \frac{T_2}{T_2 - T_1} = \frac{305}{305 - 260} = 6.78 \textbf{ Ans.}$$

**3.** ***C.O.P. of a heat engine***

**We know that C.O.P. of a heat engine,

$$(\text{C.O.P.})_E = \frac{T_2 - T_1}{T_2} = \frac{305 - 260}{305} = 0.147 \textbf{ Ans.}$$

**Example 2.3.** *A Carnot refrigeration cycle absorbs heat at 270 K and rejects it at 300 K.*

1. *Calculate the coefficient of performance of this refrigeration cycle.*
2. *If the cycle is absorbing 1130 kJ/min at 270 K, how many kJ of work is required per second ?*
3. *If the Carnot heat pump operates between the same temperatures as the above refrigeration cycle, what is the coefficient of performance ?*
4. *How many kJ/min will the heat pump deliver at 300 K if it absorbs* $Q_1$ *1130 kJ/min at 270 K.*

**Solution.** Given : $T_1 = 270$ K ; $T_2 = 300$ K

**1.** ***Coefficient of performance of Carnot refrigeration cycle***

We know that coefficient of performance of Carnot refrigeration cycle,

$$(\text{C.O.P.})_R = \frac{T_1}{T_2 - T_1} = \frac{270}{300 - 270} = 9 \textbf{ Ans.}$$

---

* We know that C.O.P. of a heat pump, $(\text{C.O.P.})_P = (\text{C.O.P.})_R + 1 = 5.78 + 1 = 6.78$ **Ans.**

** We know that C.O.P. of a heat engine, $(\text{C.O.P.})_E = \dfrac{1}{(\text{C.O.P.})_P} = \dfrac{1}{6.78} = 0.147$ **Ans.**

**2. *Work required per second***

Let $W_R$ = Work required per second.

Heat absorbed at 270 K (*i.e.* $T_1$),

$$Q_1 = 1130 \text{ kJ/min} = 18.83 \text{ kJ/s} \quad \text{...(Given)}$$

We know that $$(\text{C.O.P.})_R = \frac{Q_1}{W_R} \quad \text{or} \quad 9 = \frac{18.83}{W_R}$$

$\therefore$ $$W_R = 2.1 \text{ kJ/s} \quad \textbf{Ans.}$$

**3. *Coefficient of performance of Carnot heat pump***

We know that coefficient of performance of a Carnot heat pump,

$$(\text{C.O.P.})_P = \frac{T_2}{T_2 - T_1} = \frac{300}{300 - 270} = 10 \quad \textbf{Ans.}$$

**4. *Heat delivered by heat pump at 300 K***

Let $Q_2$ = Heat delivered by heat pump at 300 K.

Heat absorbed at 270 K (*i.e.* $T_1$),

$$Q_1 = 1130 \text{ kJ/min} \quad \text{... (Given)}$$

We know that

$$(\text{C.O.P.})_P = \frac{Q_2}{Q_2 - Q_1} \quad \text{or} \quad 10 = \frac{Q_2}{Q_2 - 1130}$$

$\therefore$ $$10Q_2 - 11\,300 = Q_2 \quad \text{or} \quad Q_2 = 1256 \text{ kJ/min} \quad \textbf{Ans.}$$

**Example 2.4.** *A cold storage is to be maintained at –5°C while the surroundings are at 35°C. The heat leakage from the surroundings into the cold storage is estimated to be 29 kW. The actual C.O.P. of the refrigeration plant is one-third of an ideal plant working between the same temperatures. Find the power required to drive the plant.*

**Solution.** Given : $T_1 = -5°C = -5 + 273 = 268$ K; $T_2 = 35°C = 35 + 273 = 308$ K ; $Q_1 = 29$ kW ;

$$(\text{C.O.P.})_{actual} = \frac{1}{3}(\text{C.O.P.})_{ideal}$$

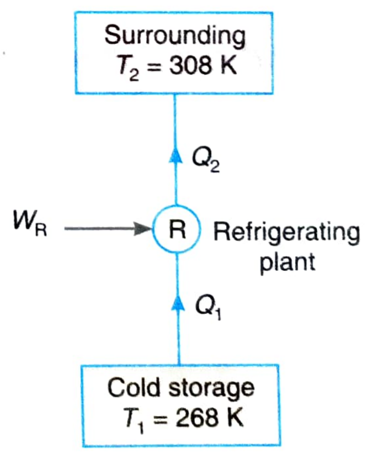



**Fig. 2.3**

The refrigerating plant operating between the temperatures $T_1$ and $T_2$ is shown in Fig. 2.3.

