14.4.4. Comparison between Vapour Compression and Vapour Absorption Systems

S. No.	*Particulars*	*Vapour compression system*	*Vapour absorption system*
1.	*Type of energy supplied*	Mechanical—a high grade energy	Mainly heat—a low grade energy
2.	*Energy supply*	Low	High
3.	*Wear and tear*	More	Less
4.	*Performance at part loads*	Poor	System not affected by variations of loads.
5.	*Suitability*	Used where high grade mechanical energy is available	Can also be used at remote places as it can work even with a simple kerosene lamp (of course in small capacities)
6.	*Charging of refrigerant*	Simple	Difficult
7.	*Leakage of refrigerant*	More chances	No chance as there is no compressor or any reciprocating component to cause leakage.
8.	*Damage*	Liquid traces in suction line may damage the compressor	Liquid traces of refregerant present in piping at the exit of evaporator constitute no danger.

WORKED EXAMPLES

Example 14.12. *A refrigeration machine is required to produce i.e., at 0°C from water at 20°C. The machine has a condenser temperature of 298 K while the evaporator temperature is 268 K. The relative efficiency of the machine is 50% and 6 kg of Freon-12 refrigerant is circulated through the system per minute. The refrigerant enters the compressor with a dryness fraction of 0.6. Specific heat of water is 4.187 kJ/kg K and the latent heat of ice is 335 kJ/kg. Calculate the amount of ice produced on 24 hours. The table of properties of Freon-12 is given below :*

Temperature K	*Liquid heat kJ/kg*	*Latent heat kJ/g*	*Entropy of liquid kJ/kg*
298	*59.7*	*138.0*	*0.2232*
268	*31.4*	*154.0*	*0.1251*

(U.P.S.C. 1992)

Solution. *Given* : m = 6 kg/min. ; $\eta_{relative}$ = 50% ; x_2 = 0.6 ; c_{pw} = 4.187 kJ/kg K ; Latent heat of ice = 335 kJ/kg.

Refer Fig. 14.23

h_{f_2} = 31.4 kJ/kg ; h_{fg_2} = 154.0 kJ/kg ; h_{f_3} = 59.7 kJ/kg ;

h_{fg_3} = 138 kJ/kg ; h_{f_4} = 59.7 kJ/kg ...From the table given above

$$h_2 = h_{f_2} + x_2 h_{fg_2}$$
$$= 31.4 + 0.6 \times 154 = 123.8 \text{ kJ/kg}$$

For *isentropic compression 2-3*, we have

$$s_3 = s_2$$

$$s_{f_3} + x_3 \frac{h_{fg_3}}{T_3} = s_{f_2} + x_2 \frac{h_{fg_2}}{T_2}$$

$$0.2232 + x_3 \times \frac{138}{298} = 0.1251 + 0.6 \times \frac{154}{268}$$
$$= 0.4698$$

$$\therefore \quad x_3 = (0.4698 - 0.2232) \times \frac{298}{138} = 0.5325$$

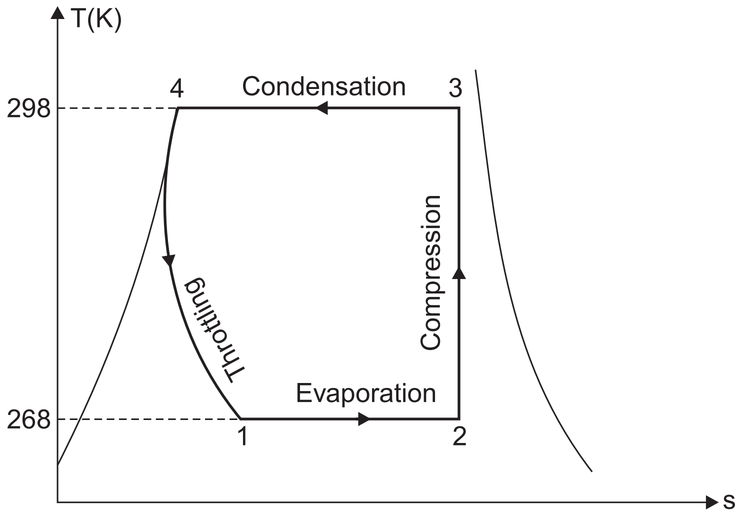

Fig. 14.23

Now, $h_3 = h_{f_3} + x_3\, h_{fg_3} = 59.7 + 0.5325 \times 138 = 133.2$ kJ/kg

Also, $h_1 = h_{f_4} = 59.7$ kJ/kg

Theoretical $\text{C.O.P.} = \frac{R_n}{W} = \frac{h_2 - h_1}{h_3 - h_2} = \frac{123.8 - 59.7}{133.2 - 123.8} = 6.82$

Actual $\text{C.O.P.} = \eta_{relative} \times (\text{C.O.P.})_{theoretical} = 0.5 \times 6.82 = 3.41$

Heat extracted from 1 kg of water at 20°C for the formation of 1 kg of ice at 0°C

$$= 1 \times 4.187 \times (20 - 0) + 335 = 418.74 \text{ kJ/kg}$$

Let m_{ice} = Mass of ice formed in kg/min.

$$(\text{C.O.P.})_{actual} = 3.41 = \frac{R_n(\text{actual})}{W} = \frac{m_{ice} \times 418.74}{m(h_3 - h_2)} = \frac{m_{ice} \times 418.74 \text{ (kJ/min)}}{6(133.2 - 123.8) \text{ (kJ/min)}}$$

$$\therefore \quad m_{ice} = \frac{6(133.2 - 123.8) \times 3.41}{418.74} = 0.459 \text{ kg/min}$$

$$= \frac{0.459 \times 60 \times 24}{1000} \text{ tonnes (in 24 hours)} = \mathbf{0.661 \text{ tonne.}} \quad \textbf{(Ans.)}$$

Example 14.13. *28 tonnes of ice from and at 0°C is produced per day in an ammonia refrigerator. The temperature range in the compressor is from 25°C to – 15°C. The vapour is dry and saturated at the end of compression and an expansion valve is used. Assuming a co-efficient of performance of 62% of the theoretical, calculate the power required to drive the compressor.*

Temp. °C	*Enthalpy (kJ/kg)*		*Entropy of liquid (kJ/kg K)*	*Entropy of vapour kJ/kg K*
	Liquid	*Vapour*		
25	*100.04*	*1319.22*	*0.3473*	*4.4852*
– 15	*– 54.56*	*1304.99*	*– 2.1338*	*5.0585*

Take latent heat of ice = 335 kJ/kg.

Solution. Theoretical C.O.P. $= \dfrac{h_2 - h_1}{h_3 - h_2}$

Here, $h_3 = 1319.22$ kJ/kg ;

$h_1 = h_4$ (*i.e.,* h_{f4}) $= 100.04$ kJ/kg ...From the table above.

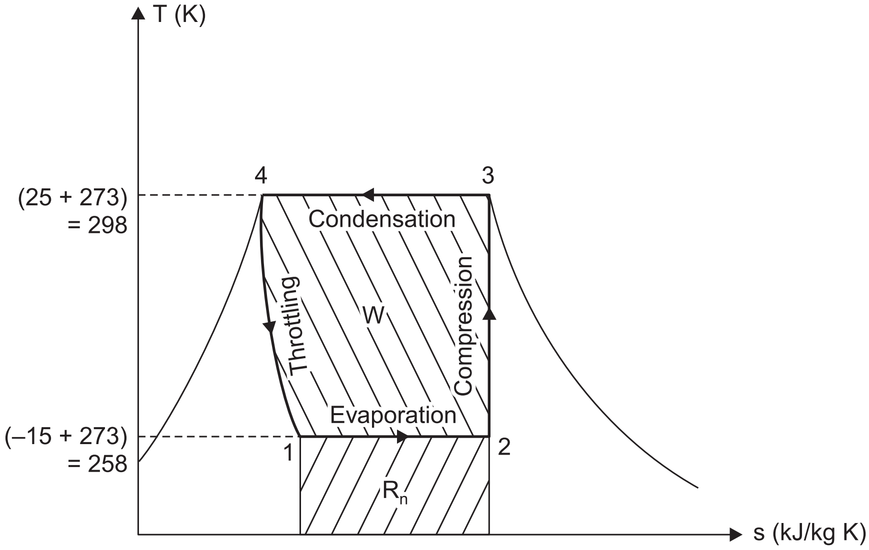

Fig. 14.24

To find h_2, let us first find dryness at point 2.

