

**THERMODYNAMICS**

**7**

**CHAPTER SEVEN**

**Vapour Compression  
Refrigeration System**



## .. Vapour Compression Refrigeration System ..

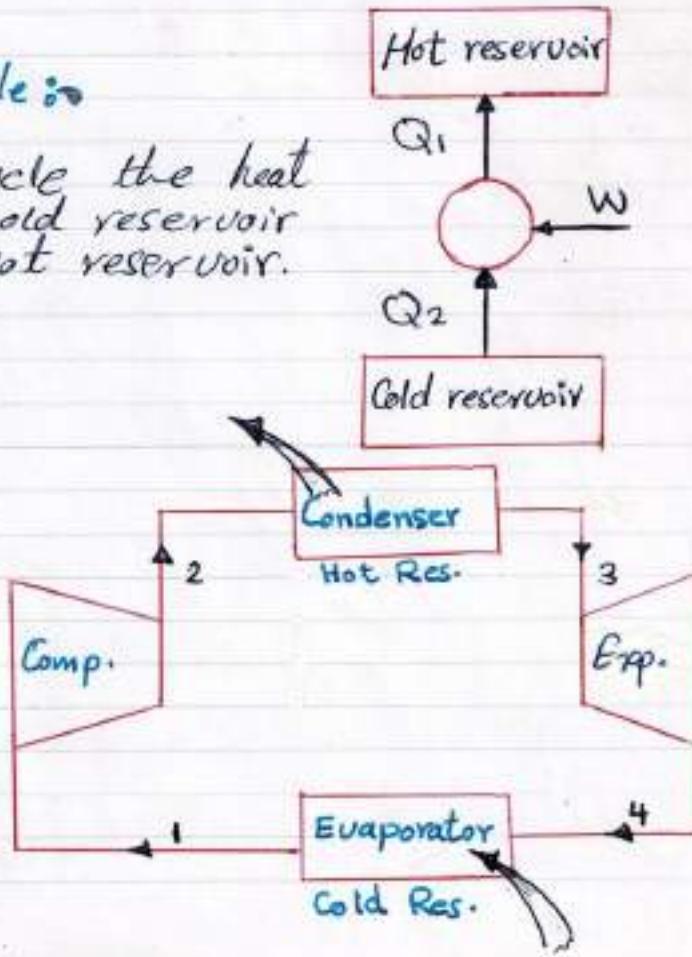
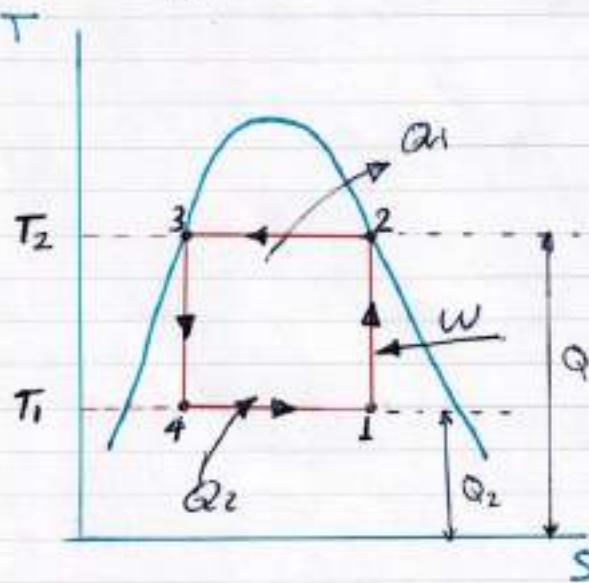
Refrigeration in the engineering sense, means maintaining a system at a temperature less than the temperature of the surroundings. This will not occur naturally, so a device must be developed that will maintain this condition.

The vapour compression refrigeration system is now used for all purpose refrigeration. It is generally used for all industrial purposes from a small domestic refrigerator to a big air conditioning plant.

A reversed Carnot engine will remove heat from a low temperature reservoir and deliver this energy, plus work necessary to transfer the heat, to high temperature reservoir. The refrigerated system in this case is the low temperature reservoir.

### \* Reversed Carnot Cycle

In Refrigeration Carnot cycle the heat is absorbed from the cold reservoir and rejected to the hot reservoir.