Let $W_R$ = Work or power required to drive the plant.

We know that the coefficient of performance of an ideal refrigeration plant,

$$(\text{C.O.P.})_{ideal} = \frac{T_1}{T_2 - T_1} = \frac{268}{308 - 268} = 6.7$$

$\therefore$ Actual coefficient of performance,

$$(\text{C.O.P.})_{actual} = \frac{1}{3}(\text{C.O.P.})_{ideal} = \frac{1}{3} \times 6.7 = 2.233$$

We also know that $$(\text{C.O.P.})_{actual} = \frac{Q_1}{W_R}$$

$\therefore$ $$W_R = \frac{Q_1}{(\text{C.O.P.})_{actual}} = \frac{29}{2.233} = 12.987 \text{ kW} \quad \textbf{Ans.}$$

**Example 2.5.** *Two refrigerators A and B operate in series. The refrigerator A absorbs energy at the rate of 1kJ/s from a body at temperature 300 K and rejects energy as heat to a body at temperature T. The refrigerator B absorbs the same quantity of energy which is rejected by the refrigerator A from the body at temperature T, and rejects energy as heat to a body at temperature 1000 K. If both the refrigerators have the same C.O.P., calculate:*

*1. The temperature T of the body;*

*2. The C.O.P. of the refrigerators; and*

*3. The rate at which energy is rejected as heat to the body at 1000 K.*

**Solution.** Given : $Q_1 = 1$ kJ/s ; $T_1 = 300$ K ; $T_2 = T$ ; $T_3 = 1000$ K

The arrangement of the refrigerators $A$ and $B$ is shown in Fig. 2.4.

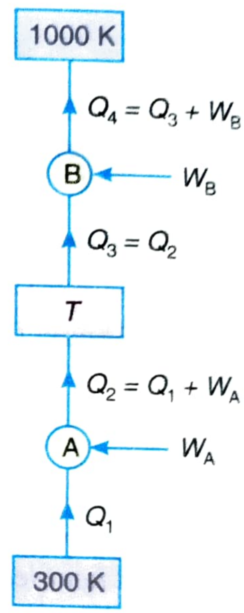



**Fig. 2.4**

*1. Temperature T of the body*

We know that C.O.P. for refrigerator $A$,

$$(\text{C.O.P.})_A = \frac{T_1}{T_2 - T_1} = \frac{300}{T - 300} \quad ...(i)$$

and C.O.P. for refrigerator $B$,

$$(\text{C.O.P.})_B = \frac{T_2}{T_3 - T_2} = \frac{T}{1000 - T} \quad ...(ii)$$

Since C.O.P. of both the refrigerators is same, therefore equating equations ($i$) and ($ii$),

$$\frac{300}{T - 300} = \frac{T}{1000 - T}$$

or $$300 \times 1000 - 300\,T = T^2 - 300\,T$$

$$\therefore \quad T = \sqrt{300 \times 1000} = 547.7 \text{ K} \quad \textbf{Ans.}$$

*2. C.O.P. of the refrigerators*

Since C.O.P. of both the refrigerators is same, therefore substituting the value of $T$ in equation ($i$) or equation ($ii$),

$$(\text{C.O.P.})_A = (\text{C.O.P.})_B = \frac{300}{547.7 - 300} = 1.21 \quad \textbf{Ans.}$$

*3. Rate at which energy is rejected as heat to the body at 1000 K*

We know that work done by refrigerator $A$,

$$W_A = \frac{Q_1}{(\text{C.O.P.})_A} = \frac{1}{1.21} = 0.826 \text{ kJ/s}$$

and heat rejected by refrigerator $A$,

$$Q_2 = Q_1 + W_A = 1 + 0.826 = 1.826 \text{ kJ/s}$$

Now workdone by refrigerator $B$,

$$W_B = \frac{Q_3}{(\text{C.O.P.})_B} = \frac{1.826}{1.21} = 1.51 \text{ kJ/s} \quad ...(\because Q_3 = Q_2)$$

