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Air Conditioning I (ENME 454)

Compound Vapour Compression Refrigeration Systems

Fall 2021

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5.1 Introduction

In the previous chapter, we have discussed the simple vapour compression refrigeration system in which the low pressure vapour refrigerant from the evaporator is compressed in a single stage (or a single compressor) and then delivered to a condenser at a high pressure. But sometimes, the vapour refrigerant is required to be delivered at a very high pressure as in the case of low temperature refrigerating systems. In such cases either we should compress the vapour refrigerant by employing a single stage compressor with a very high pressure ratio between the condenser and evaporator or compress it in two or more compressors placed in series. The compression carried out in two or more compressors is called *compound* or *multistage compression.*

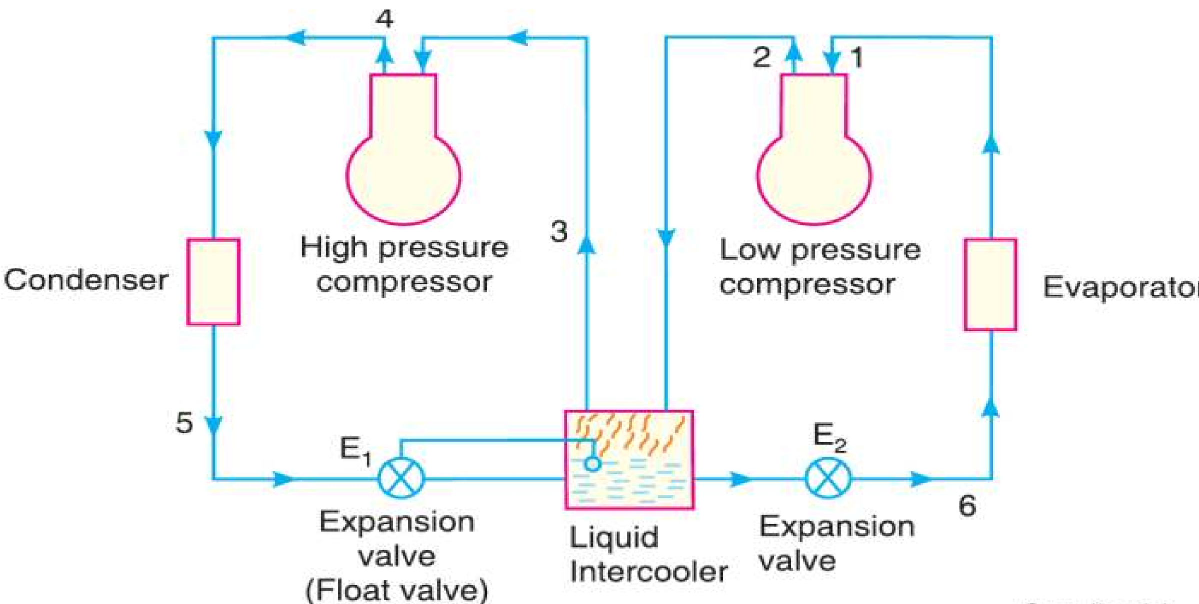
5.3 Types of Compound Vapour Compression with Intercooler

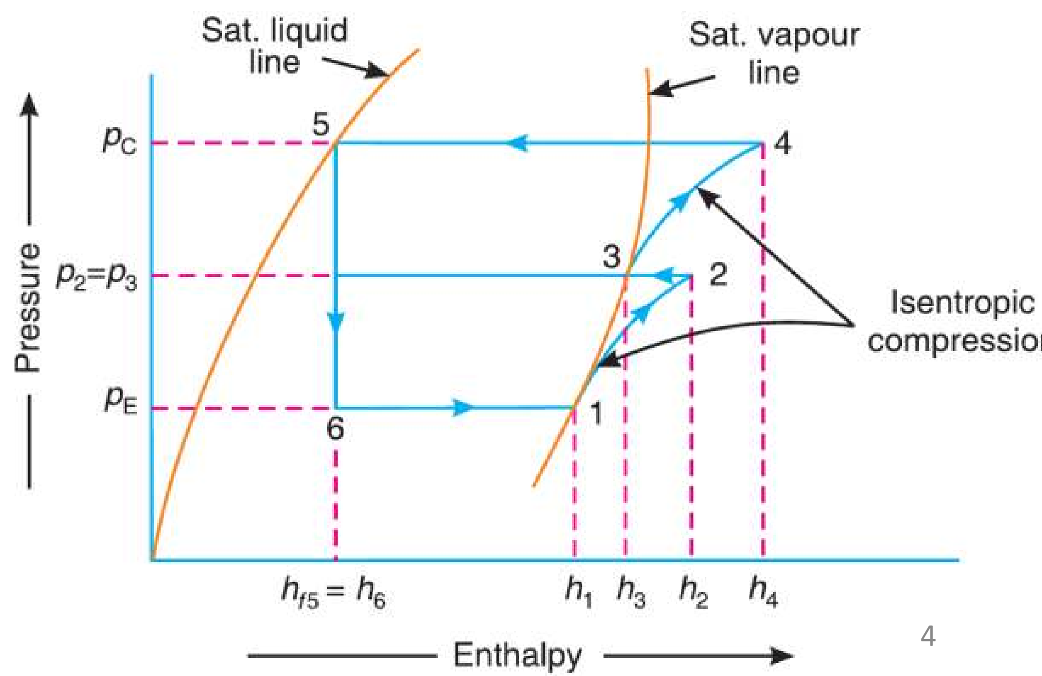
In compound compression vapour refrigeration systems, the superheated vapour refrigerant leaving the first stage of compression is cooled by suitable method before being fed to the second stage of compression and so on. Such type of cooling the refrigerant is called *intercooling*. Though there are many types of compound compression with intercoolers, yet the following are important from the subject point of view :

1. Two stage compression with liquid intercooler.
2. Two stage compression with water intercooler.
3. Two stage compression with water intercooler, liquid subcooler and liquid flash chamber.
4. Two stage compression with water intercooler, liquid subcooler and flash intercooler.
5. Three stage compression with flash chambers.
6. Three stage compression with water intercoolers.
7. Three stage compression with flash intercoolers.

The above mentioned types are now discussed, in detail, one by one in the following pages.

5.4 Two Stage Compression with Liquid Intercooler





Let m_1 = Mass of refrigerant passing through the evaporator (or low pressure compressor) in kg/min, and

m_2 = Mass of refrigerant passing through the condenser (or high pressure compressor) in kg/min.

The high pressure compressor in a given system will compress the mass of refrigerant from low pressure compressor (m_1) and the mass of liquid evaporated in the liquid intercooler during cooling or desuperheating of superheated vapour refrigerant from low pressure compressor. If m_3 is the mass of liquid evaporated in the intercooler, then

$$m_3 = m_2 - m_1$$

The value of m_2 may be obtained by considering the thermal equilibrium for the liquid intercooler as shown in Fig. 5.2, *i.e.*

Heat taken by the liquid intercooler = Heat given by the liquid intercooler

or
$$m_2 h_{f5} + m_1 h_2 = m_1 h_6 + m_2 h_3$$

$$m_2 = \frac{m_1(h_2 - h_6)}{h_3 - h_{f5}} = \frac{m_1(h_2 - h_{f5})}{h_3 - h_{f5}} \quad \ldots (\because h_6 = h_{f5})$$

and mass of liquid refrigerant evaporated in the intercooler,

$$m_3 = m_2 - m_1 = \frac{m_1(h_2 - h_{f5})}{h_3 - h_{f5}} - m_1 = \frac{m_1(h_2 - h_3)}{h_3 - h_{f5}}$$

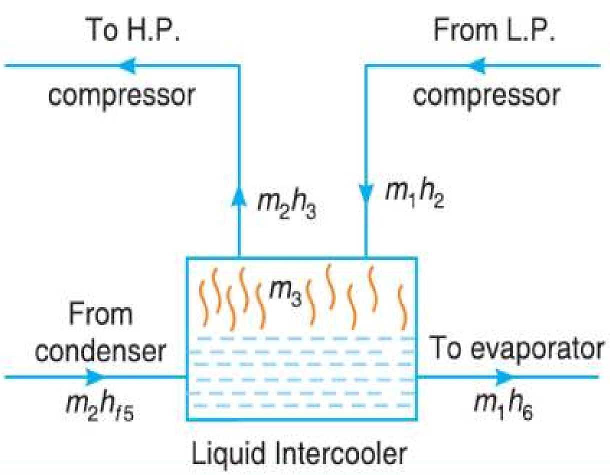


Fig. 5.2. Thermal equilibrium for liquid intercooler.