## \* Processes of Refrigeration Carnot Cycle:

- 1 → 2 : Work input to the compressor to compress <sup>to</sup> dry saturated vapour, rising its pressure and temperature to dry or superheated condition.
- 2 → 3 : heat rejected in condenser from the vapour to the ambient, changing the dry, or superheated vapour to saturated liquid.
- 3 → 4 : throttling the saturated liquid (expansion), changing it to wet vapour.
- 4 → 1 : heat absorbed from cold reservoir, changing the wet vapour of low quality to wet vapour of high quality.

$$\text{work input (Process } 1 \rightarrow 2) = Q_1 - Q_2$$

$$\text{Heat rejected (.. } 2 \rightarrow 3) = T_2(S_2 - S_3) = Q_1$$

$$\text{Heat absorbed (.. } 4 \rightarrow 1) = T_1(S_1 - S_4) = Q_2$$

$$\text{Since } S_3 = S_4 \text{ & } S_2 = S_1 \Rightarrow Q_2 = T_1(S_2 - S_3)$$

## \* Coefficient Of Performance (COP)

The performance ratio of refrigeration System is not the efficiency, but rather the Coefficient Of Performance, and define as the refrigeration effect (heat absorbed) divided by the net work done on the cycle (work input).

$$COP_R = \frac{Q_2}{W} = \frac{T_1(S_2 - S_3)}{T_2(S_2 - S_3) - T_1(S_2 - S_3)} = \frac{T_1}{T_2 - T_1}$$

$$COP_R = \frac{T_{\text{low}}}{T_{\text{high}} - T_{\text{low}}}$$



It is more suitable to change the names of the processes of the reversed Carnot Cycle to:

|               |           |                                |                        |
|---------------|-----------|--------------------------------|------------------------|
| Heat absorbed | <u>to</u> | Refrigeration effect           | $Q_2 = T_1(S_2 - S_1)$ |
| Heat rejected | <u>to</u> | Heat rejected in the Condenser | $Q_1 = T_2(S_2 - S_1)$ |
| Work input    | <u>to</u> | Work input to Compressor       | $W = Q_1 - Q_2$        |

## \* Units of Refrigeration:

The practical unit of refrigeration is expressed in terms of «tonne of refrigeration» briefly written as "TR". A tonne of refrigeration is defined as the amount of refrigeration effect produced by the uniform melting of one tonne (1000kg) of ice from and at 0°C in 24 hours. Since the latent heat of ice is 335 kJ/kg, therefore one tonne of refrigeration.

$$1 \text{ TR} = 1000 * 335 \text{ kJ} \text{ in 24 hours}$$

$$= \frac{1000 * 335}{60 * 24} = 232.6 \text{ kJ/min}$$

In actual practice, One tonne of refrigeration is taken as equivalent to 210 kJ/min or 3.5 kW (3.5 kJ/s).

**Ex:** A refrigerator has working temperature in the evaporator and condenser of -30°C and 32°C respectively, what is the maximum COP possible? If the actual COP of 0.75 of the maximum COP, calculate the refrigeration effect in kW per kW of power input.

**Sol:**  $COP = \frac{T_1}{T_2 - T_1} = \frac{-30 + 273}{(32 + 273) - (-30 + 273)} = 3.91$

actual  $COP_r = 0.75 * 3.91 = 2.939$

$$COP_r = \frac{Q_2}{W} \Rightarrow 2.939 = \frac{Q_2}{W}$$

$Q_2 = 2.939 \text{ kW of refrigeration / kW of work input.}$

**Ex:** A machine working on a Carnot Cycle operates between 305 K and 260 K. Determine the COP, when it is operated as:  
 1. a refrigerating machine,  
 2. a heat pump,  
 3. a heat engine.

**Sol:** 1. for refrigerating machine:

$$COP_R = \frac{T_1}{T_2 - T_1} = \frac{260}{305 - 260} = 5.78$$

2. for Heat pump:

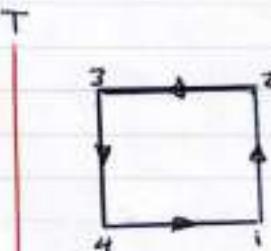
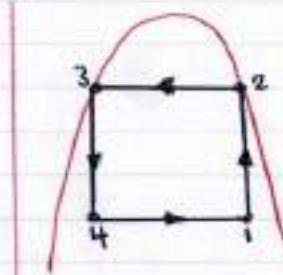
$$COP_P = \frac{T_2}{T_2 - T_1} = \frac{305}{305 - 260} = 6.78$$

$$\text{or } COP_P = COP_R + 1 = 5.78 + 1 = 6.78$$

3. for Heat Engine:

$$COP_E = \frac{T_2 - T_1}{T_2} = 1 - \frac{T_1}{T_2} = 1 - \frac{T_{\min}}{T_{\max}}$$

