Multi-Stage Vapour Compression Refrigeration Systems

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The objectives of this lesson are to:

1. Discuss limitations of single stage vapour compression refrigeration systems.
2. Classify multi-stage systems.
3. Discuss the concept of flash gas removal using flash tank.
4. Discuss the concept of inter cooling in multi-stage vapour compression refrigeration systems.
5. Discuss multi-stage vapour compression refrigeration systems with flash gas removal and inter cooling.
6. Discuss the use of flash tank for flash gas removal only.
7. Discuss the use of flash tank for inter cooling only.

1.1. Introduction

A single stage vapour compression refrigeration system has one low side weight (evaporator weight) and one high side weight (condenser weight). The execution of single stage systems demonstrates that these systems are satisfactory the length of the temperature distinction in the middle of evaporator and condenser (temperature lift) is little. Nonetheless, there are numerous applications where the temperature lift can be high. The temperature lift can get to be substantial either because of the prerequisite of low evaporator temperatures and/or because of the necessity of high consolidating temperatures. Case in point, in solidified sustenance businesses the obliged evaporator can be as low as –40 ^{o}C , while in synthetic commercial ventures temperatures as low as –150 ^{o}C may be needed for liquefaction of gasses.

On the high temperature side the obliged gathering temperatures can be high if the refrigeration system is utilized as a warmth pump for warming applications, for example, procedure warming, drying and so on. In any case, as the temperature lift builds the single stage systems get to be wasteful and unfeasible. Case in point, Fig. 1.1 demonstrates the impact of diminishing evaporator temperatures on T s and P h diagrams. It can be seen from the T s diagrams that for a given condenser temperature, as evaporator temperature decreases. Throttling losses increase

ii. Superheat losses increase

iii. Compressor discharge temperature increases

iv. Quality of the vapour at the inlet to the evaporator increases

v. Specific volume at the inlet to the compressor increases

An after effect of this, the refrigeration impact reductions and work of compression increases as shown in the P h graph. The volumic refrigeration impact additionally decreases quickly as the particular volume increases with decreasing evaporator temperature. Comparative impacts will happen, however not in the same extent when the condenser temperature increases for a given evaporator temperature. Because of these drawbacks, single stage systems are not prescribed when the evaporator temperature gets to be low and/or when the condenser temperature gets to be high. In such cases multi-stage systems are utilized as a part of practice.

For the most part, for fluorocarbon and alkali based refrigeration systems a single stage system is utilized something like an evaporator temperature of –30 °C. A two-stage system is utilized up to –60 °C and a three-stage system is utilized for temperatures underneath –60 °C. Aside from high temperature lift applications, multi-stage systems are additionally utilized as a part of utilizations obliging refrigeration at distinctive temperatures. For instance, in a dairy plant refrigeration may be needed at –30 °C for making frozen yogurt and at 2 °C for chilling milk. In such cases it might be profitable to utilize a multi-evaporator system with the low temperature evaporator working at –30 °C.

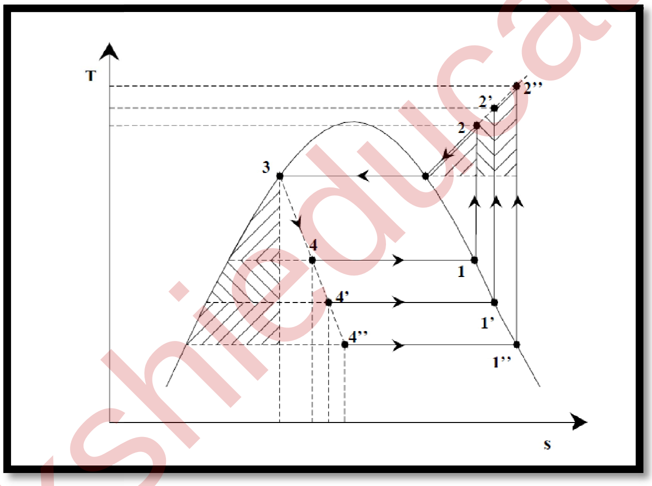


Fig.1.1(a):Effect of evaporator temperature on cycle performance (T-s diagram)

