$$\Delta t_m = \frac{(32.9 - 30) - (32.9 - 32.24)}{\ln \dfrac{32.9 - 30}{32.9 - 32.24}} = 1.5°\text{C}$$

$$A = \frac{3.87}{2.5\,(1.5)} = 1.0 \text{ m}^2$$

Power consumption, $\dot{W} = \dfrac{3.5167}{9.95} = 0.35$ kW

Saving in power consumption $= \dfrac{0.63 - 0.35}{0.63} \times 100 = 44.4\%$

Saving in area of the heat exchanger

$$= \frac{2.975 - 1}{2.975} \times 100 = 66\%$$

Note *Indiscriminate use of air-cooled window-type air conditioners is wasteful of energy and equipment. Insted of using large number of window units in a big building, it is much more desirable to install a* ***central air conditioning*** *plant which is always water-cooled. This will save power and reduce cost. It will also minimise thermal pollution of the environment by diminishing* $\dot{W}$ *and* $\dot{Q}_k$.

2.5 VAPOUR AS A REFRIGERANT IN REVERSED CARNOT CYCLE

The reversed Carnot cycle can be made almost completely practical by operating in the liquid-vapour region of a pure substance as shown in Fig. 2.14.

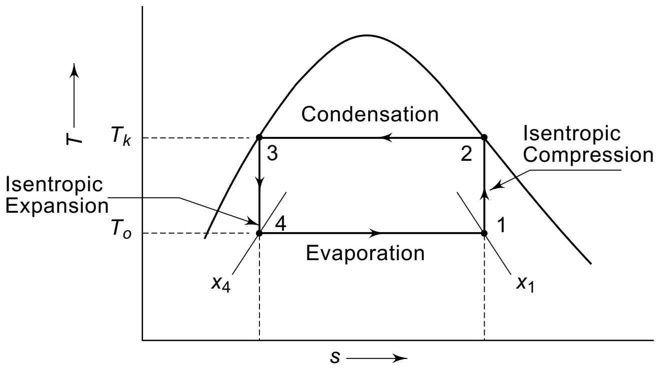

Fig. 2.14 Reversed Carnot cycle with vapour as a refrigeran

The isothermal processes of heat rejection (2-3) and heat absorption (4-1) of the Carnot cycle are achieved by making use of the phenomena of condensation and evaporation of a pure substance at constant pressure and temperature. This alternate condensation and evaporation of a working substance is accompanied by alternate isentropic compression (1-2) and expansion (3-4) processes.

It may be noted that the vapour during compression is wet although it is dry-saturated at the end of the process. Such a compression is called *wet compression*.

It may also be seen that the isentropic expansion of the liquid from 3 to 4 results in flashing of the refrigerant with consequent temperature drop from T_k to T_o although such expansion of a liquid with partial vaporization is practically difficult to achieve in a fast-moving piston and cylinder mechanism.

The thermodynamic analysis per unit mass of the refrigerant, for the four flow processes of the cycle, using steady-state steady-flow energy equation is as follows:

Refrigerating effect, $q_o = h_1 - h_4$

Heat rejected, $|q_k| = h_2 - h_3 = (h_{fg})_k$

Compressor work, $|w_C| = h_2 - h_1$

Expander work, $w_E = h_3 - h_4$

Net work, $|w| = |w_C| - w_E = (h_2 - h_1) - (h_3 - h_4)$

$= |q_k| - q_o = (h_2 - h_3) - (h_1 - h_4)$

COP for cooling,

$$\mathcal{E}_c = \frac{q_o}{|w|} = \frac{h_1 - h_4}{(h_2 - h_3) - (h_1 - h_4)}$$

$$= \frac{1}{\left(\dfrac{h_2 - h_3}{h_1 - h_4}\right) - 1} \tag{2.5}$$

Note *q_k and w_C are negative with respect to the system (refrigerating machine). From here onwards we will consider their positive values only in our calculations.*

Example 2.3

(a) A Carnot refrigerator has working temperatures of –30°C and 35°C. If it operates with R 12 as a working substance, calculate the work of isentropic compression and that of isentropic expansion, and refrigerating effect, heat rejected per kg of the refrigerant, and COP of the cycle.