We know that refrigerating effect,

$$R_E = m_1(h_1 - h_f) = m_1(h_1 - h_{f5}) = 210\ Q \text{ kJ/min}$$

where Q is the load on the evaporator in tonne of refrigeration.

Total workdone in both the compressors,

$$W = m_1(h_2 - h_1) + m_2(h_4 - h_3)$$

$\therefore$ Power required to drive the system,

$$P = \frac{m_1(h_2 - h_1) + m_2(h_4 - h_3)}{60} \text{ kW}$$

and C.O.P. of the system

$$= \frac{R_E}{W} = \frac{m_1(h_1 - h_{f5})}{m_1(h_2 - h_1) + m_2(h_4 - h_3)} = \frac{210\,Q}{P \times 60}$$

Notes: 1. In case of ammonia, when liquid refrigerant is used for intercooling, the total power requirement will decrease. It is due to the fact that the mass of liquid evaporated during intercooling is extremely small because of its high latent heat of vaporisation and the constant entropy lines of ammonia become very flat in the superheat region. Thus the intercooling by liquid refrigerant is commonly used in multi-stage ammonia plants, because of less power requirement.

2. In case of refrigerant R-12, when liquid refrigerant is used for intercooling, the total power requirements may actually increase. It is due to the fact that the latent heat of vaporisation is small and the constant entropy lines of R-12 does not change very much with the temperature. Thus in R-12 systems, the saving in work by performing the compression close to the saturated vapour line does not compensate for the increased mass flow rate through the high stage compressor. Therefore, intercooling by liquid refrigerant in R-12 systems, is never employed.

Example 5.1. *Calculate the power needed to compress 20 kg/min of ammonia from saturated vapour at 1.4 bar to a condensing pressure of 10 bar by two-stage compression with intercooling by liquid refrigerant at 4 bar. Assume saturated liquid to leave the condenser and dry saturated vapours to leave the evaporator. Use the p-h chart.*

Determine, also, the power needed when intercooling is not employed.

Solution. Given : $m_1 = 20$ kg/min ; $p_E = 1.4$ bar ; $p_C = 10$ bar ; $p_2 = p_3 = 4$ bar

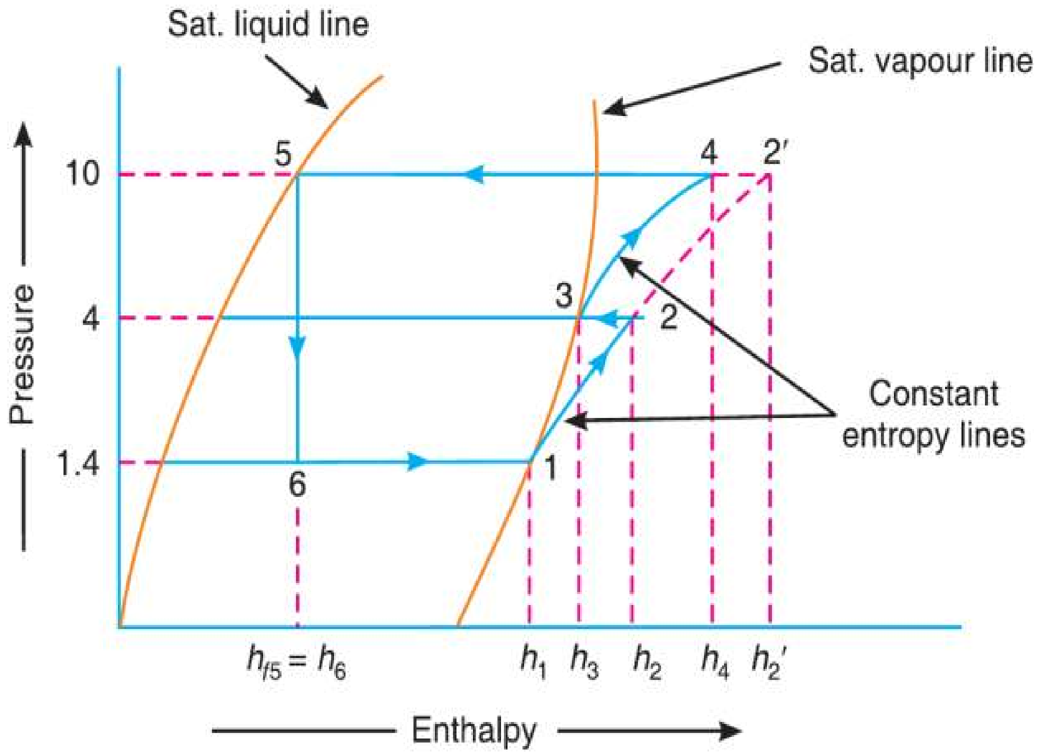


Fig. 5.3

The p-h diagram for a two stage compression with intercooling by liquid refrigerant is shown in Fig. 5.3. The various values for ammonia as read from the p-h diagram are as follows :

Enthalpy of saturated vapour refrigerant entering the low pressure compressor at point 1,

$$h_1 = 1400 \text{ kJ/kg}$$

Entropy of saturated vapour refrigerant entering the low pressure compressor at point 1,

$$s_1 = 5.75 \text{ kJ/kg K}$$

Enthalpy of superheated vapour refrigerant leaving the low pressure compressor at point 2,

$$h_2 = 1527 \text{ kJ/kg}$$

Enthalpy of saturated vapour refrigerant leaving the intercooler or entering the high pressure compressor at point 3,

$$h_3 = 1428 \text{ kJ/kg}$$

Entropy of saturated vapour refrigerant leaving the intercooler or entering the high pressure compressor at point 3,

$$s_3 = 5.39 \text{ kJ/kg K}$$

Enthalpy of superheated vapour refrigerant leaving the high pressure compressor at point 4,

$$h_4 = 1550 \text{ kJ/kg}$$

Enthalpy of saturated liquid refrigerant passing through the condenser at point 5,

$$h_{f5} = h_6 = 284 \text{ kJ/kg}$$

We know that mass of refrigerant passing through the condenser (or high pressure compressor),

$$m_2 = \frac{m_1 (h_2 - h_{f5})}{h_3 - h_{f5}} = \frac{20\,(1527 - 284)}{1428 - 284} = 21.73 \text{ kg/min}$$

Work done in low pressure compressor,

$$W_L = m_1 (h_2 - h_1) = 20 (1527 - 1400) = 2540 \text{ kJ/min}$$

Work done in high pressure compressor,

$$W_H = m_2 (h_4 - h_3) = 21.73 (1550 - 1428) = 2651 \text{ kJ/min}$$

and total work done in both the compressors,

$$W = W_L + W_H = 2540 + 2651 = 5191 \text{ kJ/min}$$

$\therefore$ Power needed $= 5191/60 = 86.5$ kW **Ans.**

Power needed when intercooling is not employed

When intercooling is not employed, the compression of refrigerant will follow the path 1-2 in the low pressure compressor and 2–2′ in the high pressure compressor. In such a case,

Work done in the high pressure compressor,

$$W_H = m_1 (h_{2'} - h_2) = 20 (1676 - 1527) = 2980 \text{ kJ /min}$$

... (From p-h diagram, $h_{2'} = 1676$ kJ/kg)

and total workdone in both the compressors,

$$W = W_L + W_H = 2540 + 2980 = 5520 \text{ kJ/min}$$

$\therefore$ Power needed $= 5520/60 = 92$ kW **Ans.**

Example 5.2. *Calculate the power needed to compress 20 kg/min of R-12 from saturated vapour at 1.4 bar to a condensing pressure of 10 bar by two-stage compression with intercooling by liquid refrigerant at 4 bar. Assume saturated liquid to leave the condenser and dry saturated vapours to leave the evaporator.*

Use the p-h chart. Sketch the cycle on a skeleton p-h chart and label the values of enthalpy at salient points.