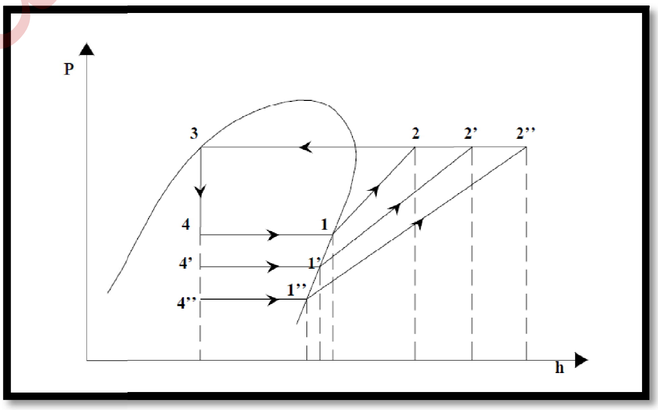


Fig.1.1(b):Effect of evaporator temperature on cycle performance (P-h diagram)

A multi-stage system is a refrigeration system with two or more low-side pressures. Multistage systems can be classified into:

a) Multi-compression systems
b) Multi-evaporator systems
c) Cascade systems, etc.

Two concepts which are normally integral to multi-pressure systems are,
i. Flash gas removal, and
ii) Inter cooling. Hence these concepts will be discussed first.

1.2. Flash gas removal using flash tank

It is mentioned over that one of the issues with high temperature lift applications is the high caliber of vapour at the channel to the evaporator. This vapour called as flash gas creates amid the throttling methodology. The flash gas must be packed to condenser pressure, it doesn't add to the refrigeration impact as it is as of now as vapour, and it builds the pressure drop in the evaporator. It is conceivable to enhance the COP of the framework if the flash gas is evacuated when it is framed and recompressed to condenser pressure. Nonetheless, constant evacuation of flash gas when it is structured and recompressing it quickly is troublesome by and by.

Restricted of enhancing the execution of the framework is to uproot the flash gas at a middle pressure utilizing a flash tank. Figure 1.2 demonstrates the schematic of a flash tank and Fig.1.3 demonstrates the development procedure utilizing flash tank. A flash tank is a pressure vessel, wherein the refrigerant fluid and vapour are differentiated at a transitional pressure. The refrigerant from condenser is initially extended to a middle of the road pressure comparing to the pressure of flash tank, Pi utilizing a low side float valve (transform 6-7). The float valve additionally keeps up a steady fluid level in the flash tank. In the flash tank, the refrigerant fluid and vapour are differentiated. The soaked fluid at direct 8 is sustained toward the evaporator in the wake of throttling it to the obliged evaporator pressure, Pe (point 9) utilizing an extension valve. Contingent on the sort of the system, the soaked vapour in the flash tank (point 3) is either compacted to the condenser pressure or throttled to the evaporator pressure.

Without flash tank, the refrigerant condition at the channel to the evaporator would have been point 9', which has an extensively high vapour quality contrasted with point 9. As specified, the refrigerant fluid and vapour must get differentiated in the flash tank. This is conceivable when the upward speed of the refrigerant vapour in the flash tank is sufficiently low (< 1 m/s) for the refrigerant fluid droplets to fall once more into the flash tank because of gravity. In this way the surface region of fluid in the flash tank can be gotten from the volumetric stream rate of refrigerant vapour and the obliged low refrigerant velocity.