(b) If the actual refrigerator operating on the same temperatures has a COP of 0.75 of the maximum, calculate the power consumption and heat rejected to the surroundings per ton of refrigeration.

Solution Referring to Fig. 2.14, from the table of properties of R 12, we have:

$s_1 = s_2 = 0.6839$ kJ/(kg. K) $\quad s_{f_4} = s_{f_1} = 0.0371$ kJ/(kg. K)

$s_3 = s_4 = 0.2559$ kJ/(kg. K) $\quad s_{g_4} = s_{g_1} = 0.7171$ kJ/(kg. K)

$h_2 = 201.5$ kJ/kg $\quad h_{f_4} = h_{f_1} = 8.9$ kJ/kg

$h_3 = 69.5$ kJ/kg $\quad h_{g_4} = h_{g_1} = 174.2$ kJ/kg

Hence, by putting $s_1 = s_4$ and $s_4 = s_3$, we get the dryness fractions at 1 and 4 as

$$x_1 = \frac{0.6839 - 0.0371}{0.7171 - 0.0371} = 0.951$$

$$x_4 = \frac{0.2559 - 0.0371}{0.7171 - 0.0371} = 0.322$$

Enthalpies at 1 and 4

$$h_1 = 8.9 + 0.951\ (174.2 - 8.9) = 166 \text{ kJ/kg}$$

$$h_4 = 8.9 + 0.322\ (174.2 - 8.9) = 62.1 \text{ kJ/kg}$$

Work of compression, $w_C = h_2 - h_1 = 201.5 - 166 = 35.5$ kJ/kg

Work of expansion, $w_E = h_3 - h_4 = 69.5 - 62.1 = 7.4$ kJ/kg

Refrigerating effect, $q_o = h_1 - h_4 = 166 - 62.1 = 103.9$ kJ/kg

Heat rejected, $q_k = h_2 - h_3 = 201.5 - 69.5 = 132$ kJ/kg

Net work, $w = w_C - w_E = 35.5 - 7.4 = 28.1$ kJ/kg

$= q_k - q_o = 132 - 103.9 = 28.1$ kJ/kg

COP of the cycle, $\mathcal{E}_c = \dfrac{q_o}{w} = \dfrac{103.9}{28.1} = 3.74$

Alternatively, we have for Carnot COP

$$(\mathcal{E}_c) \text{ Carnot} = \frac{T_o}{T_k - T_o} = \frac{273 - 30}{35 - (-30)} = 3.74$$

(b) Actual COP, $\mathcal{E}_c = 0.75 \times 3.74 = 2.8$

Power consumption per ton, $\dot{W} = \dfrac{\dot{Q}_o}{\mathcal{E}_c} = \dfrac{3.5167}{2.8} = 1.256$ kW

Heat rejected per ton, $\dot{Q}_k = \dot{Q}_o + \dot{W} = 3.516 + 1.256 = 4.722$ kW

2.6 GAS AS A REFRIGERANT IN REVERSED CARNOT CYCLE

Figure 2.15 shows the Carnot cycle 1-2-3-4 with gas as a refrigerant, illustrated on *T-s* and *p-v* diagrams.

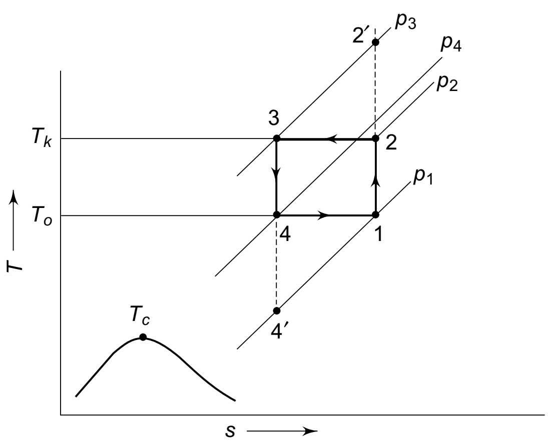

Fig. 2.15(a) Reversed Carnot cycle with gas as a refrigerant on *T-s* diagram