Entropy at '2' = Entropy at '3' (Process 2-3 being isentropic)

$$s_{f_2} + x_2\, s_{fg_2} = s_{g_3}$$

$$-\,2.1338 + x_2 \times [5.0585 - (-\,2.1338)] = 4.4852$$

$$\therefore \quad x_2 = \frac{4.4852 + 2.1338}{5.0585 + 2.1338} = 0.92$$

$$\therefore \quad h_2 = h_{f_2} + x_2\, h_{fg_2} = -\,54.56 + 0.92 \times [1304.99 - (-\,54.56)]$$

$$= 1196.23 \text{ kJ/kg.}$$

$$\therefore \quad \text{C.O.P.}_{\text{(theoretical)}} = \frac{1196.23 - 100.04}{1319.22 - 1196.23} = 8.91.$$

$\therefore$ C.O.P.$_{\text{(actual)}}$ = 0.62 × C.O.P.$_{\text{(theoretical)}}$ ... Given

i.e., C.O.P.$_{\text{(actual)}}$ = 0.62 × 8.91 = 5.52

Actual refrigerating effect per kg

$= \text{C.O.P.}_{\text{(actual)}} \times \text{work done}$

$= 5.52 \times (h_3 - h_2) = 5.52 \times (1319.22 - 1196.23)$

$= 678.9$ kJ/kg

Heat to be extracted per hour

$$= \frac{28 \times 1000 \times 335}{24} = 390833.33 \text{ kJ}$$

Heat to be extracted per second $= \dfrac{390833.33}{3600} = 108.56$ kJ/s.

$\therefore$ Mass of refrigerant circulated per second $= \dfrac{108.56}{678.9} = 0.1599$ kg

Total work done by the compressor per second

$= 0.1599 \times (h_3 - h_2) = 0.1599\ (1319.22 - 1196.23)$

$= 19.67$ kJ/s

i.e., **Power required to drive the compressor = 19.67 kW. (Ans.)**

Example 14.14. *A refrigerating plant works between temperature limits of – 5°C and 25°C. The working fluid ammonia has a dryness fraction of 0.62 at entry to compressor. If the machine has a relative efficiency of 55%, calculate the amount of ice formed during a period of 24 hours. The ice is to be formed at 0°C from water at 15°C and 6.4 kg of ammonia is circulated per minute. Specific heat of water is 4.187 kJ/kg and latent heat of ice is 335 kJ/kg.*

Properties of NH_3 (datum – 40°C).

Temp. °*C*	*Liquid heat* *kJ/kg*	*Latent heat* *kJ/kg*	*Entropy of liquid* *kJ/kg K*
25	*298.9*	*1167.1*	*1.124*
– 5	*158.2*	*1280.8*	*0.630*

Solution. Fig. 14.25 shows the *T-s* diagram of the cycle.

Enthalpy at point '2', $h_2 = h_{f_2} + x_2\, h_{fg_2} = 158.2 + 0.62 \times 1280.8 = 952.3$ kJ/kg

Enthalpy at point '1', $h_1 = h_{f_4} = 298.9$ kJ/kg

Also, entropy at point '2' = entropy at point '3'

i.e., $s_2 = s_3$

$$s_{f_2} + x_2\, s_{fg_2} = s_{f_3} + x_3\, s_{fg_3}$$

$$0.630 + 0.62 \times \frac{1280.8}{(-5 + 273)} = 1.124 + x_2 \times \frac{1167.1}{(25 + 273)}$$

i.e., $x_3 = 0.63$

$\therefore$ Enthalpy at point '3', $h_3 = h_{f_3} + x_3\, h_{fg_3}$

$= 298.9 + 0.63 \times 1167.1 = 1034.17$ kJ/kg

$$\text{C.O.P.}_{\text{(theoretical)}} = \frac{h_2 - h_1}{h_3 - h_2} = \frac{952.3 - 298.9}{1034.17 - 952.3} = \frac{653.4}{81.87} = 7.98.$$

$$\text{C.O.P.}_{\text{(actual)}} = 0.55 \times 7.98 = 4.39$$

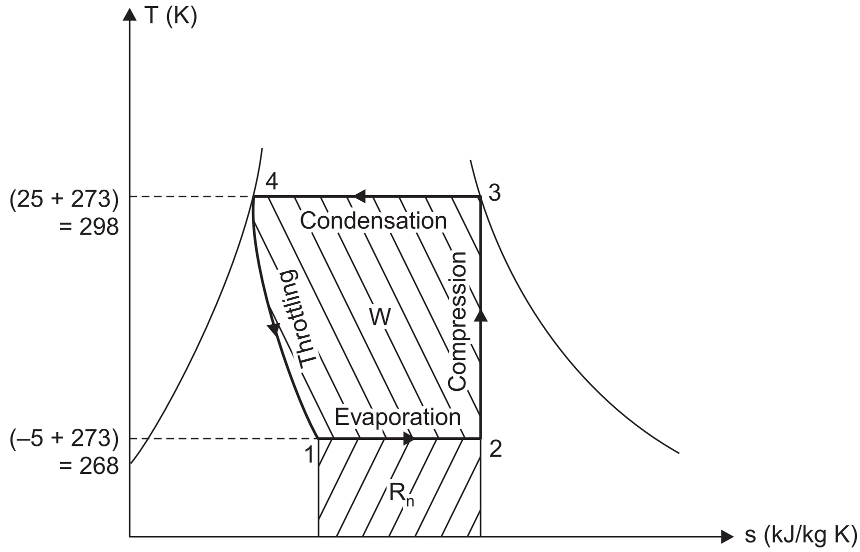

Fig. 14.25

Work done per kg of refrigerant $= h_3 - h_2 = 1034.17 - 952.3 = 81.87$ kJ/kg

Refrigerant in circulation, $m = 6.4$ kg/min.

$\therefore$ Work done per second $= 81.87 \times \dfrac{6.4}{60} = 8.73$ kJ/s

Heat extracted per kg of ice formed = 15 × 4.187 + 335 = 397.8 kJ.

Amount of ice formed in 24 hours,

$$m_{ice} = \frac{8.73 \times 3600 \times 24}{397.8} = \mathbf{1896.1\ kg.} \quad \textbf{(Ans.)}$$

☞**Example 14.15.** *A simple vapour compression plant produces 5 tonnes of refrigeration. The enthalpy values at inlet to compressor, at exit from the compressor, and at exit from the condenser are 183.19, 209.41 and 74.59 kJ/kg respectively. Estimate :*

(*i*) *The refrigerant flow rate,* (*ii*) *The C.O.P.,*

(*iii*) *The power required to drive the compressor, and*

(*iv*) *The rate of heat rejection to the condenser.* **(AMIE)**

Solution. Total refrigeration effect produced = 5 *TR* (tonnes of refrigeration)

= 5 × 14000 = 70000 kJ/h or 19.44 kJ/s ($\because$ 1 *TR* = 14000 kJ/h)

Refer Fig. 14.26.