$$\therefore COP_E = 1 - \frac{260}{305} = 0.147$$



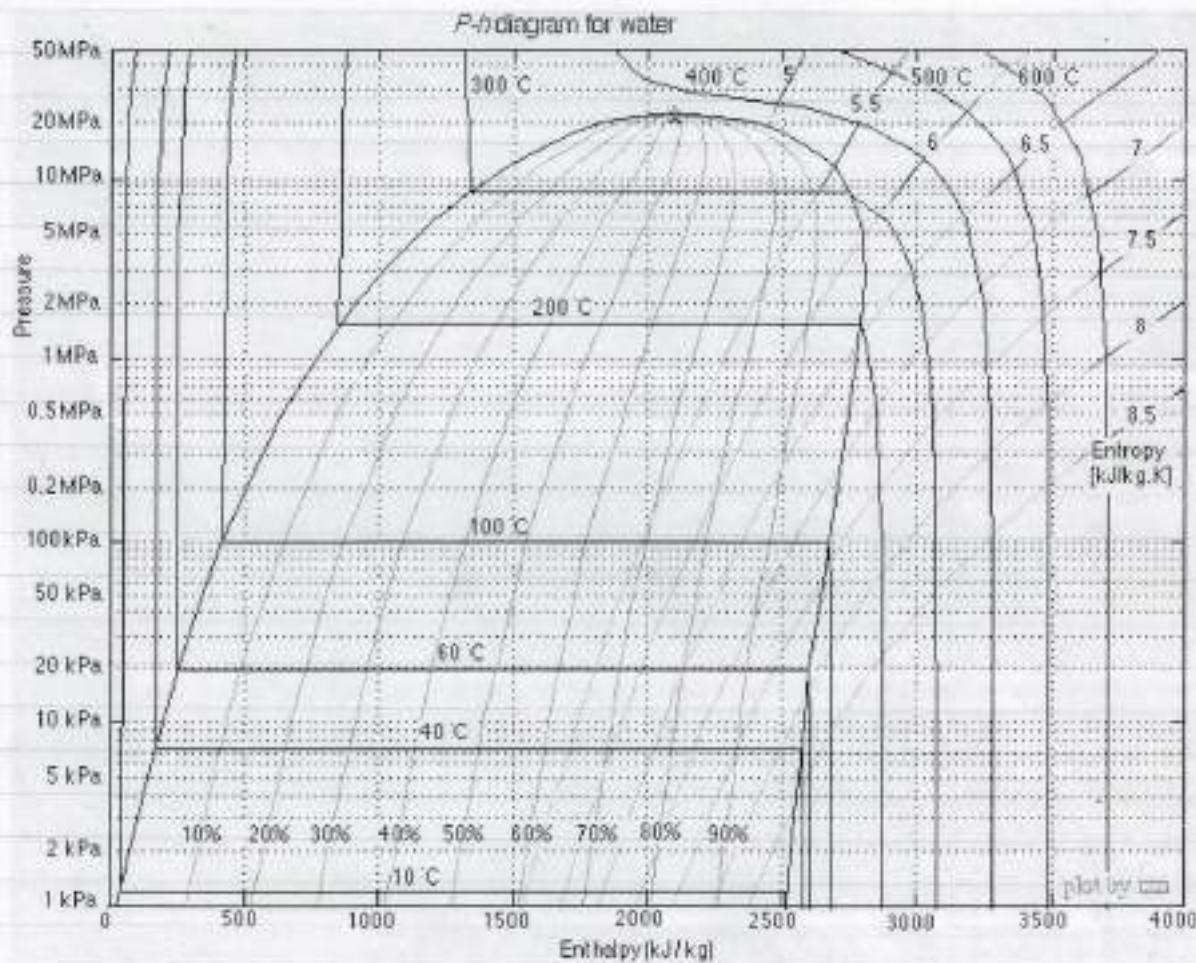
**H.W:** A carnot refrigeration cycle absorbs heat at -3°C and rejects it at 27°C.

1. Calculate the COP<sub>R</sub>.
2. If the cycle is absorbing 1130 kJ/min at -3°C, 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 COP<sub>P</sub>?
4. How many kJ/min will the heat pump deliver at 27°C if it absorbs 1130 kJ/min at -3°C?



## - Pressure - Enthalpy (p-h) Chart:

The most convenient chart for studying the behavior of a refrigerant is the p-h chart in which the vertical ordinates represent pressure and horizontal ordinates represent enthalpy.





## \* Types of Vapour Compression Cycle:

We have already discussed that a vapour compression cycle essentially consists of compression, condensation, throttling and evaporation. Many scientists have focussed their attention to increase the coefficient of performance of the cycle. Though there are many cycles, yet the following are important from the Subject point of view:

1. Cycle with dry saturated vapour after compression,
2. Cycle with wet vapour after compression,
3. Cycle with superheated vapour after compression,
4. Cycle with superheated vapour before compression, and
5. Cycle with undercooling or subcooling of refrigerant.