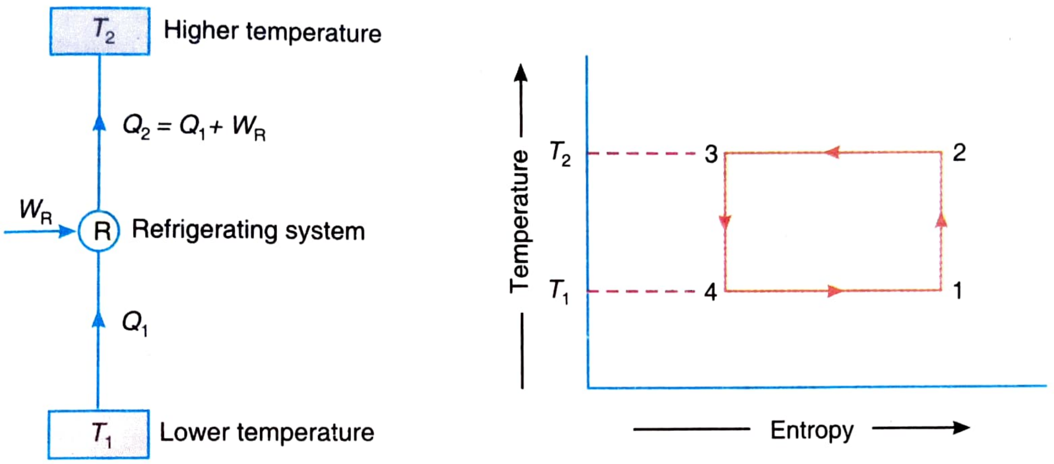
$\therefore$ Heat rejected to the body at 1000 K,

$$Q_4 = Q_3 + W_B = 1.826 + 1.51 = 3.336 \text{ kJ/s} \quad \textbf{Ans.}$$

**Example 2.6.** *A refrigerating system operates on the reversed Carnot cycle. The higher temperature of the refrigerant in the system is 35°C and the lower temperature is – 15°C. The capacity is to be 12 tonnes. Determine : 1. C.O.P. ; 2. Heat rejected from the system per hour ; and 3. Power required.*

**Solution.** Given : $T_2 = 35°\text{C} = 35 + 273 = 308$ K ; $T_1 = -15°\text{C} = -15 + 273 = 258$ K ; $Q_1 = 12$ TR $= 12 \times 210 = 2520$ kJ/min

The refrigerating system operating on the reversed Carnot cycle is shown in Fig. 2.5.




(*a*) (*b*)

**Fig. 2.5**

### 1. *C.O.P.*

We know that

$$(\text{C.O.P.})_R = \frac{T_1}{T_2 - T_1} = \frac{258}{308 - 258} = 5.16 \textbf{ Ans.}$$

### 2. *Heat rejected from the system per hour*

Let $W_R$ = Work or power required to drive the system.

We know that $(\text{C.O.P.})_R = \dfrac{Q_1}{W_R}$

$$\therefore \quad W_R = \frac{Q_1}{(\text{C.O.P.})_R} = \frac{2520}{5.16} = 488.37 \text{ kJ/min}$$

and heat rejected from the system,

$$Q_2 = Q_1 + W_R = 2520 + 488.37 = 3008.37 \text{ kJ/min}$$

$$= 3008.37 \times 60 = 180\,502.2 \text{ kJ/h} \textbf{ Ans.}$$

### 3. *Power required*

We know that work or power required,

$$W_R = 488.37 \text{ kJ/min} = \frac{488.37}{60} = 8.14 \text{ kJ/s or kW} \textbf{ Ans.}$$

**Example 2.7.** *1.5 kW per tonne of refrigeration is required to maintain the temperature of − 40°C in the refrigerator. If the refrigeration cycle works on Carnot cycle, determine the following:*

*1. C.O.P. of the cycle ; 2. Temperature of the sink ; 3. Heat rejected to the sink per tonne of refrigeration ; and 4. Heat supplied and E.P.R., if the cycle is used as a heat pump.*

**Solution.** Given : $W_R = 1.5$ kW ; $Q_1 = 1$ TR ; $T_1 = -40°C = -40 + 273 = 233$ K

*1. C.O.P. of the cycle*

The refrigeration cycle working on Carnot cycle is shown in Fig 2.6.