Given : $h_2 = 183.19$ kJ/kg ; $h_3 = 209.41$ kJ/kg ;

$h_4 (= h_1) = 74.59$ kJ/kg (Throttling process)

(*i*) **The refrigerant flow rate, $\dot{m}$:**

Net refrigerating effect produced per kg $= h_2 - h_1$

$= 183.19 - 74.59 = 108.6$ kJ/kg

$\therefore$ Refrigerant flow rate, $\dot{m} = \dfrac{19.44}{108.6} = \mathbf{0.179\ kg/s.}$ **(Ans.)**

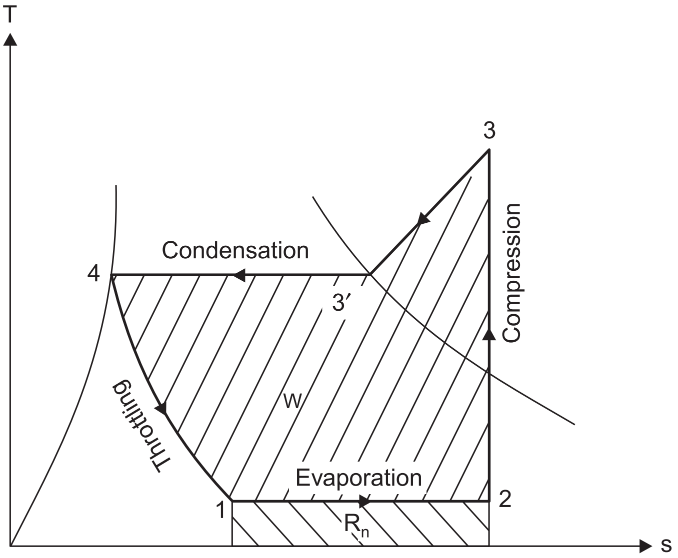

Fig. 14.26

(*ii*) **The C.O.P. :**

$$\text{C.O.P.} = \frac{R_n}{W} = \frac{h_2 - h_1}{h_3 - h_2} = \frac{183.19 - 74.59}{209.41 - 183.19} = \textbf{4.142.} \quad \textbf{(Ans.)}$$

(*iii*) **The power required to drive the compressor, P :**

$$P = \dot{m}\ (h_3 - h_2) = 0.179\ (209.41 - 183.19) = \textbf{4.69 kW.} \quad \textbf{(Ans.)}$$

(*iv*) **The rate of heat rejection to the condenser :**

The rate of heat rejection to the condenser

$$= \dot{m}\ (h_3 - h_4) = 0.179\ (209.41 - 74.59) = \textbf{24.13 kW.} \quad \textbf{(Ans.)}$$

Example 14.16. (*i*) *What are the advantages of using an expansion valve instead of an expander in a vapour compression refrigeration cycle ?*

(*ii*) *Give a comparison between centrifugal and reciprocating compressors.*

(*iii*) *An ice-making machine operates on ideal vapour compression refrigeration cycle using refrigerant R-12. The refrigerant enters the compressor as dry saturated vapour at – 15°C and leaves the condenser as saturated liquid at 30°C. Water enters the machine at 15°C and leaves as ice at – 5°C. For an ice production rate of 2400 kg in a day, determine the power required to run the unit. Find also the C.O.P. of the machine. Use refrigerant table only to solve the problem. Take the latent heat of fusion for water as 335 kJ/kg.* **(AMIE Summer, 1998)**

Solution. (*i*) If an expansion cylinder is used in a vapour compression system, *the work recovered would be extremely small, in fact not even sufficient to overcome the mechanical friction*. It will not be possible to gain any work. Further, the *expansion cylinder is bulky*. On the other hand the *expansion valve is a very simple and handy device, much cheaper than the expansion cylinder*. It *does not need installation, lubrication or maintenance*.

The expansion valve *also controls the refrigerant flow rate according to the requirement, in addition to serving the function of reducting the pressure of the refrigerant.*

(*ii*) **The comparison between centrifugal and reciprocating compressors :**

The comparison between centrifugal and reciprocating compressors is given in the table below :

S. No.	*Particulars*	*Centrifugal compressor*	*Reciprocating compressor*
1.	*Suitability*	Suitable for handling large volumes of air at low pressures	Suitable for low discharges of air at high pressure.
2.	*Operational speeds*	Usually high	Low
3.	*Air supply*	Continuous	Pulsating
4.	*Balancing*	Less vibrations	Cyclic vibrations occur
5.	*Lubrication system*	Generally simple lubrication systems are required.	Generally complicated
6.	*Quality of air delivered*	Air delivered is relatively more clean	Generally contaminated with oil.
7.	*Air compressor size*	Small for given discharge	Large for same discharge
8.	*Free air handled*	2000-3000 m^3/min	250-300 m^3/min
9.	*Delivery pressure*	Normally below 10 bar	500 to 800 bar
10.	*Usual standard of compression*	Isentropic compression	Isothermal compression
11.	*Action of compressor*	Dynamic action	Positive displacement.

(*iii*) Using property table of R-12 :

$$h_2 = 344.927 \text{ kJ/kg}$$
$$h_4 = h_1 = 228.538 \text{ kJ/kg}$$
$$(c_p)_v = 0.611 \text{ kJ/kg°C}$$
$$s_2 = s_3$$

or $$1.56323 = 1.5434 + 0.611 \log_e \left[\frac{t_3 + 273}{30 + 273}\right]$$

or $$t_3 = 39.995°\text{C}$$
$$h_3 = 363.575 + 0.611(39.995 - 30)$$
$$= 369.68 \text{ kJ/kg.}$$
$$R_n/\text{kg} = h_2 - h_1 = 344.927 - 228.538$$
$$= 116.389 \text{ kJ/kg}$$
$$W/\text{kg} = h_3 - h_2 = 369.68 - 344.927 = 24.753$$

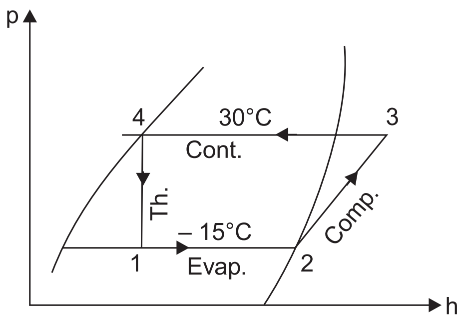

Fig. 14.27

$$\textbf{C.O.P.} = \frac{R_n}{W} = \frac{116.389}{24.753} = \textbf{4.702.} \quad \textbf{(Ans.)}$$

Assuming c_p for ice = 2.0935 kJ/kg°C

Heat to be removed to produce ice

$$= \frac{2400}{24 \times 3600} [4.187(15 - 0) + 335 + 2.0935(0 - (-5))]$$
$$= 11.3409 \text{ kJ/s} = \text{Work required, kJ/s (kW)} \times \text{C.O.P.}$$

$$\therefore \quad \text{Work required (Power)} = \frac{11.3409}{4.702} = \textbf{2.4 kW.} \quad \textbf{(Ans.)}$$

Example 14.17. *A R-12 refrigerator works between the temperature limits of – 10°C and + 30°C. The compressor employed is of 20 cm × 15 cm, twin cylinder, single-acting compressor having a volumetric efficiency of 85%. The compressor runs at 500 r.p.m. The refrigerant is* *sub-cooled and it enters at 22°C in the expansion valve. The vapour is superheated and enters the compressor at – 2°C. Work out the following :*

(*i*) *Show the process on T-s and p-h diagrams ;* (*ii*) *The amount of refrigerant circulated per minute ;* (*iii*) *The tonnes of refrigeration ;* (*iv*) *The C.O.P. of the system.* **(M.U.)**

Solution. (*i*) **Process on T-s and p-h diagrams :**

The processes on *T-s* and *p-h* diagrams are shown in Fig. 14.28.

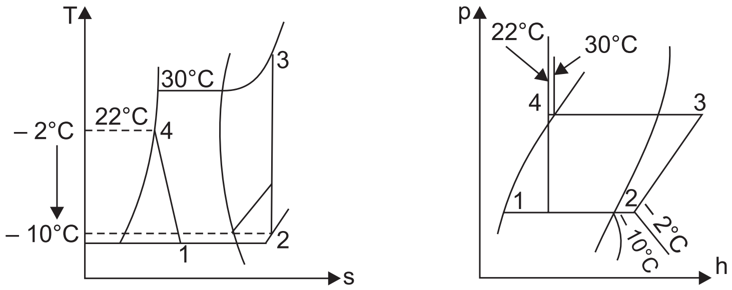

Fig. 14.28

(*ii*) **Mass of refrigerant circulated per minute :**

The value of enthalpies and specific volume read from *p-h* diagram are as under :

$$h_2 = 352 \text{ kJ/kg} \;;\; h_3 = 374 \text{ kJ/kg}$$

$$h_4 = h_1 = 221 \text{ kJ/kg} \;;\; v_2 = 0.08 \text{ m}^3\text{/kg}$$

Refrigerants effect per kg $= h_2 - h_1 = 352 - 221 = 131$ kJ/kg

Volume of refrigerant admitted per min.