### \* 1 \* Vapour Compression Cycle with dry Saturated Vapour after compression:

+ Process: 1 → 2: Compression process

$$W_{1-2} = h_2 - h_1 \quad \text{kg/kg}$$

2 → 3: Condensing process

$$\text{heat rejected} = Q_{2-3} = h_2 - h_3, \quad T_2 = T_3 \Rightarrow P_2 = P_3 \\ = T_2(S_2 - S_3) = T_2 \cdot S_{fg}$$

3 → 4: Expansion process  
(throttling process)

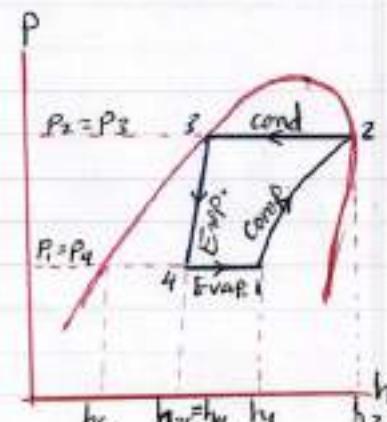
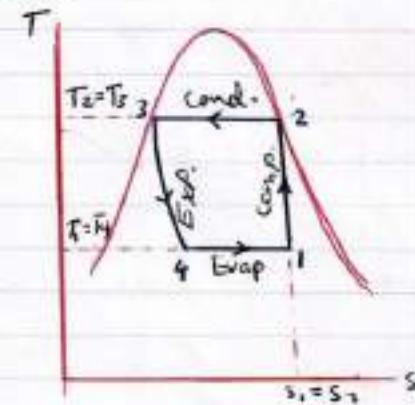
$$h_3 = h_4 \Rightarrow h_3 = h_f \text{ at } P_{\text{cond.}}$$

for Expansion process using expansion valve  
or a capillary (small bore tube).

4 → 1: Vaporising process

$$R_E = h_1 - h_4 \Rightarrow h_4 = h_3 \\ = T_1(S_4 - S_1)$$

$$\text{COP} = \frac{\text{Refrigerating Effect}}{\text{Work done}} = \frac{h_1 - h_4}{h_2 - h_1}$$





**Ex:** The temperature limits of an ammonia refrigerating system are 25°C and -10°C. If the gas is dry saturated 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 kg/kg | Latent heat kg/kg | Liquid entropy kg/kg·K |
|------------------|-------------------|-------------------|------------------------|
| 25               | 298.9             | 1166.94           | 1.1242                 |
| -10              | 135.37            | 1297.68           | 0.5443                 |

$$\text{Sol: } S_1 = S_f + x_1 S_{fg} \quad , \quad h_{fg_{4-1}} = T_1 \cdot S_{fg} \Rightarrow S_{fg} = \frac{h_{fg}}{T_1}$$

$$S_1 = 0.5443 + x_1 \cdot \frac{1297.68}{263} = 0.5443 + 4.934 x_1$$

$$S_2 = S_g \text{ at } T_{\text{cond.}} \quad , \quad S_2 - S_3 = S_g - S_f$$

$$h_2 - h_3 = h_{fg} = T_2 \cdot S_{fg \text{ cond.}} \Rightarrow S_2 = S_f + \frac{h_{fg \text{ cond.}}}{T_2}$$

$$= 1.1242 + \frac{1166.94}{298}$$

$$= 5.04 \text{ kg/kg·K} = S_1$$

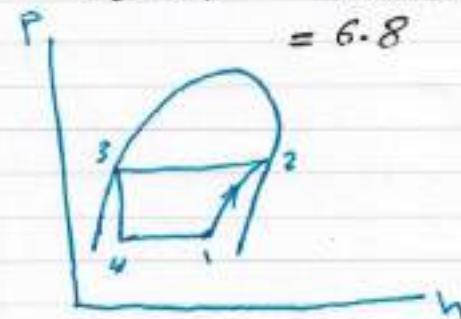
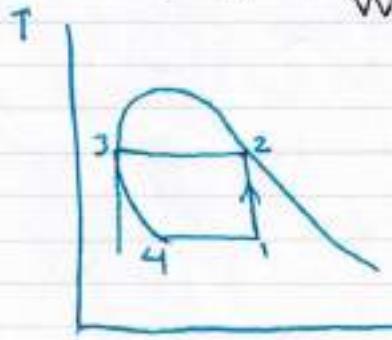
$$\therefore 5.04 = 0.5443 + 4.934 \cdot x_1 \Rightarrow x_1 = 0.91$$

$$h_1 = h_f + x_1 h_{fg} = 135.37 + 0.91 \cdot 1297.68 = 1316.26 \text{ kJ}$$

$$h_2 = h_g = h_{fg_2} + h_{f_2} = 298.9 + 1166.94 \text{ kJ/kg}$$

$$h_4 = h_3 = h_{f \text{ cond.}} = h_{f_3}$$

$$COP_R = \frac{R_E}{W_{in}} = \frac{h_1 - h_{f_3}}{h_2 - h_1} = \frac{1316.26 - 298.9}{1465.84 - 1316.26}$$