Since 1.5 kW per tonne of refrigeration is required to maintain the temperature in the refrigerator, therefore amount of work required to be done,

$$W_R = 1.5 \text{ kW} = 1.5 \text{ kJ/s} = 1.5 \times 60 = 90 \text{ kJ/min}$$

and heat extracted from the cold body,

$$Q_1 = 1 \text{ TR} = 210 \text{ kJ/min}$$

We know that $$(\text{C.O.P.})_R = \frac{Q_1}{W_R} = \frac{210}{90} = 2.33 \textbf{ Ans.}$$

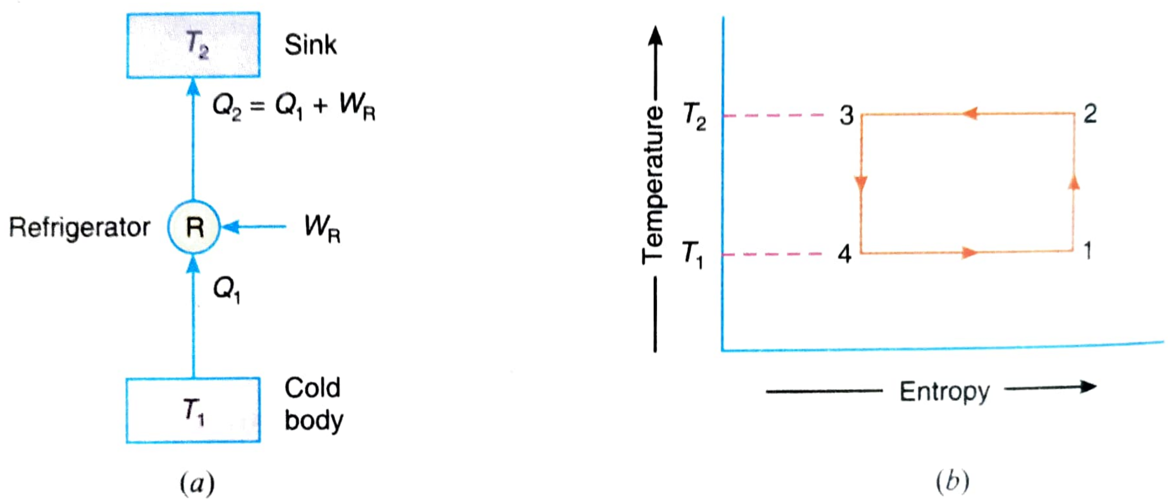



**Fig. 2.6**

*2. Temperature of the sink*

Let $T_2$ = Temperature of the sink.

We know that $$(\text{C.O.P.})_R = \frac{T_1}{T_2 - T_1} \quad \text{or} \quad 2.33 = \frac{233}{T_2 - 233}$$

$$\therefore \quad T_2 = \frac{233}{2.33} + 233 = 333 \text{ K} = 333 - 273 = 60°\text{C} \textbf{ Ans.}$$

*3. Heat rejected to the sink per tonne of refrigeration*

We know that heat rejected to the sink,

$$Q_2 = Q_1 + W_R = 210 + 90 = 300 \text{ kJ/min} \textbf{ Ans.}$$

*4. Heat supplied and E.P.R., if the cycle is used as a heat pump*

We know that heat supplied when the cycle is used as a heat pump is

$$Q_2 = 300 \text{ kJ/min} \textbf{ Ans.}$$

and $$\text{E.P.R.} = (\text{C.O.P.})_R + 1 = 2.33 + 1 = 3.33 \textbf{ Ans.}$$

**Example 2.8.** *The capacity of a refrigerator is 200 TR when working between – 6°C and 25°C. Determine the mass of ice produced per day from water at 25°C. Also find the power required to drive the unit. Assume that the cycle operates on reversed Carnot cycle and latent heat of ice is 335 kJ/kg.*

**Solution.** Given : $Q = 200$ TR ; $T_1 = -6°C = -6 + 273 = 267$ K ; $T_2 = 25°C = 25 + 273 = 298$ K ; $t_w = 25°C$ ; $h_{fg(ice)} = 335$ kJ/kg