$$= \frac{\pi}{4} D^2 L \times \text{r.p.m.} \times 2 \times \eta_{vol}, \text{ for twin cylinder, single acting}$$

$$= \frac{\pi}{4} (0.2)^2 \times 0.15 \times 500 \times 2 \times 0.85 = 4 \text{ m}^3\text{/min}$$

Mass of refrigerant per min $= \frac{4}{0.08} =$ **50 kg/min. (Ans.)**

(*iii*) **Cooling capacity in tonnes of refrigeration :**

Cooling capacity $= 50(h_2 - h_1) = 50 \times 131$

$= 6550$ kJ/min or 393000 kJ/h

or $= \frac{393000}{14000} =$ **28.07 TR**. **(Ans.)**

($\because$ 1 tonne of refrigeration TR = 14000 kJ/h)

(*iv*) Work per kg $= (h_2 - h_1) = 374 - 352 = 22$ kJ/kg

$$\text{C.O.P.} = \frac{131}{22} = \mathbf{5.95.} \quad \textbf{(Ans.)}$$

Example 14.18. *In a standard vapour compression refrigeration cycle, operating between an evaporator temperature of – 10°C and a condenser temperature of 40°C, the enthalpy of the refrigerant, Freon-12, at the end of compression is 220 kJ/kg. Show the cycle diagram on T-s plane. Calculate :*

(*i*) *The C.O.P. of the cycle.*

(*ii*) *The refrigerating capacity and the compressor power assuming a refrigerant flow rate of 1 kg/min. You may use the extract of Freon-12 property table given below :*

t(°C)	*p(MPa)*	h_f*(kJ/kg)*	h_g*(kJ/kg)*
– 10	*0.2191*	*26.85*	*183.1*
40	*0.9607*	*74.53*	*203.1*

(GATE 1997)

Solution. The cycle is shown on *T-s* diagram in Fig. 14.29.

Given : Evaporator temperature = – 10°C

Condenser temperature = 40°C

Enthalpy at the end of compression, h_3 = 220 kJ/kg

From the table given, we have

$$h_2 = 183.1 \text{ kJ/kg} \ ; \ h_1 = h_{f_4} = 26.85 \text{ kJ/kg}$$

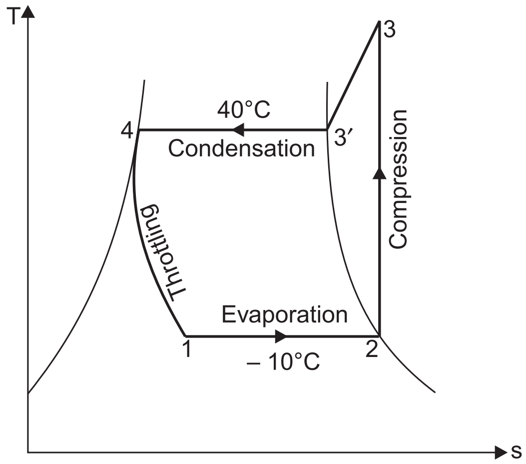

Fig. 14.29

(*i*) **The C.O.P. the cycle :**

$$\text{C.O.P.} = \frac{R_n}{W} = \frac{h_2 - h_1}{h_3 - h_2}$$

$$= \frac{183.1 - 74.53}{220 - 183.1} = \mathbf{2.94.} \quad \textbf{(Ans.)}$$

(*ii*) **Refrigerating capacity :**

Refrigerating capacity $= m(h_2 - h_1)$

[where m = mass flow rate of refrigerant = 1 kg/min ...(Given)]

$= 1 \times (183.1 - 74.53) =$ **108.57 kJ/min. (Ans.)**

Compressor power :

Compressor power $= m(h_3 - h_2)$

$= 1 \times (220 - 183.1) = 36.9$ kJ/min or 0.615 kJ/s

= **0.615 kW. (Ans.)**

Example 14.19. *A Freon-12 refrigerator producing a cooling effect of 20 kJ/s operates on a simple cycle with pressure limits of 1.509 bar and 9.607 bar. The vapour leaves the evaporator dry saturated and there is no undercooling. Determine the power required by the machine.*

If the compressor operaters at 300 r.p.m. and has a clearance volume of 3% of stroke volume, determine the piston displacement of the compressor. For compressor assume that the expansion following the law $pv^{1.13}$ = constant.

Given :

Temperature °C	p_s *bar*	v_g m^3/kg	*Enthalpy* h_f	*kJ/kg* h_g	*Entropy* s_f	*kJ/kg K* s_g	*Specific heat kJ/kg K*
– 20	1.509	0.1088	17.8	178.61	0.073	0.7082	—
40	9.607	—	74.53	203.05	0.2716	0.682	0.747

(U.P.S.C. 1996)

Solution. *Given* : (From the table above) :

h_2 = 178.61 kJ/kg ; h_3' = 203.05 kJ/kg ; h_{f_4} = 74.53 kJ/kg = h_1

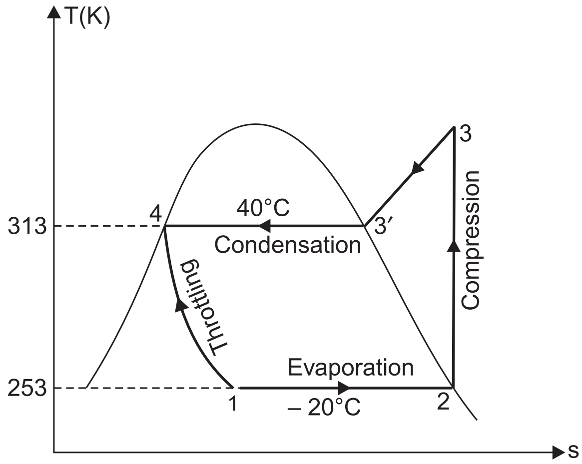

Fig. 14.30

Now, cooling effect $= \dot{m}(h_2 - h_1)$

$$20 = \dot{m}(178.61 - 74.53)$$

$$\therefore \quad \dot{m} = \frac{20}{(178.61 - 74.53)} = 0.192 \text{ kg/s}$$

Also, $s_3 = s_2$

$$s_3' + c_p \ln\left(\frac{T_3}{T_3'}\right) = 0.7082$$

$$0.682 + 0.747 \ln\left(\frac{T_3}{313}\right) = 0.7082$$

or $$\ln\left(\frac{T_3}{313}\right) = \frac{0.7082 - 0.682}{0.747} = 0.03507$$

or $$\frac{T_3}{313} = e^{0.03507} = 1.0357$$

$\therefore$ $$T_3 = 313 \times 1.0357 = 324.2 \text{ K}$$

Now, $$h_3 = h_3' + c_p(324.2 - 303)$$
$$= 203.05 + 0.747(324.2 - 313) = 211.4 \text{ kJ/kg}$$

Power required :

Power required by the machine $= \dot{m}(h_3 - h_2)$

$$= 0.192(211.4 - 178.61) = \mathbf{6.29\ kW.} \quad \textbf{(Ans.)}$$

Piston displacement, V :

Volumetric efficiency, $$\eta_{vol.} = 1 + C - C\left(\frac{p_d}{p_s}\right)^{1/n}$$

$$= 1 + 0.03 - 0.03\left(\frac{9.607}{1.509}\right)^{\frac{1}{1.13}} = 0.876 \quad \text{or} \quad 87.6\%$$

The volume of refrigerant at the intake conditions is

$$\dot{m} \times v_g = 0.192 \times 0.1088 = 0.02089 \text{ m}^3/\text{s}$$

Hence the swept volume $$= \frac{0.02089}{\eta_{vol.}} = \frac{0.02089}{0.876} = 0.02385 \text{ m}^3/\text{s}$$

$\therefore$ $$\mathbf{V} = \frac{0.02385 \times 60}{300} = \mathbf{0.00477\ m^3.} \quad \textbf{(Ans.)}$$

Example 14.20. *A food storage locker requires a refrigeration capacity of 50 kW. It works between a condenser temperature of 35°C and an evaporator temperature of – 10°C. The refrigerant is ammonia. It is sub-cooled by 5°C before entering the expansion valve by the dry saturated vapour leaving the evaporator. Assuming a single cylinder, single-acting compressor operating at 1000 r.p.m. with stroke equal to 1.2 times the bore.*