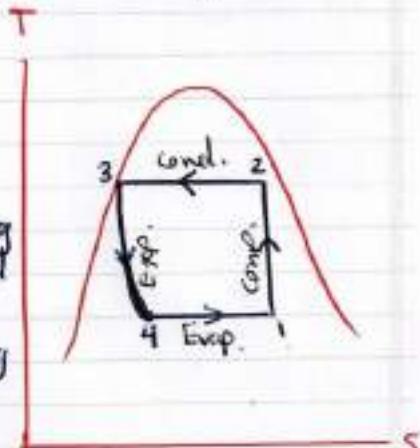




## 2. Vapour Compression Cycle with Wet Vapour after Compression:

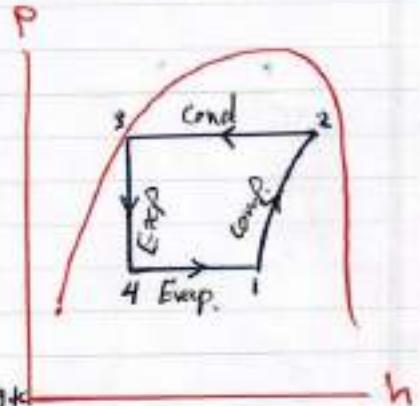
$$COP = \frac{R.E.}{W_{in}} = \frac{h_1 - h_3}{h_2 - h_1}$$

Ex: Fin the COP for a  $\text{CO}_2$  machine working between the temperature range of  $25^\circ\text{C}$  and  $-5^\circ\text{C}$ . The dryness fraction of  $\text{CO}_2$  gas during the suction stroke is  $0.6$ . Following properties of  $\text{CO}_2$  are given:



| T<br>$^{\circ}\text{C}$ | $h_f$<br>kJ/kg | $h_{fg}$<br>kJ/kg | $h_g$<br>kJ/kg | $S_f$<br>kJ/kg.K | $S_g$<br>kJ/kg.K |
|-------------------------|----------------|-------------------|----------------|------------------|------------------|
| 25                      | 81.3           | 121.4             | 202.6          | 0.251            | 0.63             |
| -5                      | -7.54          | 245.3             | 237            | -0.042           | 0.84             |

Sol  $S_1 = S_{f1} + x_1 S_{fg} \Rightarrow S_{fg1} = \frac{h_{fg}}{T_1}$   
 $= -0.042 + \frac{0.6 * 245.3}{268} = 0.507 \text{ kJ/kg.K}$



$$\therefore 0.507 = 0.251 + x_2 \cdot \frac{121.4}{298} \Rightarrow x_2 = 0.629$$

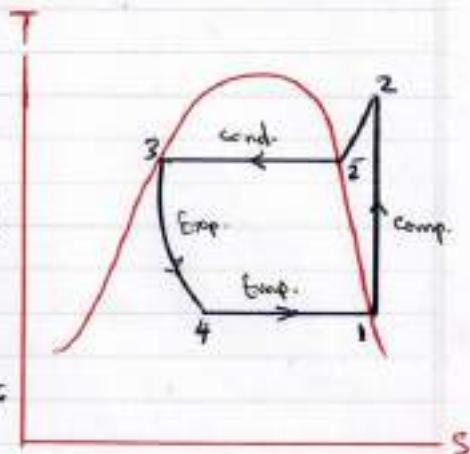
$$h_1 = h_{f1} + x_1 h_{fg1} = -7.54 + 0.6 * 245.3 = 139.64 \text{ kJ/kg}$$

$$h_2 = h_{f2} + x_2 h_{fg2} = 81.3 + 0.629 * 121.4 = 157.66 \text{ kJ/kg}$$

$$\therefore COP = \frac{h_1 - h_3}{h_2 - h_1} = \frac{139.64 - 81.3}{157.66 - 139.64} = 3.24$$

### 3. Vapour Compression Cycle with Superheated Vapour after Compression

Ex: A vapour compression refrigerator uses methyl chloride (R40) and operating between temperature limits of -10°C and 45°C. At entry to the compressor, the refrigerant is dry saturated and after compression it acquires at temperature of 60°C. Find the COP of refrigerator.



| Tsat. (°C) | hf<br>kJ/kg | hg<br>kJ/kg | Sf<br>kJ/kg.K | Sg<br>kJ/kg.K |
|------------|-------------|-------------|---------------|---------------|
| -10        | 45.4        | 460.7       | 0.183         | 1.637         |
| 45         | 133.0       | 483.6       | 0.485         | 1.587         |