***Mass of ice produced per day***

We know that heat extraction capacity of the refrigerator

$$= 200 \times 210 = 42\ 000 \text{ kJ/min} \quad \ldots (\because 1\text{TR} = 210 \text{ kJ/min})$$

and heat removed from 1 kg of water at 25°C to form ice at 0°C

$$= \text{Mass} \times \text{Sp. heat} \times \text{Rise in temperature} + h_{fg(ice)}$$

$$= 1 \times 4.187(25 - 0) + 335 = 439.7 \text{ kJ / kg}$$

∴ Mass of ice produced per min

$$= \frac{42\ 000}{439.7} = 95.52 \text{ kg / min}$$

and mass of ice produced per day $= 95.52 \times 60 \times 24 = 137\ 550$ kg $= 137.55$ tonnes **Ans.**

***Power required to drive the unit***

We know that C.O.P. of the reversed Carnot cycle

$$= \frac{T_1}{T_2 - T_1} = \frac{267}{298 - 267} = 8.6$$

Also
$$\text{C.O.P.} = \frac{\text{Heat extraction capacity}}{\text{Work done per min}}$$

∴
$$8.6 = \frac{42\ 000}{\text{Work done per min}}$$

or
$$\text{Work done per min} = 42\ 000 / 8.6 = 4884 \text{ kJ/min}$$

∴ Power required to drive the unit

$$= 4884 / 60 = 81.4 \text{ kW}$$ **Ans.**

**Example 2.9.** *Five hundred kgs of fruits are supplied to a cold storage at 20°C. The cold storage is maintained at –5°C and the fruits get cooled to the storage temperature in 10 hours. The latent heat of freezing is 105 kJ/kg and specific heat of fruit is 1.256 kJ/kg K. Find the refrigeration capacity of the plant.*

**Solution.** Given : $m = 500$ kg ; $T_2 = 20°C = 20 + 273 = 293$ K; $T_1 = -5°C = -5 + 273 = 268$ K ; $h_{fg} = 105$ kJ/kg ; $c_F = 1.256$ kJ/kg K

We know that heat removed from the fruits in 10 hours,

$$Q_1 = m\, c_F (T_2 - T_1)$$

$$= 500 \times 1.256\ (293 - 268) = 15\ 700 \text{ kJ}$$

and total latent heat of freezing,

$$Q_2 = m \times h_{fg} = 500 \times 105 = 52\ 500 \text{ kJ}$$

∴ Total heat removed in 10 hours,

$$Q = Q_1 + Q_2 = 15\ 700 + 52\ 500 = 68\ 200 \text{ kJ}$$

and total heat removed in one minute

$= 68\,200/10 \times 60 = 113.7$ kJ/min

$\therefore$ Refrigeration capacity of the plant

$= 113.7/210 = 0.541$ TR **Ans.** ...($\because$ 1TR = 210 kJ/min)

**Example 2.10.** *A cold storage plant is required to store 20 tonnes of fish. The fish is supplied at a temperature of 30°C. The specific heat of fish above freezing point is 2.93 kJ/kg K. The specific heat of fish below freezing point is 1.26 kJ/kg K. The fish is stored in cold storage which is maintained at – 8°C. The freezing point of fish is – 4°C. The latent heat of fish is 235 kJ/kg. If the plant requires 75 kW to drive it, find :*

*1. The capacity of the plant, and 2. Time taken to achieve cooling.*

*Assume actual C.O.P. of the plant as 0.3 of the Carnot C.O.P.*

**Solution.** Given : $m = 20$ t $= 20\,000$ kg ; $T_2 = 30°C = 30 + 273 = 303$ K ; $c_{AF} = 2.93$ kJ/kg K ; $c_{BF} = 1.26$ kJ/kgK ; $T_1 = -8°C = -8 + 273 = 265$ K ; $T_3 = -4°C = -4 + 273 = 269$ K; $h_{fg(Fish)} = 235$ kJ/kg ; $P = 75$ kW $= 75$ kJ/s

**1.** ***Capacity of the plant***

We know that Carnot C.O.P.