Determine : (*i*) *The power required, and*

(*ii*) *The cylinder dimensions.*

Properties of ammonia are :

Saturation temperature, °C	*Pressure bar*	*Enthalpy, kJ/kg*		*Entropy, kJ/kg K*		*Specific volume, m³/kg*		*Specific heat kJ/kg K*	
		Liquid	*Vapour*	*Liquid*	*Vapour*	*Liquid*	*Vapour*	*Liquid*	*Vapour*
– 10	*2.9157*	*154.056*	*1450.22*	*0.82965*	*5.7550*	—	*0.417477*	—	*2.492*
35	*13.522*	*366.072*	*1488.57*	*1.56605*	*5.2086*	*1.7023*	*0.095629*	*4.556*	*2.903*

(U.P.S.C. 1997)

Solution. *Given* : (From the table above)

h_2 = 1450.22 kJ/kg ; h_3' = 1488.57 kJ/kg ; h_{f_4} = 366.072 kJ/kg ;

$$h_{f_4'} = h_1 = h_{f_4} - 4.556(308 - 303)$$
$$= 366.07 - 4.556(308 - 303) = 343.29 \text{ kJ/kg}$$

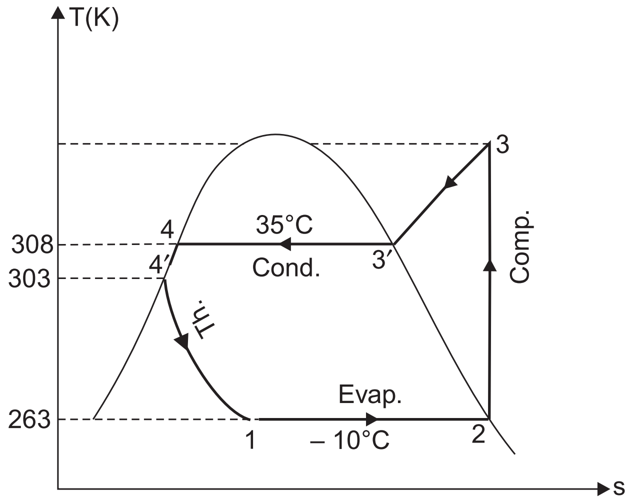

Fig. 14.31

Also $s_3 = s_2$

or $$s_3' + c_p \ln \left(\frac{T_3}{T_3'}\right) = 5.755$$

$$5.2086 + 2.903 \ln \left(\frac{T_3}{308}\right) = 5.755$$

or $$\ln\left(\frac{T_3}{308}\right) = \frac{5.755 - 5.2086}{2.903} = 0.1882$$

$$\frac{T_3}{308} = e^{0.1882} = 371.8 \text{ K}$$

Now, $h_3 = h_3' + c_p(T_3 - T_3')$

$= 1488.57 + 2.903\ (371.8 - 308) = 1673.8$ kJ/kg

Mass of refrigerant, $$\dot{m} = \frac{50}{h_2 - h_1} = \frac{50}{1450.22 - 343.29}$$

$= 0.04517$ kJ/s

(*i*) **Power required :**

Power required $= \dot{m}\ (h_3 - h_2)$

$= 0.04517\ (1673.8 - 1450.22) =$ **10.1 kW. (Ans.)**

(*ii*) **Cylinder dimensions :**

$$\dot{m} = \frac{\pi}{4} D^2 \times L \times \frac{N}{60} \times 0.417477 = 0.04517 \text{ (calculated above)}$$

or $$\frac{\pi}{4} D^2 \times 1.2D \times \frac{1000}{60} \times 0.417477 = 0.04517$$

or $$D^3 = \frac{0.04517 \times 4 \times 60}{\pi \times 1.2 \times 1000 \times 0.417477} = 0.006888$$

∴ Diameter of cylinder, **D** $= (0.006888)^{1/3} =$ **0.19 m. (Ans.)**

and, Length of the cylinder, $L = 1.2D = 1.2 \times 0.19 =$ **0.228 m. (Ans.)**

Example 14.21. *A refrigeration cylce uses Freon-12 as the working fluid. The temperature of the refrigerant in the evaporator is – 10°C. The condensing temperature is 40°C. The cooling load is 150 W and the volumetric efficiency of the compressor is 80%. The speed of the compressor is 720 rpm. Calculate the mass flow rate of the refrigerant and the displacement volume of the compressor.*

Properties of Freon-12

Temperature (°C)	*Saturation pressure (MPa)*	*Enthalpy (kJ/kg)*		*Specific volume (m^3/kg) Saturated vapour*
		Liquid	*Vapour*	
– 10	*0.22*	*26.8*	*183.0*	*0.08*
40	*0.96*	*74.5*	*203.1*	*0.02*

(GATE, 1995)

Solution. *Given* : Cooling load = 150 W ; $\eta_{vol.}$ = 0.8 ; N = 720 r.p.m.

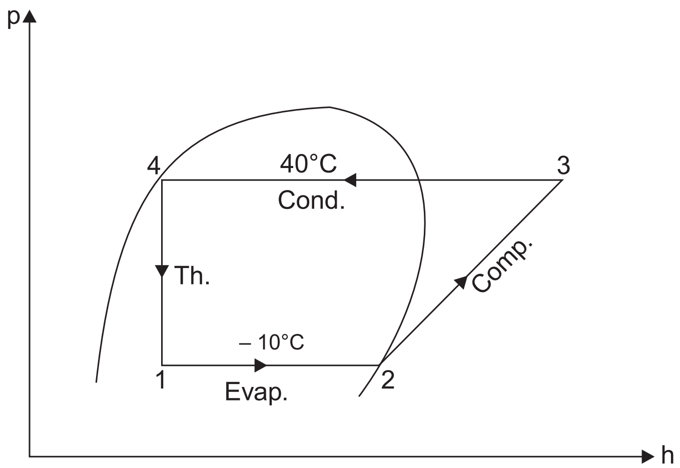

Fig. 14.32

Mass flow rate of the refrigerant $\dot{m}$:

Refrigerating effect = $h_2 - h_1$

= 183 – 74.5 = 108.5 kJ/kg

Cooling load = $\dot{m}$ × (108.5 × 1000) = 150

or $\dot{m} = \frac{150}{108.5 \times 1000}$ = **0.001382 kJ/s. (Ans.)**

Displacement volume of the compressor :

Specific volume at entry to compressor,

v_2 = 0.08 m³/kg (From table)

∴ Displacement volume of compressor = $\frac{\dot{m}v_2}{\eta_{vol.}} = \frac{0.001382 \times 0.08}{0.8}$

= **0.0001382 m³/s. (Ans.)**

Example 14.22. *In a simple vapour compression cycle, following are the properties of the refrigerant R-12 at various points :*

Compressor inlet : $h_2 = 183.2\ kJ/kg$ $v_2 = 0.0767\ m^3/kg$
Compressor discharge : $h_3 = 222.6\ kJ/kg$ $v_3 = 0.0164\ m^3/kg$
Compressor exit : $h_4 = 84.9\ kJ/kg$ $v_4 = 0.00083\ m^3/kg$

The piston displacement volume for compressor is 1.5 litres per stroke and its volumetric efficiency is 80%. The speed of the compressor is 1600 r.p.m.

Find : (i) Power rating of the compressor (kW) ;
(ii) Refrigerating effect (kW). **(GATE 1996)**

Solution. Piston displacement volume = $\frac{\pi}{4}d^2 \times l$ = 1.5 litres

= 1.5 × 1000 × 10^{-6} m^3/stoke = 0.0015 m^3/revolution.

(*i*) **Power rating of the compressor (kW) :**

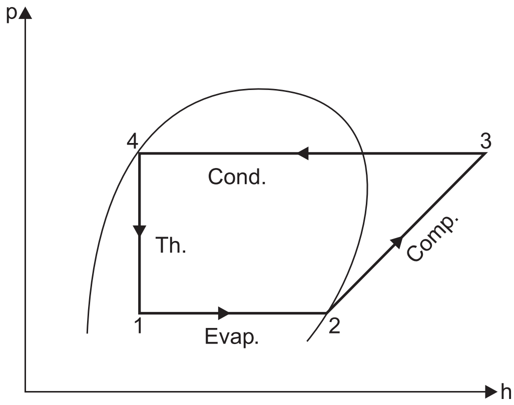

Fig. 14.33

Compressor discharge

= 0.0015 × 1600 × 0.8 ($\eta_{vol.}$) = 1.92 m^3/min.