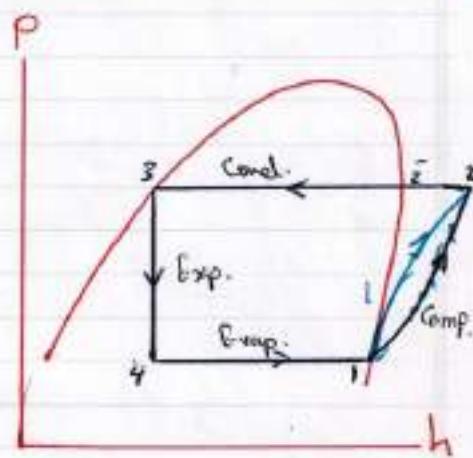
Sol:

$$S_2 - S_{\bar{2}} = C_p \ln \frac{T_2}{T_{\bar{2}}}$$

$$S_2 = S_{\bar{2}} + C_p \ln \frac{T_2}{T_{\bar{2}}} = S_1$$

$$1.637 = 1.587 + C_p \ln \frac{333}{318}$$

$$\therefore C_p = 1.09 \text{ kJ/kg.K}$$



$$h_2 = h_{\bar{2}} + C_p \times \text{DOS}$$

$$= h_{\bar{2}} + C_p(T_2 - T_{\bar{2}})$$

$$h_2 = 483.6 + 1.09(333 - 318) = 500.1 \text{ kJ/kg}$$

, DOS = Degree of Superheat

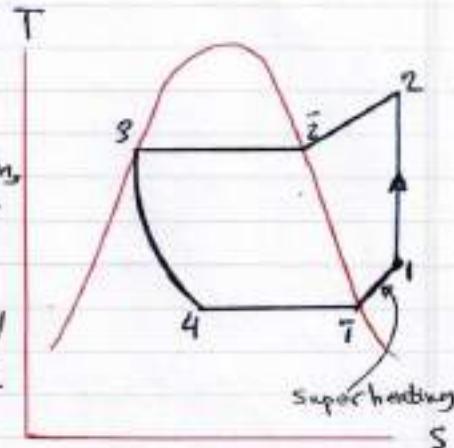
$$\therefore \text{COP} = \frac{h_1 - h_{\bar{2}}}{h_2 - h_1} = \frac{460.7 - 133}{500.1 - 460.7} = 3.77$$



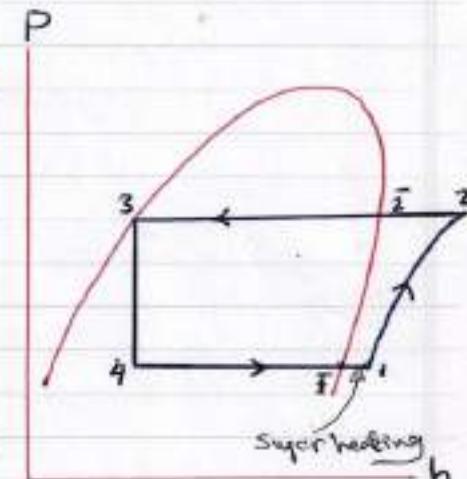
## 4. Vapour Compression Cycle with Superheated Vapour before Compression:

**Ex-10** A vapour compression refrigeration plant works between pressure limits of 5.3 bar and 2.1 bar. The vapour is superheated at the end of compression, its temperature being 37°C. The vapour is superheated by 5°C before entering the compressor.

If the specific heat of superheated vapour is 0.63 kJ/kg.K find the COP of the plant. Use data given below:



| Pressure (bar) | T <sub>sat</sub> (°C) | h <sub>f</sub> (kJ/kg) | h <sub>fg</sub> (kJ/kg) |
|----------------|-----------------------|------------------------|-------------------------|
| 5.3            | 15.5                  | 56.15                  | 144.9                   |
| 2.1            | -14.0                 | 25.12                  | 158.7                   |



Sol

$$h_i = h_{\bar{i}} + C_p(T_i - T_{\bar{i}}) \rightarrow h_i = h_g \\ h_{\bar{i}} = h_{fg} + h_f$$

$$\therefore h_i = (25.12 + 158.7) + 0.63 \times (5) \\ = 186.97 \text{ kJ/kg}$$

$$h_2 = h_{\bar{i}} + C_p(T_2 - T_{\bar{i}}) = (h_{f\bar{i}} + h_{g\bar{i}}) + C_p(T_2 - T_{\bar{i}})$$