Solution. Given : $m_1 = 20$ kg / min ; $p_E = 1.4$ bar ; $p_C = 10$ bar ; $p_2 = p_3 = 4$ bar

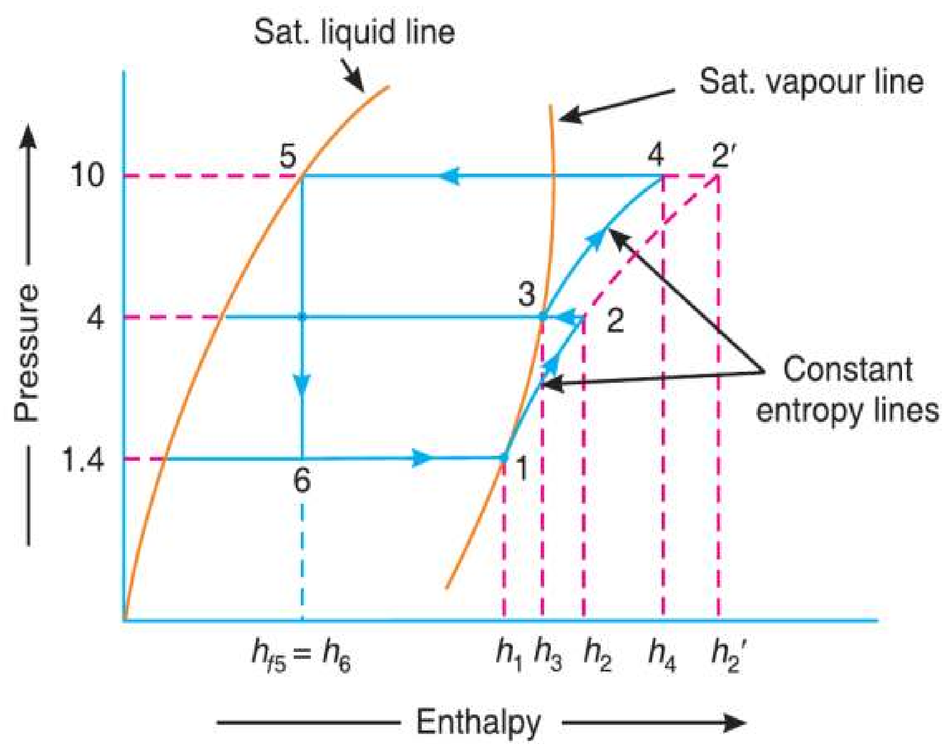


Fig. 5.4

The p-h diagram for a two-stage compression with intercooling by liquid refrigerant is shown in Fig. 5.4. The various values for R-12 as read from the p-h diagram are as follows :

Enthalpy of saturated vapour refrigerant entering the low pressure compressor at point 1,

$$h_1 = 178 \text{ kJ/kg}$$

Entropy of saturated vapour refrigerant entering the low pressure compressor at point 1,

$$s_1 = 0.71 \text{ kJ/kg K}$$

Enthalpy of superheated vapour refrigerant leaving the low pressure compressor at point 2,

$$h_2 = 195 \text{ kJ/kg}$$

Enthalpy of saturated vapour refrigerant leaving the intercooler or entering the high pressure compressor at point 3,

$$h_3 = 191 \text{ kJ/kg}$$

Entropy of saturated vapour refrigerant entering the high pressure compressor at point 3,

$$s_3 = 0.695 \text{ kJ/kg K}$$

Enthalpy of superheated vapour refrigerant leaving the high pressure compressor at point 4,

$$h_4 = 210 \text{ kJ/kg}$$

Enthalpy of saturated liquid refrigerant leaving the condenser at point 5,

$$h_{f5} = h_6 = 77 \text{ kJ/kg}$$

We know that mass of refrigerant passing through the condenser (or high pressure compressor),

$$m_2 = \frac{m_1(h_2 - h_{f5})}{h_3 - h_{f5}} = \frac{20(195-77)}{191-77} = 20.7 \text{ kg/min}$$

Work done in low pressure compressor,

$$W_L = m_1 (h_2 - h_1) = 20 (195 - 178) = 340 \text{ kJ/min}$$

Work done in high pressure compressor,

$$W_H = m_2 (h_4 - h_3) = 20.7 (210 - 191) = 393 \text{ kJ/min}$$

and total work done in both the compressors,

$$W = W_L + W_H = 340 + 393 = 733 \text{ kJ/min}$$

$\therefore$ Power needed $= 733/60 = 12.2$ kW **Ans.**

Note: When intercooling is not employed, the compression of refrigerant will follow the path 1-2 in the low pressure compressor and 2-2′ in the high pressure compressor. In such a case

Work done in high pressure compressor,

$$W_H = m_1 (h_{2'} - h_2) = 20\ (211 - 195) = 320 \text{ kJ/min}$$

... (From *p-h* chart, $h_{2'} = 211$ kJ/kg)

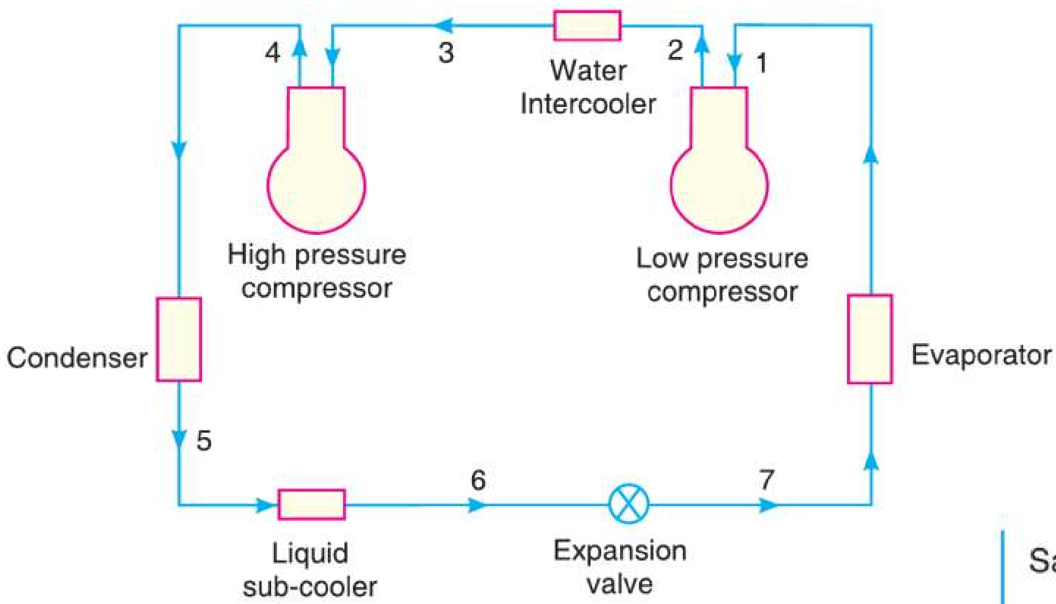
and total work done in both compressors,