$$= \frac{T_1}{T_2 - T_1} = \frac{265}{303 - 265} = 6.97$$

$\therefore$ Actual C.O.P. $= 0.3 \times 6.97 = 2.091$

and heat removed by the plant = Actual C.O.P. × Work required

$= 2.091 \times 75 = 156.8$ kJ/s

$= 156.8 \times 60$ kJ/min $= 9408$ kJ/min

$\therefore$ Capacity of the plant

$= 9408 / 210 = 44.8$ TR **Ans.** ... ($\because$ 1TR = 210 kJ/min)

**2.** ***Time taken to achieve cooling***

We know that heat removed from the fish above freezing point,

$$Q_1 = m \times c_{AF}(T_2 - T_3)$$
$$= 20\,000 \times 2.93\,(303 - 269) = 1.992 \times 10^6 \text{ kJ}$$

Similarly, heat removed from the fish below freezing point,

$$Q_2 = m \times c_{BF}(T_3 - T_1)$$
$$= 20\,000 \times 1.26\,(269 - 265) = 0.101 \times 10^6 \text{ kJ}$$

and total latent heat of fish,

$$Q_3 = m \times h_{fg(Fish)} = 20\,000 \times 235 = 4.7 \times 10^6 \text{ kJ}$$

$\therefore$ Total heat removed by the plant

$$= Q_1 + Q_2 + Q_3$$
$$= 1.992 \times 10^6 + 0.101 \times 10^6 + 4.7 \times 10^6 = 6.793 \times 10^6 \text{ kJ}$$

and time taken to achieve cooling

$$= \frac{\text{Total heat removed by the plant}}{\text{Heat removed by the plant per min}}$$

$$= \frac{6.793 \times 10^6}{9408} = 722 \text{ min} = 12.03 \text{ h}$$ **Ans.**

*refrigeration efficiency* ($\eta_R$) or performance index (P.I.).

**Example 4.1.** *In an ammonia vapour compression system, the pressure in the evaporator is 2 bar. Ammonia at exit is 0.85 dry and at entry its dryness fraction is 0.19. During compression, the work done per kg of ammonia is 150 kJ. Calculate the C.O.P. and the volume of vapour entering the compressor per minute, if the rate of ammonia circulation is 4.5 kg/min. The latent heat and specific volume at 2 bar are 1325 kJ/kg and 0.58 m³/kg respectively.*

**Solution.** Given : $p_1 = p_4 = 2$ bar ; $x_1 = 0.85$ ; $x_4 = 0.19$ ; $w = 150$ kJ/kg ; $m_a = 4.5$ kg/min ; $h_{fg} = 1325$ kJ/kg ; $v_g = 0.58$ m³/kg

*C.O.P.*

The *T-s* and *p-h* diagrams are shown in Fig. 4.3 (*a*) and (*b*) respectively.

Since the ammonia vapour at entry to the evaporator (*i.e.* at point 4) has dryness fraction ($x_4$) equal to 0.19, therefore enthalpy at point 4,

$$h_4 = x_4 \times h_{fg} = 0.19 \times 1325 = 251.75 \text{ kJ/kg}$$

Similarly, enthalpy of ammonia vapour at exit *i.e.* at point 1,

$$h_1 = x_1 \times h_{fg} = 0.85 \times 1325 = 1126.25 \text{ kJ/kg}$$

∴ Heat extracted from the evaporator or refrigerating effect,

$$R_E = h_1 - h_4 = 1126.25 - 251.75 = 874.5 \text{ kJ/kg}$$

We know that work done during compression,

$$w = 150 \text{ kJ/kg}$$

$$\therefore \quad \text{C.O.P.} = R_E / w = 874.5 / 150 = 5.83 \text{ Ans.}$$

*Volume of vapour entering the compressor per minute*

We know that volume of vapour entering the compressor per minute

= Mass of refrigerant / min × Specific volume

$= m_a \times v_g = 4.5 \times 0.58 = 2.61$ m³/min **Ans.**

**Example 4.2.** *The temperature limits of an ammonia refrigerating system are 25°C and –10°C. If the gas is dry at the end of compression, calculate the coefficient of performance of the cycle assuming no undercooling of the liquid ammonia. Use the following table for properties of ammonia :*

| *Temperature (°C)* | *Liquid heat (kJ/kg)* | *Latent heat (kJ/kg)* | *Liquid entropy (kJ/kg K)* |
|---|---|---|---|
| 25 | 298.9 | 1166.94 | 1.1242 |
| –10 | 135.37 | 1297.68 | 0.5443 |