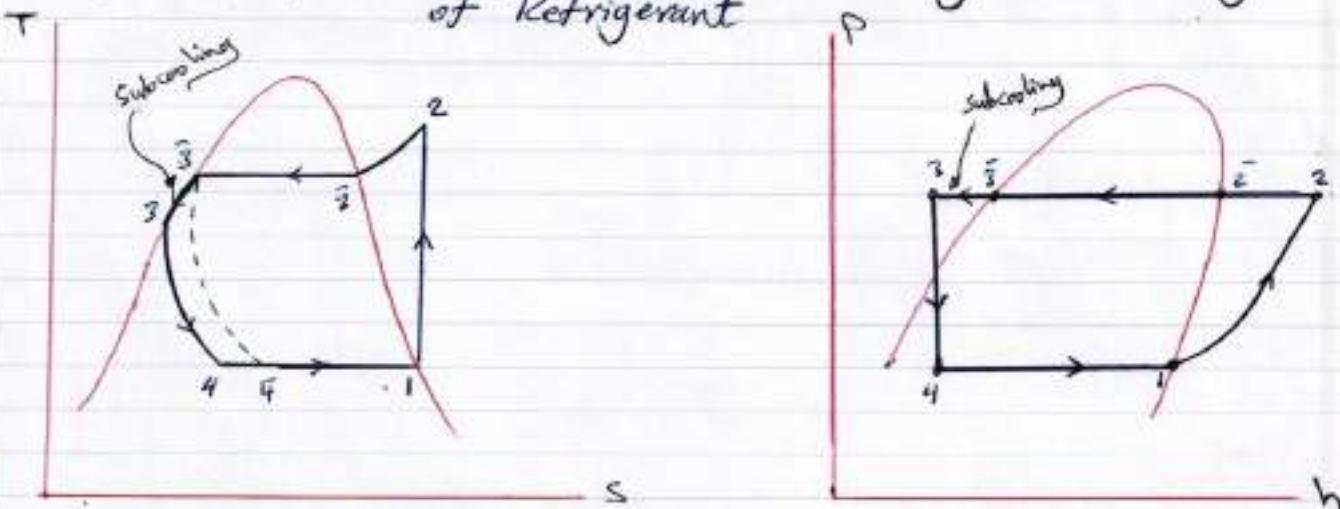
$$\therefore h_2 = (56.15 + 144.9) + 0.63 \times (310 - 288.5) \\ = 214.6 \text{ kJ/kg}$$

$$\text{COP} = \frac{R.E}{W_{in}} = \frac{h_2 - h_{\bar{3}}}{h_2 - h_i} = \frac{186.97 - 56.15}{214.6 - 186.97}$$

$$\therefore \text{COP} = 4.735$$



## 5. Vapour Compression Cycle with undercooling or subcooling of Refrigerant



Ex: A food storage locker requires a refrigeration capacity of 12TR, and works between the evaporating temperature of  $-8^{\circ}\text{C}$  and condensing temperature of  $30^{\circ}\text{C}$ . The refrigerant R12 is subcooled by  $5^{\circ}\text{C}$  before entry to expansion valve and the vapour is superheated to  $-2^{\circ}\text{C}$  before leaving the evaporator coils. Determine: 1. COP 2. Power per TR.  
use the following data for R-12:  $C_p = 1.235 \frac{\text{kJ}}{\text{kg.K}}$ ,  $C_v = 0.733 \frac{\text{kJ}}{\text{kg.K}}$

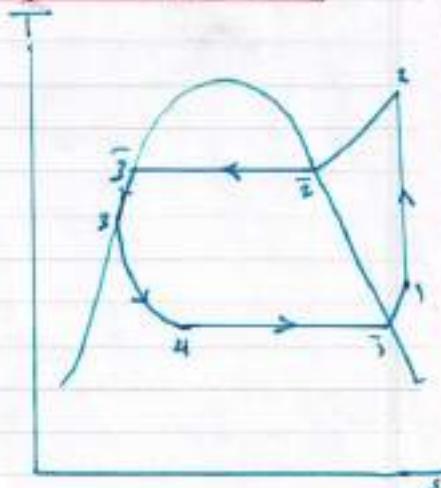
| Temp (C) | Pressure<br>(bars) | Enthalpy $\text{kJ/kg}$ |        | Entropy $\text{kJ/kg.K}$ |        |
|----------|--------------------|-------------------------|--------|--------------------------|--------|
|          |                    | $h_f$                   | $h_g$  | $S_f$                    | $S_g$  |
| -8       | 2.354              | 28.72                   | 184.07 | 0.1149                   | 0.7007 |
| 30       | 7.451              | 64.59                   | 199.62 | 0.2400                   | 0.6853 |

Sol  $\therefore S_1 = S_{\bar{1}} + C_p \ln \frac{T_1}{T_{\bar{1}}}$   
 $= 0.7007 + 0.733 \ln \frac{271}{265} \Rightarrow$

$$S_1 = 0.7171 \text{ kJ/kg.K}$$

$$S_2 = S_{\bar{2}} + C_p \ln \frac{T_2}{T_{\bar{2}}}$$

$$= 0.6853 + 0.733 \ln \frac{120}{303} = S_1$$





$$\therefore 0.7171 = 0.6853 + 0.733 \ln \frac{T_2}{303}$$

$$\therefore T_2 = 316.4 \text{ K} \quad \text{or } 43.4^\circ\text{C}$$

$$h_1 = h_{\bar{1}} + C_p (T_1 - \bar{T}_1)$$

$$= 184.07 + 0.733(271 - 265) = 188.47 \text{ kJ/kg}$$

$$h_2 = h_{\bar{2}} + C_p (T_2 - \bar{T}_2)$$

$$= 199.62 + 0.733(316.4 - 303) = 209.44 \text{ kJ/kg}$$

$$Q_{\text{in}} = C_p (\bar{T}_2 - \bar{T}_1) = h_{\bar{2}} - h_{\bar{1}} \quad \rightarrow h_{\bar{2}} = h_f$$