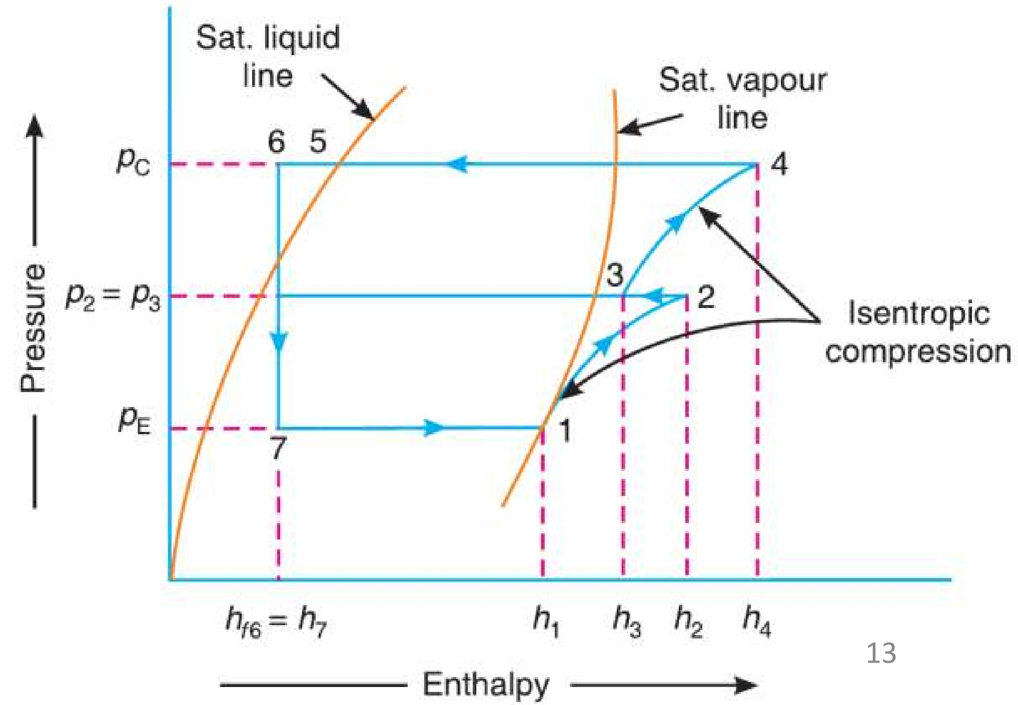
$$W = W_L + W_H = 340 + 320 = 660 \text{ kJ/min}$$

$$\therefore \quad \text{Power needed} = 660/60 = 11 \text{ kW}$$

From above we see that the power needed is more when intercooling by liquid refrigerant is employed than without intercooling.

5.5 Two Stage Compression with Water Intercooler and Liquid Sub-cooler





Let Q = Load on the evaporator in tonnes of refrigeration.

∴ Mass of refrigerant passing through the evaporator (or passing through the L.P. compressor),

$$m = \frac{210\,Q}{h_1 - h_7} = \frac{210\,Q}{h_1 - h_{f6}} \text{ kg/min} \quad \ldots (\because h_7 = h_{f6})$$

Since the mass of refrigerant passing through the compressors is same, therefore, total work done in both the compressors,

$$W = \text{Work done in L.P. compressor + Work done in H.P. compressor}$$

$$= m\,(h_2 - h_1) + m\,(h_4 - h_3) = m\,[(h_2 - h_1) + (h_4 - h_3)]$$

∴ Power required to drive the system,

$$P = \frac{m[(h_2 - h_1) + (h_4 - h_3)]}{60} \text{ kW}$$

We know that refrigerating effect,

$$R_E = m\,(h_1 - h_{f6}) = 210\,Q \text{ kJ/min}$$

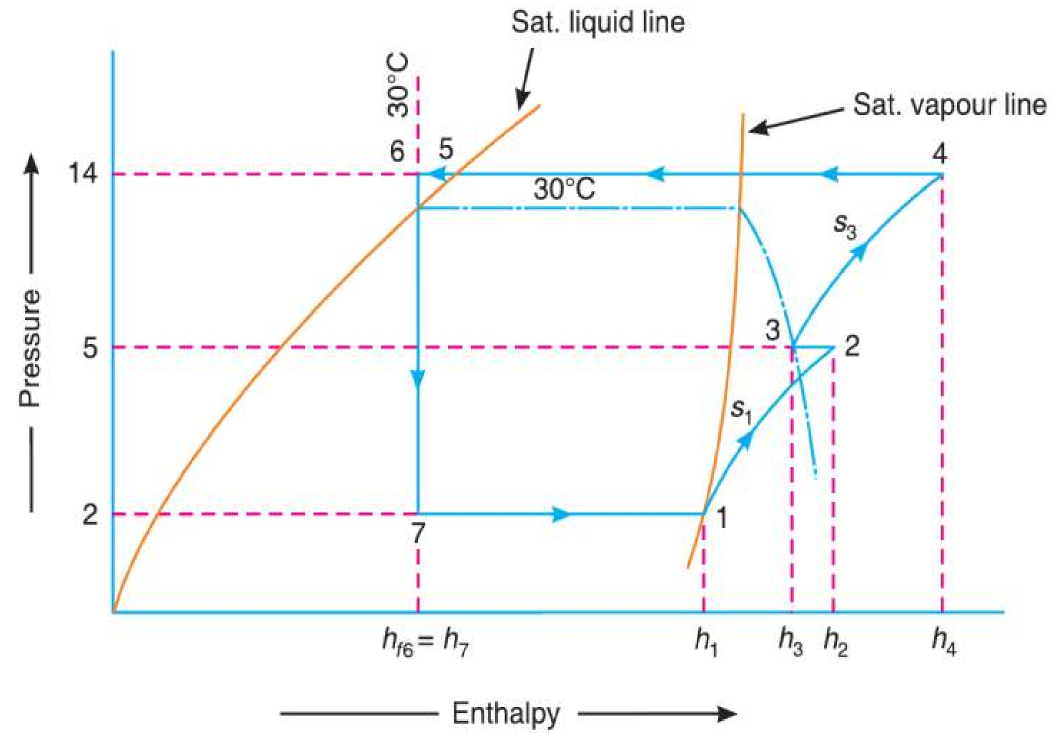
$$\therefore \quad \text{C.O.P. of the system} = \frac{R_E}{W} = \frac{m\,(h_1 - h_{f6})}{m\,[(h_2 - h_1) + (h_4 - h_3)]} = \frac{210\,Q}{P \times 60}$$

Example 5.3. *The following data refer to a two stage compression ammonia refrigerating system with water intercooler.*

Condenser pressure = 14 bar ; Evaporator pressure = 2 bar ; Intercooler pressure = 5 bar ; Load on the evaporator = 2TR.

If the temperature of the de-superheated vapour and sub-cooled liquid refrigerant are limited to 30°C, find (a) the power required to drive the system, and (b) C.O.P. of the system.

Solution. Given : $p_C = 14$ bar ; $p_E = 2$ bar ; $p_2 = p_3 = 5$ bar ; $Q = 10$ TR ; $t_3 = t_6 = 30$°C



Enthalpy of saturated vapour refrigerant entering the low pressure compressor at point 1,

$$h_1 = 1420 \text{ kJ/kg}$$

Entropy of saturated vapour refrigerant at point 1,

$$s_1 = 5.6244 \text{ kJ/kg K}$$

Enthalpy of superheated vapour refrigerant leaving the water intercooler at point 3,

$$h_3 = 1510 \text{ kJ/kg}$$

Entropy of superheated vapour refrigerant at point 3,

$$s_3 = 5.424 \text{ kJ/kg K}$$

Enthalpy of superheated vapour refrigerant leaving the high pressure compressor at point 4,

$$h_4 = 1672 \text{ kJ/kg}$$

Enthalpy of liquid refrigerant leaving the liquid sub-cooler,

$$h_{f6} = h_7 = 323 \text{ kJ/kg}$$

The points 2 and 4 on the *p-h* diagram are obtained in the similar way as discussed in Art. 5.3.