Mass flow rate of compressor,

$$m = \frac{\text{Compressor discharge}}{v_2}$$

$$= \frac{1.92}{0.0767} = 25.03 \text{ kg/min.}$$

Power rating of the compressor

$$= \dot{m}(h_3 - h_2)$$

$$= \frac{25.03}{60} (222.6 - 183.2) = \mathbf{16.44\ kW.} \quad \textbf{(Ans.)}$$

(*ii*) **Refrigerating effect (kW) :**

Refrigerating effect $= \dot{m}\,(h_2 - h_1) = \dot{m}\,(h_2 - h_4)$ $(\because\ h_1 = h_4)$

$$= \frac{25.03}{60} (183.2 - 84.9)$$

= **41 kW. (Ans.)**

Example 14.23. *A refrigerator operating on standard vapour compression cycle has a co-efficiency performance of 6.5 and is driven by a 50 kW compressor. The enthalpies of saturated liquid and saturated vapour refrigerant at the operating condensing temperature of 35°C are 62.55 kJ/kg and 201.45 kJ/kg respectively. The saturated refrigerant vapour leaving evaporator has an enthalpy of 187.53 kJ/kg. Find the refrigerant temperature at compressor discharge. The* c_p *of refrigerant vapour may be taken to be 0.6155 kJ/kg°C.* **(GATE 1992)**

Solution. *Given* : C.O.P. = 6.5 ; W = 50 kW, h_3' = 201.45 kJ/kg,

$$h_{f_4} = h_1 = 69.55 \text{ kJ/kg} ;\ h_2 = 187.53 \text{ kJ/kg}$$

$$c_p = 0.6155 \text{ kJ/kg K}$$

Temperature, t_3 :

Refrigerating capacity = 50 × C.O.P.

= 50 × 6.5 = 325 kW

Heat extracted per kg of refrigerant

$= 187.53 - 69.55 = 117.98$ kJ/kg

Refrigerant flow rate $= \dfrac{325}{117.98} = 2.755$ kg/s

Compressor power $= 50$ kW

$\therefore$ Heat input per kg $= \dfrac{50}{2.755} = 18.15$ kJ/kg

Enthalpy of vapour after compression

$= h_2 + 18.15 = 187.53 + 18.15$

$= 205.68$ kJ/kg

Superheat $= 205.68 - h_3' = 205.68 - 201.45$

$= 4.23$ kJ/kg

But $4.23 = 1 \times c_p (t_3 - t_3') = 1 \times 0.6155 \times (t_3 - 35)$

$\therefore$ $\mathbf{t_3} = \dfrac{4.23}{0.6155} + 35 = \mathbf{41.87°C.}$ **(Ans.)**

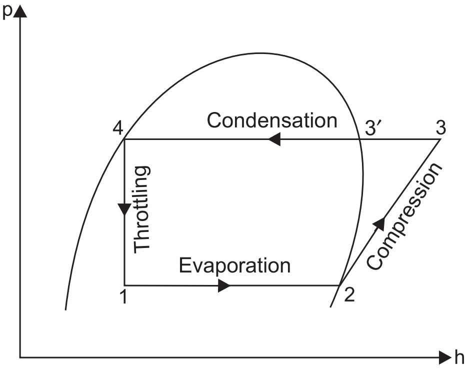

Fig. 14.34

Note. The compressor rating of 50 kW is assumed to be the enthalpy of compression, in the absence of any data on the efficiency of compressor.

Example 14.24. *A vapour compression heat pump is driven by a power cycle having a thermal efficiency of 25%. For the heat pump, refrigerant-12 is compressed from saturated vapor at 2.0 bar to the condenser pressure of 12 bar. The isentropic efficiency of the compressor is 80%. Saturated liquid enters the expansion valve at 12 bar. For the power cycle 80% of the heat rejected by it is transferred to the heated space which has a total heating requirement of 500 kJ/min. Determine the power input to the heat pump compressor. The following data for refrigerant-12 may be used :*

Pressure, bar	*Temperature, °C*	*Enthalpy, kJ/kg*		*Entropy, kJ/kg K*	
		Liquid	*Vapour*	*Liquid*	*Vapour*
2.0	*– 12.53*	*24.57*	*182.07*	*0.0992*	*0.7035*
12.0	*49.31*	*84.21*	*206.24*	*0.3015*	*0.6799*

Vapour specific heat at constant pressure = 0.7 kJ/kg K. **(U.P.S.C. 1995)**

Solution. Heat rejected by the cycle $= \dfrac{500}{0.8} = 625$ kJ/min.

Assuming isentropic compression of refrigerant, we have

Entropy of dry saturated vapour at 2 bar

= Entropy of superheated vapour at 12 bar

$$0.7035 = 0.6799 + c_p \ln \frac{T}{(49.31 + 273)} = 0.6799 + 0.7 \times \ln \left(\frac{T}{322.31}\right)$$

or $$\ln \left(\frac{T}{322.31}\right) = \frac{0.7035 - 0.6799}{0.7} = 0.03371$$

or $$T = 322.31\,(e)^{0.03371} = 333.4 \text{ K}$$

$\therefore$ Enthalpy of superheated vapour at 12 bar

$= 206.24 + 0.7(333.4 - 322.31) = 214$ kJ/kg

Heat rejected per cycle $= 214 - 84.21 = 129.88$ kJ/kg

Mass flow rate of refrigerant $= \dfrac{625}{129.88} = 4.812$ kg/min

Work done on compressor = 4.812 (214 – 182.07)

= 153.65 kJ/min = 2.56 kW

Actual work of compresson = $\dfrac{2.56}{\eta_{\text{compressor}}} = \dfrac{2.56}{0.8}$ = 3.2 kW

Hence power input to the heat pump compressor = **3.2 kW. (Ans.)**

☞**Example 14.25.** *A food storage locker requires a refrigeration system of 2400 kJ/min. capacity at an evaporator temperature of 263 K and a condenser temperature of 303 K. The refrigerant used is freon-12 and is subcooled by 6°C before entering the expansion valve and vapour is superheated by 7°C before leaving the evaporator coil. The compression of refrigerant is reversible adiabatic. The refrigeration compressor is two-cylinder single-acting with stroke equal to 1.25 times the bore and operates at 1000 r.p.m.*

Properties of freon-12

Saturation temp, K	*Absolute pressure, bar*	*Specific volume of vapour, m³/kg*	*Enthalpy, kJ/kg*		*Entropy, kJ/kg K*	
			Liquid	*Vapour*	*Liquid*	*Vapour*
263	*2.19*	*0.0767*	*26.9*	*183.2*	*0.1080*	*0.7020*
303	*7.45*	*0.0235*	*64.6*	*199.6*	*0.2399*	*0.6854*

Take : Liquid specific heat = 1.235 kJ/kg K ; Vapour specific heat = 0.733 kJ/kg K. Determine :

(*i*) *Refrigerating effect per kg.*

(*ii*) *Mass of refrigerant to be circulated per minute.*

(*iii*) *Theoretical piston displacement per minute.*

(*iv*) *Theoretical power required to run the compressor, in kW.*

(*v*) *Heat removed through condenser per min.*

(*vi*) *Theoretical bore and stroke of compressor.*

Solution. The cycle of refrigeration is represented on *T-s* diagram on Fig. 14.35.