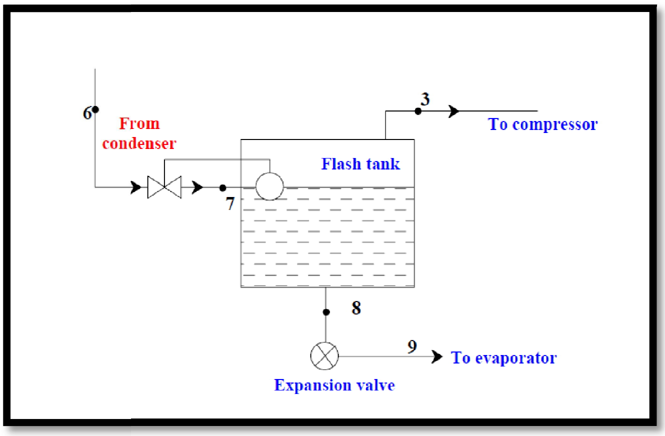


Fig.1.2(a): Working principle of a flash tank

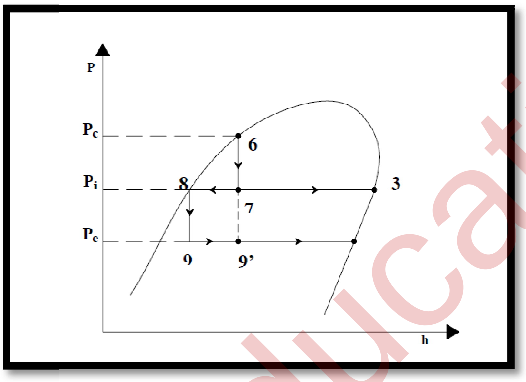


Fig.1.3: Expansion process using a flash tank on P-h diagram

1.3. Inter cooling in multi-stage compression

The specific work input, w in reversible, polytropic compression of refrigerant vapour is given by:

$$w = -\int_1^2 v.dP = \left(\frac{n}{n-1}\right)P_1 v_1 \left[1 - \left(\frac{P_2}{P_1}\right)^{(n-1)/n}\right]$$

where P1 and P2 are the inlet and outlet pressure of the compressor, v1 is the particular volume of the refrigerant vapour at the inlet to the compressor and n is the polytropic type. From the above interpretation, it can be seen that particular work info lessens as particular volume, v1 is lessened. At a given pressure, the particular volume can be lessened by diminishing the temperature. This is the guideline behind bury cooling in multi-stage pressure. Figures 1.4 (an) and (b) demonstrate the procedure of entomb cooling in two-stage pressure on Pressure particular volume (P-v) and P-h diagrams.

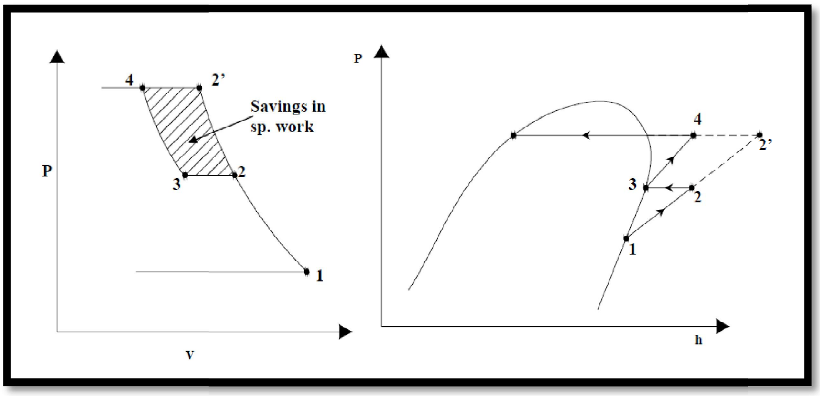


Fig.1.4 (a) & (b): Inter cooling in two-stage compression

As shown in the figures, instead of compressing the vapour in a single stage from state 1 to state 2', if the refrigerant is compressed from state 1 to an intermediate pressure, state 2, intercooled from 2 to 3 and then compressed to the required pressure (state 4), reduction in work input results. If the processes are reversible, then the savings in specific work is given by the shaded area 2-3-4-2' on P-v diagram. The savings in work input can also be verified from the P-h diagram. On P-h diagram, lines 1-2-2' and 3-4 represent isentropes. Since the slope of isentropes on P-h diagram reduces (lines become flatter) as they move away from the saturated vapour line,

$$(h_4-h_3) < (h_{2'}-h_2) \Rightarrow (h_2-h_1)+(h_4-h_3) < (h_{2'}-h_1)$$

Inter cooling of the vapour may be achieved by using either a water-cooled heat exchanger or by the refrigerant in the flash tank. Figures 1.5(a) and (b) show these two systems. Inter cooling may not be always possible using water-cooled heat exchangers as it depends on the availability of sufficiently cold water to which the refrigerant from low stage compressor can reject heat. Moreover, with water cooling the refrigerant at the inlet to the high stage compressor may not be saturated. Water cooling is commonly used in air compressors. Inter cooling not only reduces the work input but also reduces the compressor discharge temperature leading to better lubrication and longer compressor life.