From the *p-h* diagram, we find that enthalpy of superheated vapour refrigerant at point 2,

$$h_2 = 1550 \text{ kJ/kg}$$

(a) *Power required to drive the system*

We know that mass of refrigerant circulating through the system,

$$m = \frac{210\,Q}{h_1 - h_{f6}} = \frac{210 \times 10}{1420 - 323} = 1.91 \text{ kg/min}$$

Total work done in both the compressors,

$$W = m\,[(h_2 - h_1) + (h_4 - h_3)]$$

$$= 1.91\,[(1550 - 1420) + (1672 - 1510) = 557.7 \text{ kJ/min}$$

∴ Power required to drive the system,

$$P = 557.7/60 = 9.3 \text{ kW}$$ **Ans.**

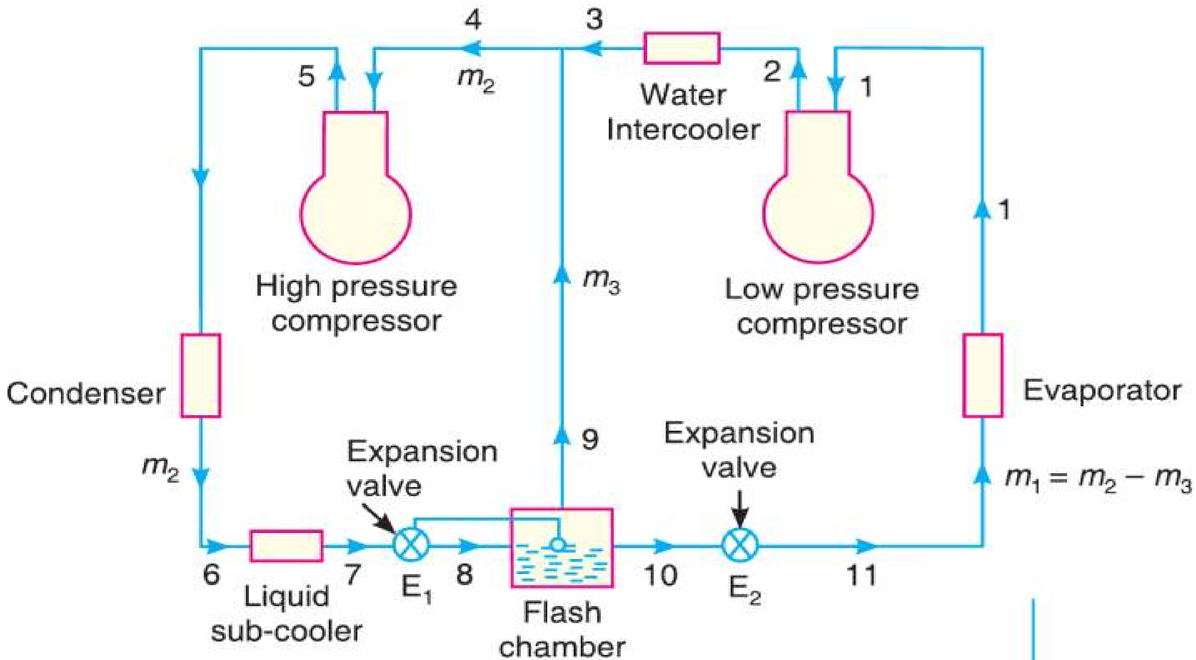
(b) *C.O.P. of system*

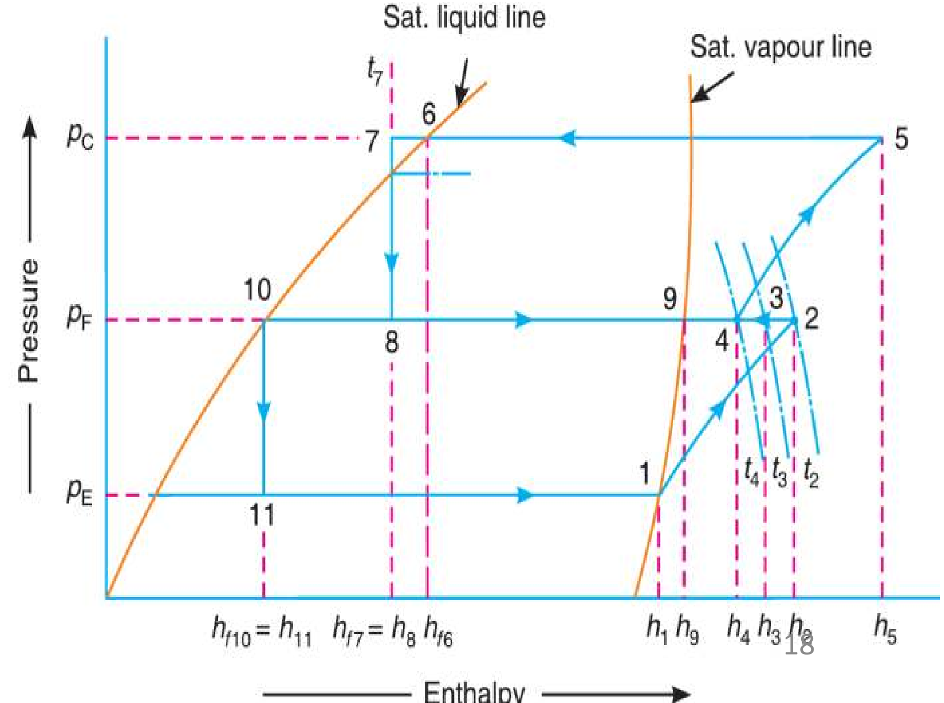
We know that refrigerating effect of the system,

$$R_E = 210\,Q = 210 \times 10 = 2100 \text{ kJ/min}$$

∴ C.O.P. of the system $= \frac{R_E}{W} = \frac{2100}{557.7} = 3.76$ **Ans.**

5.6 Two Stage Compression with Water Intercooler, Liquid Sub-cooler and Liquid Flash Chamber





Let m_2 = Mass of refrigerant passing through the condenser (or high pressure compressor), and

m_3 = Mass of vapour refrigerant formed in the flash chamber.

∴ Mass of refrigerant passing through the evaporator (or low pressure compressor),

$$m_1 = m_2 - m_3$$

If Q tonne of refrigeration is the load on the evaporator, then the mass of refrigerant passing through the evaporator,

$$m_1 = \frac{210\,Q}{h_1 - h_{11}} = \frac{210\,Q}{h_1 - h_{f10}} \text{ kg/min} \qquad \ldots (\because h_{11} = h_{f10})$$

Now let us consider the thermal equilibrium of the flash chamber. Since the flash chamber is an insulated vessel, therefore there is no heat exchange between the flash chamber and atmosphere. In other words, the heat taken and given by the flash chamber are same. Mathematically,

Heat taken by the flash chamber = Heat given by the flash chamber

or

$$m_2\,h_8 = m_3\,h_9 + m_1\,h_{f10}$$

$$= m_3\,h_9 + (m_2 - m_3)\,h_{f10} \qquad \ldots (\because m_1 = m_2 - m_3)$$

$$m_2\,(h_8 - h_{f10}) = m_3\,(h_9 - h_{f10})$$

∴

$$m_3 = m_2\left(\frac{h_8 - h_{f10}}{h_9 - h_{f10}}\right) = m_2\left(\frac{h_{f7} - h_{f10}}{h_9 - h_{f10}}\right) \qquad \ldots (\because h_8 = h_{f7}) \ \ldots (i)$$

The vapour refrigerant from the water intercooler (represented by point 3) is mixed with vapour refrigerant m_3 from the flash chamber (represented by point 9) at the same pressure before entering the high pressure compressor. The enthalpy of the mixed refrigerant (represented by point 4) may be calculated by using the equation,

$$m_2 h_4 = m_3 h_9 + m_1 h_3$$
$$= m_3 h_9 + (m_2 - m_3) h_3$$

We know that refrigerating effect of the system,

$$R_E = m_1 (h_1 - h_{11}) = 210 Q \text{ kJ/min}$$

Work done in low pressure compressor,

$$W_L = m_1 (h_2 - h_1)$$

Work done in high pressure compressor,

$$W_H = m_2 (h_5 - h_4)$$

Total workdone in both the compressors,

$$W = W_L + W_H = m_1 (h_2 - h_1) + m_2 (h_5 - h_4)$$

∴ Power required to drive the system,

$$P = \frac{m_1(h_2 - h_1) + m_2(h_5 - h_4)}{60} \text{ kW}$$

and C.O.P. of the system $= \dfrac{R_E}{W} = \dfrac{m_1(h_1 - h_{11})}{m_1(h_2 - h_1) + m_2(h_5 - h_4)} = \dfrac{210 Q}{P \times 60}$