Enthalpy at '2', $h_2 = h_2' + c_p (T_2 - T_2')$

From the given table :

$h_2' = 183.2$ kJ/kg

$(T_2 - T_2')$ = Degree of superheat as the vapour enters the compressor = 7°C

$\therefore \quad h_2 = 183.2 + 0.733 \times 7 = 188.33$ kJ/kg

Also, entropy at '2', $s_2 = s_2' + c_p \log_e \dfrac{T_2}{T_2'}$

$= 0.7020 + 0.733 \log_e \left(\dfrac{270}{263}\right) = 0.7212$ kJ/kg K

For isentropic process 2-3

Entropy at '2' = Entropy at '3'

$0.7212 = s_3' + c_p \log_e \left(\dfrac{T_3}{T_3'}\right)$

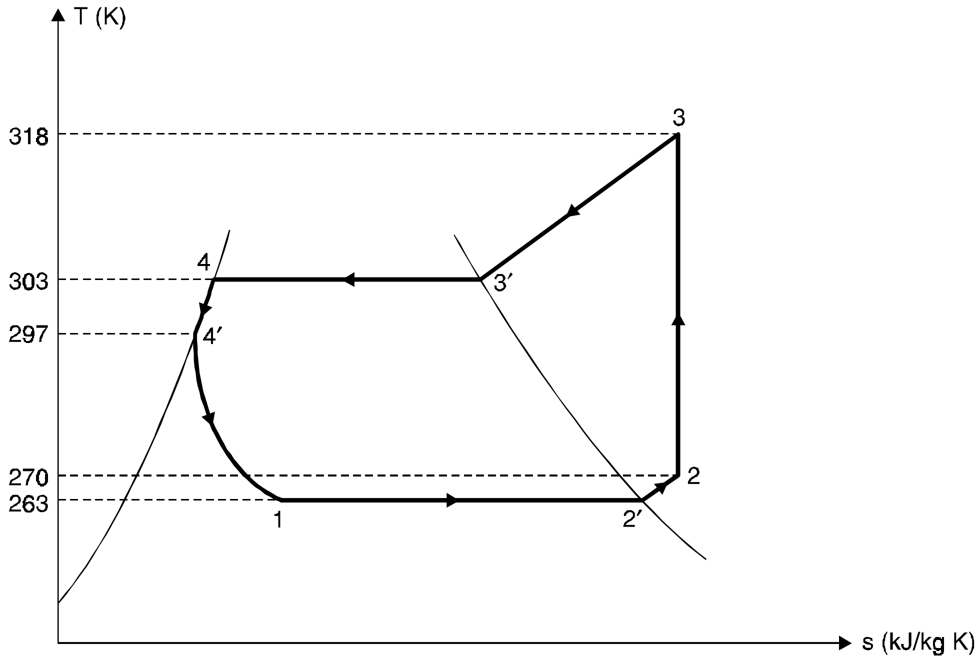

Fig. 14.35

$$= 0.6854 + 0.733 \log_e \left(\frac{T_3}{303}\right)$$

$$\therefore \qquad \log_e \left(\frac{T_3}{303}\right) = 0.0488$$

i.e., $\qquad T_3 = 318$ K

Now, enthalpy at '3', $\quad h_3 = h_3' + c_p\,(T_3 - T_3')$

$$= 199.6 + 0.733\,(318 - 303) = 210.6 \text{ kJ/kg.}$$

Also, enthalpy at 4′, $\quad h_{f_4'} = h_{f_4} - (c_p)_{\text{liquid}}\,(T_4 - T_4') = 64.6 - 1.235 \times 6 = 57.19$ kJ/kg

For the *process 4′-1,*

Enthalpy at 4′ = enthalpy at 1 = 57.19 kJ/kg

For specific volume at 2,

$$\frac{v_2'}{T_2'} = \frac{v_2}{T_2}$$

$$\therefore \qquad v_2 = \frac{v_2'}{T_2'} \times T_2 = 0.0767 \times \frac{270}{263} = 0.07874 \text{ m}^3\text{/kg}$$

(*i*) **Refrigerating effect per kg**

$$= h_2 - h_1 = 188.33 - 57.19 = \mathbf{131.14\ kJ/kg.}\quad \textbf{(Ans.)}$$

(*ii*) **Mass of refrigerant to be circulated per minute** for producing effect of 2400 kJ/min.

$$= \frac{2400}{131.14} = \mathbf{18.3\ kg/min.}\quad \textbf{(Ans.)}$$

(*iii*) **Theoretical piston displacement per minute**

= Mass flow/min. × specific volume at suction

= 18.3 × 0.07874 = 1.441 m^3/min.

(*iv*) **Theoretical power required to run the compressor**

= Mass flow of refrigerant per sec. × compressor work/kg

$$= \frac{18.3}{60} \times (h_3 - h_2) = \frac{18.3}{60} (210.6 - 188.33) \text{ kJ/s} = 6.79 \text{ kJ/s}$$

or **6.79 kW. (Ans.)**

(*v*) **Heat removed through the condenser per min.**

= Mass flow of refrigerant × heat removed per kg of refrigerant

= 18.3 ($h_3 - h_{f_4'}$) = 18.3 (210.6 – 57.19) = **2807.4 kJ/min. (Ans.)**

(*vi*) **Theoretical bore (d) and stroke (l) :**

Theoretical piston displacement per cylinder

$$= \frac{\text{Total displacement per minute}}{\text{Number of cylinder}} = \frac{1.441}{2} = 0.7205 \text{ m}^3\text{/min.}$$

Also, length of stroke = 1.25 × diameter of piston

Hence, $0.7205 = \pi/4 \, d^2 \times (1.25 \, d) \times 1000$

i.e., d = 0.09 m or **90 mm. (Ans.)**

and $l = 1.25 \, d = 1.25 \times 90$ = **112.5 mm. (Ans.)**

☞**Example 14.26.** *A refrigeration system of 10.5 tonnes capacity at an evaporator temperature of – 12°C and a condenser temperature of 27°C is needed in a food storage locker. The refrigerant ammonia is sub-cooled by 6°C before entering the expansion valve. The vapour is 0.95 dry as it leaves the evaporator coil. The compression in the compressor is of adiabatic type.*

Using p-h chart find :

(*i*) *Condition of volume at outlet of the compressor*

(*ii*) *Condition of vapour at entrance to evaporator*

(*iii*) *C.O.P.*

(*iv*) *Power required, in kW.*

Neglect valve throttling and clearance effect.

Solution. Refer Fig. 14.36.

Using *p-h* chart for ammonia,

- Locate point '2' where – 12°C cuts 0.95 dryness fraction line.
- From point '2' move along constant entropy line and locate point '3' where it cuts constant pressure line corresponding to + 27°C temperature.
- From point '3' follow constant pressure line till it cuts + 21°C temperature line to get point '4'.
- From point '4' drop a vertical line to cut constant pressure line corresponding to – 12°C and get the point '5'.

The values as read from the chart are :

h_2 = 1597 kJ/kg

h_3 = 1790 kJ/kg

$h_4 = h_1$ = 513 kJ/kg

t_3 = 58°C

x_1 = 0.13.

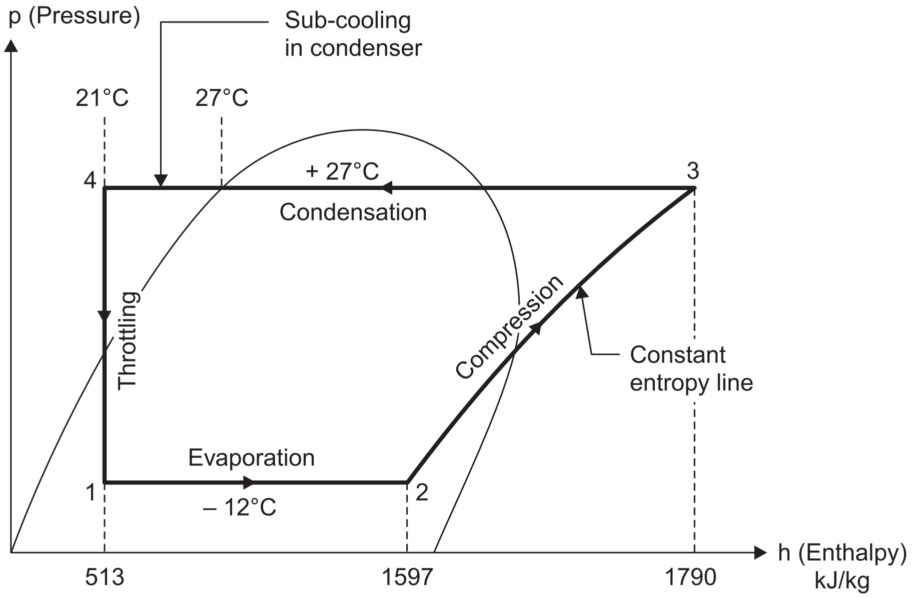

Fig. 14.36

(*i*) **Condition of the vapour at the outlet of the compressor**

$$= 58 - 27 = \textbf{31°C superheat.} \quad \textbf{(Ans.)}$$

(*ii*) **Condition of vapour at entrance to evaporator,**

$$x_1 = \textbf{0.13.} \quad \textbf{(Ans.)}$$

(*iii*)
$$\textbf{C.O.P.} = \frac{h_2 - h_1}{h_3 - h_2} = \frac{1597 - 513}{1790 - 1597} = \textbf{5.6.} \quad \textbf{(Ans.)}$$