$$h_3 = h_{f\bar{3}} - C_p (\bar{T}_3 - T_3)$$

$$= 64.59 - 1.235 \times 5$$

$$= 58.42 \text{ kJ/kg} = h_4$$

$$COP = \frac{R.F}{W_{\text{in}}} = \frac{h_1 - h_4}{h_2 - h_1} = \frac{188.47 - 58.42}{209.44 - 188.47} = 6.2$$

$$\underline{2.} \quad R.F = h_1 - h_4 = 188.47 - 58.42 = 130.05 \text{ kJ/kg}$$

$$\text{Refrigerating Capacity (Q)} = 12 \text{ TR}$$

$$= 12 \times 210 = 2520 \text{ kg/min}$$

$$\text{or } Q = 12 \times 3.5 = 42 \text{ kW}$$

$$Q = m * R.F \Rightarrow m = \frac{Q}{R.F} = \frac{42}{130.05} = 0.32295 \text{ kg/s}$$

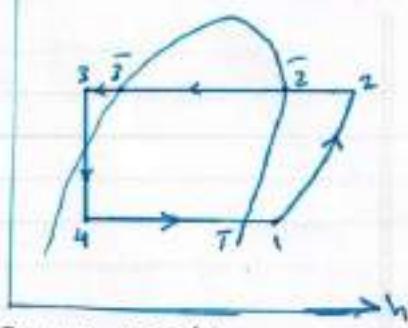
$$\text{Power} = W_{\text{in}} = m(h_2 - h_1) = 0.32295 \times (209.44 - 188.47)$$

$$= 6.7723 \text{ kW}$$

$$\text{Power per tonne of Refrigeration} = \frac{W}{Q}$$

$$= \frac{6.7723}{12}$$

$$= 0.564 \frac{\text{kW}}{\text{TR}}$$



## „Sheet No. 9 „

**Q1:** The temperature in evaporator coils is  $-6^{\circ}\text{C}$  and that in the condenser coil is  $22^{\circ}\text{C}$ . Assuming that the machine operates on the reversed Carnot cycle. Calculate the COP, the refrigeration effect per kW of input work, and the heat rejected to the condenser.

Ans. (9.54, 9.54, 10.4 kW)

**Q2:** A vapour compression refrigerator using R134a works between temperature limits of  $-5^{\circ}\text{C}$  and  $40^{\circ}\text{C}$ . The refrigerant leaves the compressor dry saturated. Calculate the refrigeration effect and COP if, a the refrigerant leaves the condenser saturated, and b the refrigerant is subcooled to  $20^{\circ}\text{C}$  before entering the throttle valve.

Ans. (131.15 kg, 4.54, b. 163.08 kg, 5.65)

**Q3:** In a refrigerator, R134a is compressed isentropically from a Saturated State at  $-5^{\circ}\text{C}$  to a pressure of 11.59 bar. The refrigerant is then cooled at constant pressure to  $25^{\circ}\text{C}$ , and is throttled down to a temperature of  $-5^{\circ}\text{C}$  at which it is evaporated. Determine the temperature and enthalpy after compression in two ways: (a) by using the tables (b) by assuming the  $C_p = 1.153 \text{ kJ/kg} \cdot ^\circ\text{C}$ . Sketch the cycle on T-S and p-h diagrams and calculate the COP by each method.

Ans. (a.  $50.66^{\circ}\text{C}$ , 428.05 kJ/kg, 4.94, b.  $50.62^{\circ}\text{C}$ , 428.01, 4.95)

**Q4:** An ammonia refrigerating machine fitted with an expansion valve works between the temperature limits of  $-10^{\circ}\text{C}$  and  $30^{\circ}\text{C}$ . The vapour is 95% dry at the end of isentropic compression and the fluid leaving the condenser is at  $30^{\circ}\text{C}$ . If the actual coefficient of performance is 60% of the maximum, find the ice produced per kW hour at  $0^{\circ}\text{C}$  from water at  $10^{\circ}\text{C}$ . The latent heat of ice is  $335 \text{ kJ/kg}$ . The ammonia has the following properties:

| Temperature (°C) | hf (kJ/kg) | hfg (kJ/kg) | S <sub>f</sub> | S <sub>g</sub> |
|------------------|------------|-------------|----------------|----------------|
| 30               | 323.08     | 1145.79     | 1.2037         | 4.9842         |
| -10              | 135.37     | 1297.68     | 0.5443         | 5.477          |

Ans. (33.75 kg/kW.h)