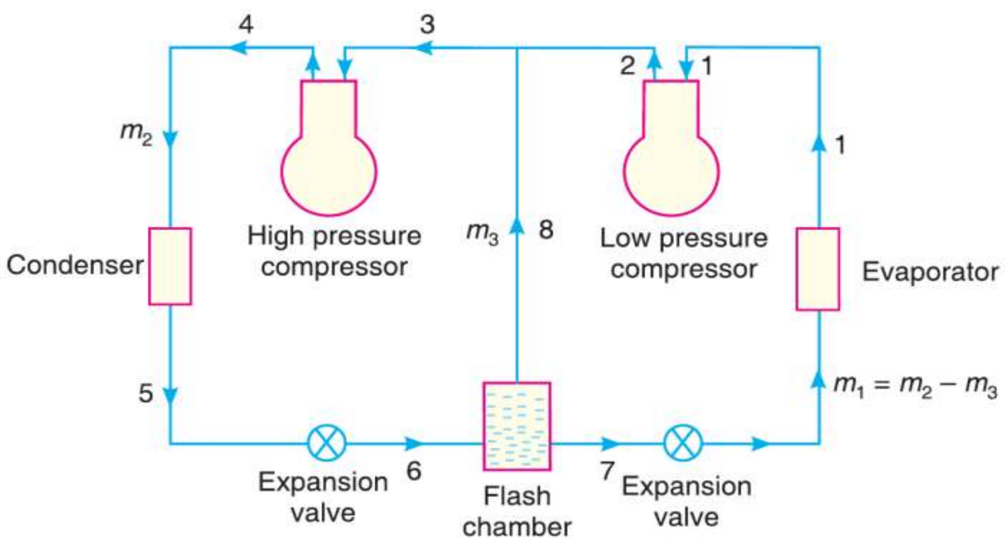
Note: Since the mass of vapour refrigerant m_1 is cooled in the water intercooler from condition 2 to 3, therefore cooling capacity of the intercooler

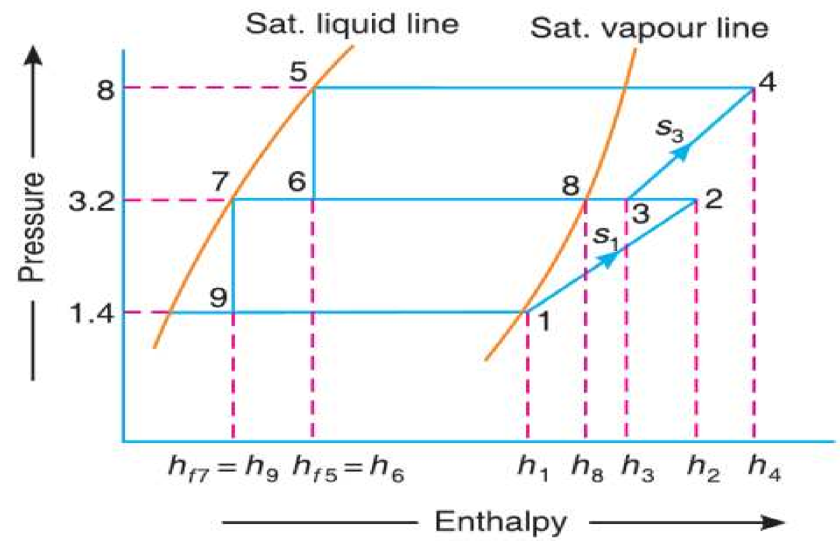
$$= m_1 (h_2 - h_3)$$

Example 5.4. *A two stage refrigerating system is operating between the pressure limits of 8 bar and 1.4 bar. The working fluid is R-134a. The refrigerant leaves the condener as a saturated liquid and is throttled to a flash chamber operating at 3.2 bar. The part of refrigerant evaporates during the flashing process and this vapour is mixed with the refrigerant leaving the low pressure compressor. The mixture is then compressed to the condensor pressure by the high pressure compressor. The liquid in the flash chamber is throttled to the evaporator pressure and cools the refrigerated space as it vaporises in the evaporator. Assuming the refrigerant leaves the evaporator as a saturated vapour and both compressions are isentropic, determine :*

1. *The fraction of refrigerant that evaporates as it is throttled to the flash chamber ;*
2. *The amount of heat removed from the refrigerated space and the compressor work per unit mass of refrigerant flowing through the condensor ; and*
3. *The coefficient of performance.*

Solution. Given : $p_C = 8$ bar ; $p_E = 1.4$ bar ; $p_F = 3.2$ bar





The arrangement for a two stage refrigerating system with the given conditions is shown in Fig 5.8 (*a*) and the corresponding *p*-*h* diagram is shown in Fig. 5.8 (*b*). The various values as read from the *p*-*h* diagram for *R*-134*a* are as follows :

Enthalpy of saturated vapour refrigerant entering the low pressure compressor at point 1,

$$h_1 = 387 \text{ kJ/kgK}$$

Entropy of saturated vapour refrigerant entering the low pressure compressor at point 1,

$$s_1 = 1.7387 \text{ kJ/kgK}$$

Enthalpy of superheated vapour refrigerant leaving the low pressure compressor at point 2,

$$h_2 = 404 \text{ kJ/kg}$$

Enthalpy of saturated vapour refrigerant leaving the flash chamber at point 8,

$$h_8 = 400 \text{ kJ/kg}$$

Enthalpy of saturated liquid refrigerant leaving the condenser at point 5,

$$h_{f5} = h_6 = 244 \text{ kJ/kg}$$

Enthalpy of saturated liquid refrigerant leaving the flash chamber at point 7,

$$h_{f7} = h_9 = 203 \text{ kJ/kg}$$

1. *Fraction of refrigerant that evaporates in the flash chamber*

Considering the mass of refrigerant passing through the condenser (or high pressure compressor) be 1 kg, *i.e.* taking

$$m_2 = 1 \text{ kg}$$

Let m_3 = Mass of vapour refrigerant formed in the flash chamber.

∴ Mass of refrigerant passing through the evaporator (or low pressure compressor),

$$m_1 = m_2 - m_3$$

For the thermal equilibrium of the flash chamber, the heat taken by the flash chamber must be equal to the heat given by the flash chamber. In other words

$$m_2 h_6 = m_3 h_8 + m_1 h_{f7}$$

$$1 \times 244 = m_3 \times 400 + (1 - m_3) 203$$

$$= 400\, m_3 + 203 - 203\, m_3 = 197\, m_3 + 203$$

$$\therefore \quad m_3 = \frac{244 - 203}{197} = 0.208 \text{ kg}$$

It means that fraction of refrigerant that evaporates in the flash chamber is 0.208 of the refrigerant passing through the condenser. In other words, $m_3 / m_2 = 0.208$ **Ans.**