(*iv*) **Power required :**

$$\text{C.O.P.} = \frac{\text{Net refrigerating effect}}{\text{Work done}} = \frac{R_n}{W}$$

$$5.6 = \frac{10.5 \times 14000}{W \times 60}$$

$$\therefore \quad W = \frac{10.5 \times 14000}{5.6 \times 60} \text{ kJ/min} = 437.5 \text{ kJ/min.}$$

$$= 7.29 \text{ kJ/s.}$$

i.e., **Power required = 7.29 kW. (Ans.)**

☞**Example 14.27.** *The evaporator and condenser temperatures of 20 tonnes capacity freezer are – 28°C and 23°C respectively. The refrigerant – 22 is subcooled by 3°C before it enters the expansion valve and is superheated to 8°C before leaving the evaporator. The compression is isentropic. A six-cylinder single-acting compressor with stroke equal to bore running at 250 r.p.m. is used. Determine :*

(*i*) *Refrigerating effect/kg.*

(*ii*) *Mass of refrigerant to be circulated per minute.*

(*iii*) *Theoretical piston displacement per minute.*

(*iv*) *Theoretical power.*

(*v*) *C.O.P.*

(*vi*) *Heat removed through condenser.*

(*vii*) *Theoretical bore and stroke of the compressor.*

Neglect valve throttling and clearance effect.

Solution. Refer Fig. 14.37. Following the procedure as given in the previous example plot the points 1, 2, 3 and 4 on *p-h* chart for freon-22. The following values are obtained :

$$h_2 = 615 \text{ kJ/kg}$$
$$h_3 = 664 \text{ kJ/kg}$$
$$h_4 = h_1 = 446 \text{ kJ/kg}$$
$$v_2 = 0.14 \text{ m}^3/\text{kg}.$$

(*i*) **Refrigerating effect per kg** = $h_2 - h_1$ = 615 – 446 = **169 kJ/kg. (Ans.)**

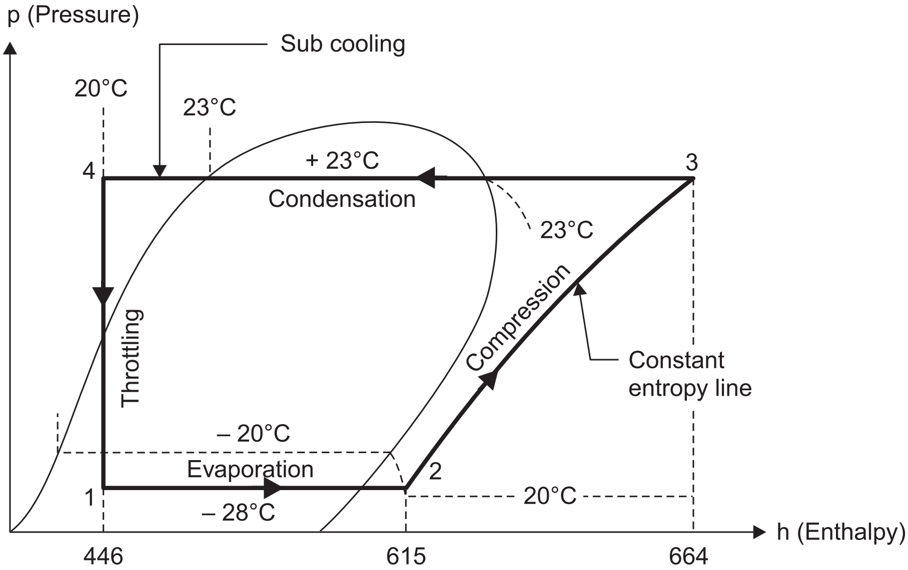

Fig. 14.37

(*ii*) **Mass of refrigerant to be circulated per minute,**

$$m = \frac{20 \times 14000}{169 \times 60} = \textbf{27.6 kg/min. (Ans.)}$$

(*iii*) **Theoretical piston displacement**

= Specific volume at suction × Mass of refrigerant used/min

= 0.14 × 27.6 = 3.864 m^3/min

(*iv*) **Theoretical power**

$$= m \times (h_3 - h_2) = \frac{27.6}{60} (664 - 615) = 22.54 \text{ kJ/s}$$

= **22.54 kW. (Ans.)**

(*v*) $$\textbf{C.O.P.} = \frac{h_2 - h_1}{h_3 - h_2} = \frac{615 - 446}{664 - 615} = \textbf{3.45. (Ans.)}$$

(*vi*) ***Heat removed through the condenser***

$$= m\ (h_3 - h_4) = 27.6\ (664 - 446) = \mathbf{6016.8\ kJ/min.}\quad \mathbf{(Ans.)}$$

(*vii*) Theoretical displacement per minute per cylinder

$$= \frac{\text{Total displacement/ min.}}{\text{Number of cylinders}} = \frac{3.864}{6} = 0.644\ \text{m}^3/\text{min}$$

Let diameter of the cylinder = d

Then, stroke length, $l = d$

Now, $$\frac{\pi}{4}\, d^2 \times l = \frac{0.644}{950}$$

or $$\frac{\pi}{4}\, d^2 \times d = \frac{0.644}{950}$$

i.e., $\mathbf{d}$ = 0.0952 m or **95.2 mm.** **(Ans.)**

and $\mathbf{l}$ = **95.2 mm.** **(Ans.)**

14.5. REFRIGERANTS

A ***'refrigerant'*** *is defined as any substance that absorbs heat through expansion or vaporisation and loses it through condensation in a refrigeration system*. The term 'refrigerant' in the broadest sense is also applied to such *secondary cooling mediums* as cold water or brine, solutions. Usually refrigerants include only those working mediums which pass through the cycle of *evaporation, recovery, compression, condensation* and *liquification. These substances absorb heat at one place at low temperature level and reject the same at some other place having higher temperature and pressure. The rejection of heat takes place at the cost of some mechanical work.* Thus circulating cold mediums and cooling mediums (such as ice and solid carbondioxide) are not primary refrigerants. In the early days only four refrigerants, *Air, ammonia* (NH_3), *Carbon dioxide* (CO_2), *Sulphur dioxide* (SO_2), possessing chemical, physical and thermodynamic properties permitting their efficient application and service in the practical design of refrigeration equipment were used. All the refrigerants change from liquid state to vapour state during the process.

14.5.1. Classification of Refrigerants

The refrigerants are classified as follows :

1. Primary refrigerants.
2. Secondary refrigerants.

1. **Primary refrigerants** *are those working mediums or heat carriers which directly take part in the refrigeration system and cool the substance by the absorption of latent heat e.g. Ammonia, Carbon dioxide, Sulphur dioxide, Methyl chloride, Methylene chloride, Ethyl chloride and Freon group etc.*

2. **Secondary refrigerants** *are those circulating substances which are first cooled with the help of the primary refrigerants and are then employed for cooling purposes*, *e.g. ice, solid carbon dioxide* etc. These refrigerants cool substances by absorption of their sensible heat.

The primary refrigerants are grouped as follows :

(*i*) **Halocarbon compounds.** In 1928, Charles Kettening and Dr. Thomas Mighey invented and developed this group of refrigerant. In this group are included refrigerants which contain one or more of three halogens, chlorine and bromine and they are sold in the market under the names as *Freon, Genetron, Isotron*, and *Areton*. Since the refrigerants belonging to this