**Solution.** Given : $T_2 = T_3 = 25°C = 25 + 273 = 298$ K ; $T_1 = T_4 = -10°$ C $= -10 + 273 = 263$ K ; $h_{f3} = h_4 = 298.9$ kJ/kg ; $h_{fg2} = 1166.94$ kJ/kg ; $s_{f2} = 1.1242$ kJ/kg K ; $h_{f1} = 135.37$ kJ/ kg ; $h_{fg1} = 1297.68$ kJ/kg ; $s_{f1} = 0.5443$ kJ/kg K

The *T-s* and *p-h* diagrams are shown in Fig. 4.4 (*a*) and (*b*) respectively.

Let $x_1$ = Dryness fraction at point 1.

We know that entropy at point 1,

$$s_1 = s_{f1} + \frac{x_1 h_{fg1}}{T_1} = 0.5443 + \frac{x_1 \times 1297.68}{263}$$

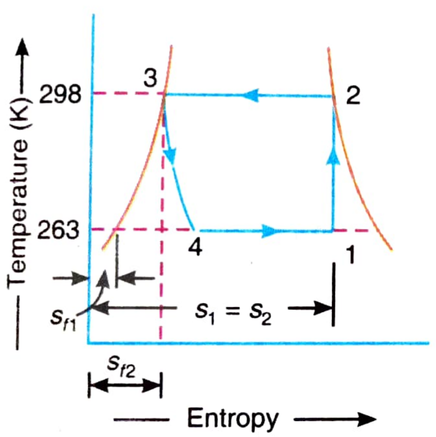
$$= 0.5443 + 4.934\, x_1 \quad \ldots (i)$$

Similarly, entropy at point 2,

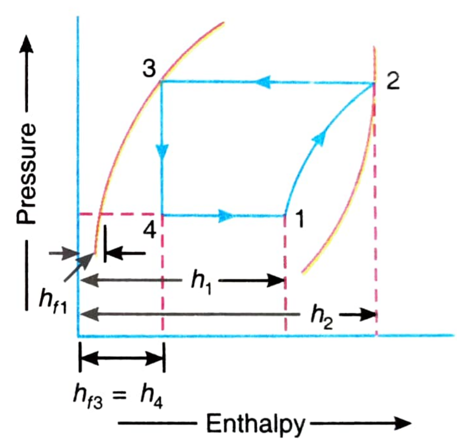
$$s_2 = s_{f2} + \frac{h_{fg2}}{T_2} = 1.1242 + \frac{1166.94}{298} = 5.04 \quad \ldots (ii)$$

Since the entropy at point 1 is equal to entropy at point 2, therefore equating equations (*i*) and (*ii*),

$$0.5443 + 4.934\, x_1 = 5.04 \quad \text{or} \quad x_1 = 0.91$$




(*a*) *T-s* diagram.




(*b*) *p-h* diagram.

**Fig. 4.4**

We know that enthalpy at point 1,

$$h_1 = h_{f1} + x_1 h_{fg1} = 135.37 + 0.91 \times 1297.68 = 1316.26 \text{ kJ/kg}$$

and enthalpy at point 2,

$$h_2 = h_{f2} + h_{fg2} = 298.9 + 1166.94 = 1465.84 \text{ kJ/kg}$$

∴ Coefficient of performance of the cycle

$$= \frac{h_1 - h_{f3}}{h_2 - h_1} = \frac{1316.26 - 298.9}{1465.84 - 1316.26} = 6.8 \textbf{ Ans.}$$

**Example 4.3.** *A vapour compression refrigerator works between the pressure limits of 60 bar and 25 bar. The working fluid is just dry at the end of compression and there is no under-cooling of the liquid before the expansion valve. Determine : 1. C.O.P. of the cycle ; and 2. Capacity of the refrigerator if the fluid flow is at the rate of 5 kg/min.*