2. *Amount of heat removed from the rerigerated space and the compressor work*

The vapour refrigerant as represented by point 2 is mixed with vapour refrigerant from the flash chamber as represented by point 8. The enthalpy of the mixed refrigerant entering the high pressure compressor as represented by point 3 is given by

$$m_2 h_3 = m_3 h_8 + m_1 h_2 = m_3 h_8 + (m_2 - m_3) h_2$$

or $$h_3 = \frac{m_3}{m_2} \times h_8 + h_2 \left(1 - \frac{m_3}{m_2}\right)$$

$$= 0.208 \times 400 + 404\ (1 - 0.208) = 403 \text{ kJ/kg}$$

We see from *p-h* diagram that at point 3 (intersection of pressure 3.2 bar and enthalpy (h_3) of 403 kJ/kg), the entropy is s_3 = 1.736 kJ/kg. Now from point 3, draw a line of entropy equal to 1.736 kJ/kg K along the constant entropy line which intersects the condenser pressure (8 bar) line at point 4. From *p-h* diagram, we find that enthalpy of refrigerant leaving the high pressure compressor (or entering the condenser) at point 4 is

$$h_4 = 422 \text{ kJ/kg}$$

∴ Amount of heat removed from the refrigerated space or refrigerated effect,

$$R_E = m_1\ (h_1 - h_9) = (m_2 - m_3)\ (h_1 - h_{f7})$$

$$\ldots (\because\ m_1 = m_2 - m_3\ ;\ \text{and } h_9 = h_{f7})$$

$$= (1 - 0.208)\ (387 - 203) = 145.7 \text{ kJ}$$ **Ans.**

We know that compressor work *i.e.* workdone in both the compressors,

W = Workdone is L.P. compressor + Workdone in H.P. compressor

$$= m_1\ (h_2 - h_1) + m_2\ (h_4 - h_3)$$

$$= (1 - 0.208)\ (404 - 387) + 1(422 - 403)$$

$$= 13.46 + 19 = 32.46 \text{ kJ}$$ **Ans.**

3. Coefficient of performance

We know that coefficient of performance

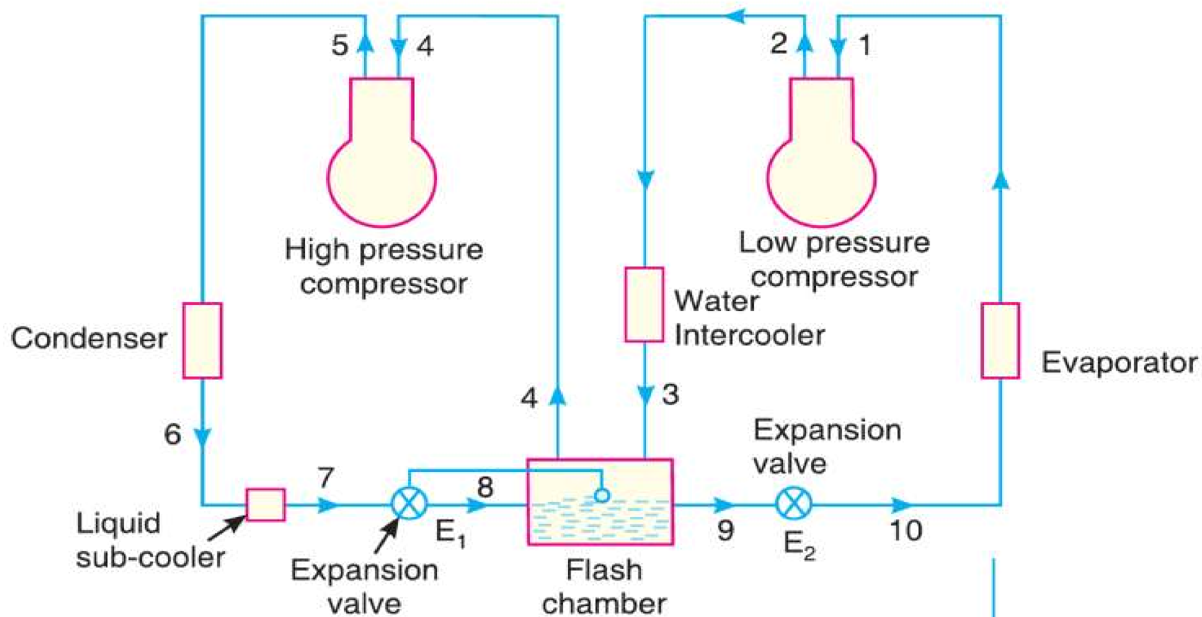
$$= \frac{R_E}{W} = \frac{145.7}{32.46} = 4.5$$ **Ans.**

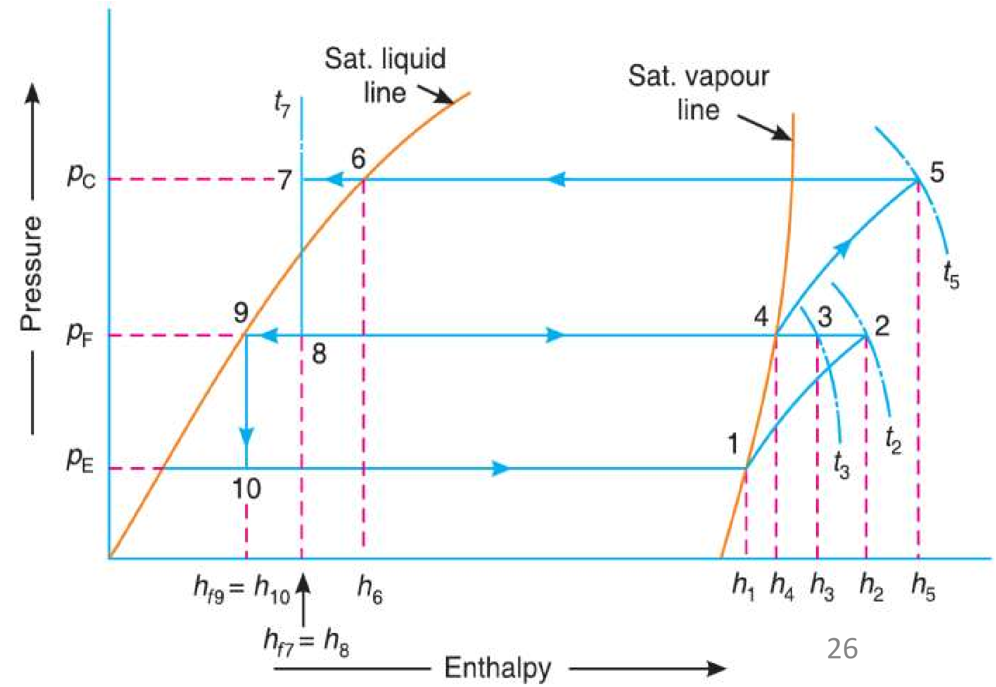
Home Work

Example 5.5. *A two stage compression ammonia refrigeration system operates between overall pressure limits of 14 bar and 2 bar. The temperature of the desuperheated vapour and subcooled liquid refrigerant are limited to 30°C. The flash tank separates dry vapour at 5 bar pressure and the liquid refrigerant then expands to 2 bar.*

Estimate the C.O.P. of the machine and power required to drive the compressor, if the mechanical efficiency of the drive is 80% and load on the evaporator is 10 TR.

5.7 Two Stage Compression with Water Intercooler, Liquid Sub-cooler and Flash Intercooler





Let m_1 = Mass of the refrigerant passing through the evaporator (or low pressure compressor), and

m_2 = Mass of the refrigerant passing through the condenser (or high pressure compressor).

If Q tonne of refrigeration is the load on the evaporator, then the mass of refrigerant passing through the evaporator is given by,

$$m_1 = \frac{210\,Q}{h_1 - h_{10}} = \frac{210\,Q}{h_1 - h_{f9}} \text{ kg / min} \qquad \ldots (\because h_{10} = h_{f9})$$

Now for the thermal equilibrium of the flash intercooler,

Heat taken by the flash intercooler

= Heat given by the flash intercooler

$$m_2\, h_8 + m_1\, h_3 = m_2\, h_4 + m_1\, h_{f9}$$

$$m_1\,(h_3 - h_{f9}) = m_2\,(h_4 - h_8)$$

$$\therefore \qquad m_2 = m_1 \left(\frac{h_3 - h_{f9}}{h_4 - h_8} \right) = m_1 \left(\frac{h_3 - h_{f9}}{h_4 - h_{f7}} \right) \text{ kg/min} \qquad (\because h_8 = h_{f7})$$

We know that refrigerating effect,

$$R_E = m_1\,(h_1 - h_{10}) = m_1\,(h_1 - h_{f9}) = 210\,Q \text{ kJ/min}$$

and work done in both the compressors,

W = Work done in L.P. compressor + Work done in H.P. compressor

$$= m_1\,(h_2 - h_1) + m_2\,(h_5 - h_4)$$

$\therefore$ Power required to drive the system,

$$P = \frac{m_1\,(h_2 - h_1) + m_2\,(h_5 - h_4)}{60} \text{ kW}$$

and coefficient of performance of the system,

$$\text{C.O.P.} = \frac{R_E}{W} = \frac{m_1(h_1 - h_{f9})}{m_1(h_2 - h_1) + m_2(h_5 - h_4)} = \frac{210\,Q}{P \times 60}$$

Example 5.6. *In a 15 TR ammonia plant, compression is carried out in two stages with water and flash intercooling and water subcooling. The particulars of the plant are as follows:*

Condenser pressure = 12 bar

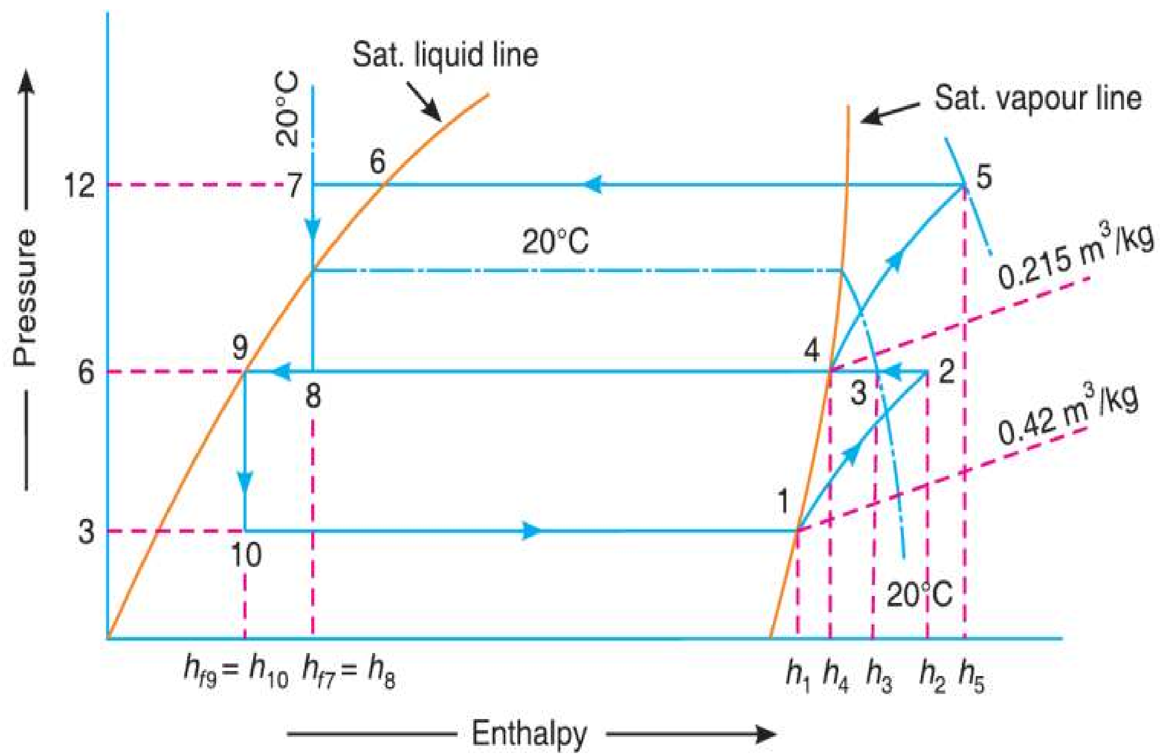
Evaporator pressure = 3 bar

Flash intercooler pressure = 6 bar

Limiting temperature for intercooling and sub-cooling = 20°C

Draw the cycle on p-h chart and estimate (a) the coefficient of performance of the plant, (b) the power required for each compressor, and (c) the swept volume for each compressor if the volumetric efficiency of both the compressors is 80%.

Solution. Given : $Q = 15$ TR ; $p_C = 12$ bar ; $p_E = 3$ bar ; $p_F = 6$ bar ; $t_3 = t_7 = 20°$ C ; $\eta_v = 80\% = 0.8$



Enthalpy of saturated vapour refrigerant entering the low pressure compressor at point 1,

$$h_1 = 1422 \text{ kJ/kg}$$

Entropy of saturated vapour refrigerant entering the low pressure compressor at point 1,

$$s_1 = 5.49 \text{ kJ/kg K}$$

Specific volume of saturated vapour refrigerant entering the low pressure compressor at point 1,

$$v_1 = 0.42 \text{ m}^3\text{/kg}$$

Enthalpy of superheated vapour refrigerant leaving the low pressure compressor at point 2,

$$h_2 = 1505 \text{ kJ/kg}$$

Enthalpy of superheated vapour refrigerant leaving the water intercooler at point 3,

$$h_3 = 1465 \text{ kJ/kg}$$

Enthalpy of saturated vapour refrigerant leaving the flash intercooler at point 4,

$$h_4 = 1440 \text{ kJ/kg}$$

Entropy of saturated vapour refrigerant at point 4,

$$s_4 = 5.25 \text{ kJ/kg K}$$

Specific volume of saturated vapour refrigerant at point 4,

$$v_4 = 0.215 \text{ m}^3\text{/kg}$$

Enthalpy of superheated vapour refrigerant at point 5,

$$h_5 = 1530 \text{ kJ/kg}$$

Enthalpy of liquid refrigerant leaving the liquid sub-cooler at point 7,

$$h_{f7} = h_8 = 265 \text{ kJ/kg}$$

Enthalpy of saturated liquid refrigerant leaving the flash intercooler at point 9,

$$h_{f9} = h_{10} = 224 \text{ kJ/kg}$$

(a) Coefficient of performance of the plant

We know that mass of refrigerant passing through the evaporator (or low pressure compressor),

$$m_1 = \frac{210\,Q}{h_1 - h_{f9}} = \frac{210 \times 15}{1422 - 224} = 2.63 \text{ kg/min}$$

and mass of refrigerant passing through the condenser (or high pressure compressor),

$$m_2 = m_1\left(\frac{h_3 - h_{f9}}{h_4 - h_{f7}}\right) = 2.63\left(\frac{1465 - 224}{1440 - 265}\right) = 2.78 \text{ kg/min}$$

∴ Coefficient of performance of the plant,

$$\text{C.O.P.} = \frac{m_1(h_1 - h_{f9})}{m_1(h_2 - h_1) + m_2(h_5 - h_4)}$$

$$= \frac{2.63\,(1422 - 224)}{2.63\,(1505 - 1422) + 2.78\,(1530 - 1440)} = 6.725 \text{ Ans.}$$

(b) Power required for each compressor

We know that work done in low pressure compressor,

$$W_L = m_1\,(h_2 - h_1) = 2.63\,(1505 - 1422) = 218.3 \text{ kJ/min}$$

$\therefore$ Power required for low pressure compressor,

$$P_L = 218.3/60 = 3.64 \text{ kW } \textbf{Ans.}$$

Similarly, work done in high pressure compressor,

$$W_H = m_2 (h_5 - h_4) = 2.78 (1530 - 1440) = 250.2 \text{ kJ/min}$$

$\therefore$ Power required for high presssure compressor,

$$P_H = 250.2/60 = 4.17 \text{ kW } \textbf{Ans.}$$

(c) Swept volume for each compressor

We know that swept volume for low pressure compressor

$$= \frac{m_1 \times v_1}{\eta_v} = \frac{2.63 \times 0.42}{0.8} = 1.46 \text{ m}^3\text{/min } \textbf{Ans.}$$

and swept volume for high pressure compressor

$$= \frac{m_2 \times v_4}{\eta_v} = \frac{2.78 \times 0.215}{0.8} = 0.747 \text{ m}^3\text{/min } \textbf{Ans.}$$