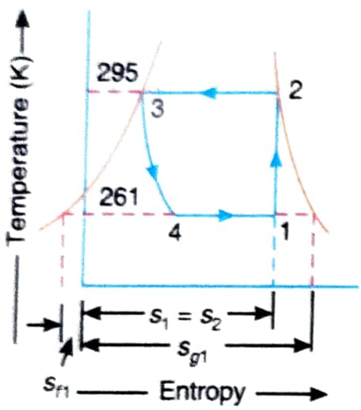
*Data :*

| *Pressure (bar)* | *Saturation temperature (K)* | *Enthalpy (kJ/kg)* | | *Entropy (kJ/kg K)* | |
|---|---|---|---|---|---|
| | | *Liquid* | *Vapour* | *Liquid* | *Vapour* |
| 60 | 295 | 151.96 | 293.29 | 0.554 | 1.0332 |
| 25 | 261 | 56.32 | 322.58 | 0.226 | 1.2464 |

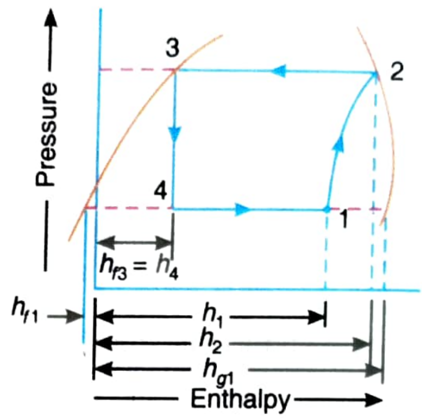
**Solution.** Given : $p_2 = p_3 = 60$ bar ; $p_1 = p_4 = 25$ bar ; $T_2 = T_3 = 295$ K ; $T_1 = T_4 = 261$ K ; $h_{f3} = h_4 = 151.96$ kJ/kg ; $h_{f1} = 56.32$ kJ/kg ; $h_{g2} = h_2 = 293.29$ kJ/kg ; $h_{g1} = 322.58$ kJ/kg ; *$s_{f2} = 0.554$ kJ/kg K ; $s_{f1} = 0.226$ kJ/kg K ; $s_{g2} = s_2 = 1.0332$ kJ/kg K ; $s_{g1} = 1.2464$ kJ/kg K

*1. C.O.P. of the cycle*

The *T-s* and *p-h* diagrams are shown in Fig. 4.5 (*a*) and (*b*) respectively.




(*a*) *T-s* diagram.




(*b*) *p-h* diagram.

**Fig. 4.5**

Let $x_1$ = Dryness fraction of the vapour refrigerant entering the compressor at point 1.

We know that entropy at point 1,

$$s_1 = s_{f1} + x_1 s_{fg1} = s_{f1} + x_1(s_{g1} - s_{f1}) \quad \ldots (\because s_{g1} = s_{f1} + s_{fg1})$$

$$= 0.226 + x_1 (1.2464 - 0.226) = 0.226 + 1.0204\, x_1 \quad \ldots (i)$$

and entropy at point 2, $\quad s_2 = s_{g2} = 1.0332$ kJ/kg K $\quad$ ... (Given) ... (*ii*)

Since the entropy at point 1 is equal to entropy at point 2, therefore equating equations (*i*) and (*ii*),

$$0.226 + 1.0204\, x_1 = 1.0332 \quad \text{or} \quad x_1 = 0.791$$

We know that enthalpy at point 1,

$$h_1 = h_{f1} + x_1 h_{fg1} = h_{f1} + x_1 (h_{g1} - h_{f1}) \ldots (\because h_{g1} = h_{f1} + h_{fg1})$$

$$= 56.32 + 0.791 (322.58 - 56.32) = 266.93 \text{ kJ/kg}$$

∴ C.O.P. of the cycle

$$= \frac{h_1 - h_{f3}}{h_2 - h_1} = \frac{266.93 - 151.96}{293.29 - 266.93} = 4.36 \textbf{ Ans.}$$

*2. Capacity of the refrigerator*

We know that the heat extracted or refrigerating effect produced per kg of refrigerant

$$= h_1 - h_{f3} = 266.93 - 151.96 = 114.97 \text{ kJ/kg}$$

Since the fluid flow is at the rate of 5 kg/min, therefore total heat extracted

$$= 5 \times 114.97 = 574.85 \text{ kJ/min}$$

∴ Capacity of the refrigerator

$$= \frac{574.85}{210} = 2.74 \text{ TR } \textbf{Ans.} \quad \ldots (\because 1 \text{ TR} = 210 \text{ kJ/min})$$

* Superfluous data