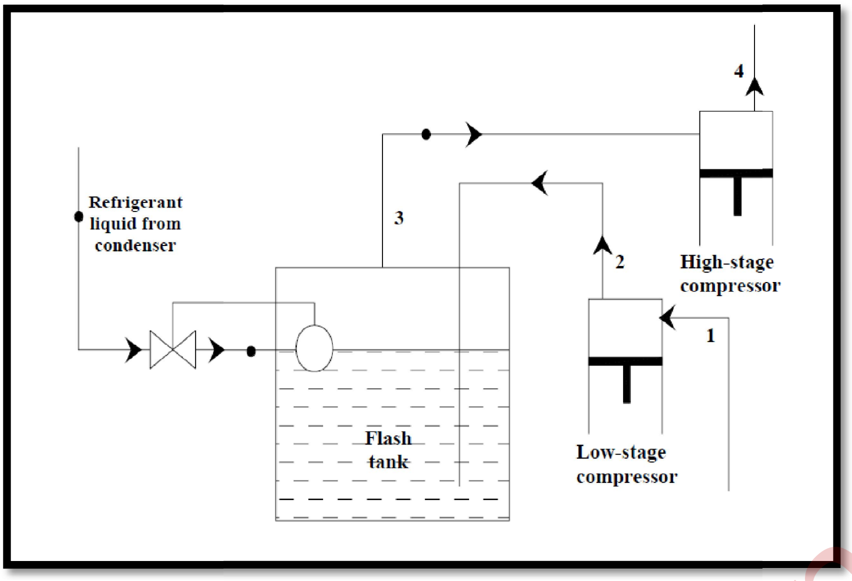


Fig.1.5(a): Inter cooling using liquid refrigerant in flash tank

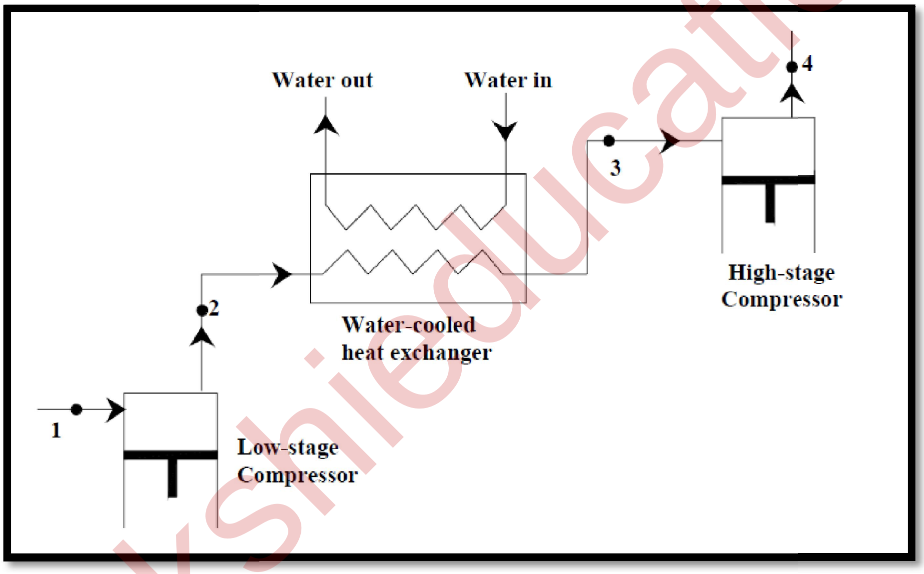


Fig.1.5(b): Inter cooling using external water cooled heat exchanger

Inter cooling using liquid refrigerant from condenser in the flash tank could conceivably decrease the power input to the framework, as it relies on the way of the refrigerant. This is because of the way that the heat dismisses by the refrigerant during inter cooling creates extra vapour in the flash tank, which has to be compressed by the high stage compressor. Thus the mass stream rate of refrigerant through the high stage compressor will be more than that of the low stage compressor. Whether aggregate power input to the framework decreases or not relies on upon whether the increased power consumption because of higher mass stream rate is repaid by lessening in specific work of compression or not.

For alkali, the power input more often than not decreases with inter cooling by liquid refrigerant, however, for refrigerants such as R12, R22, the power input marginally increases. Thus inter cooling using liquid refrigerant is not viable for R12 and R22. However, as said one advantage of inter cooling is the diminishment in compressor discharge temperature, which prompts better compressor grease and its more extended life. It is likewise conceivable to intercool the refrigerant vapour by a combination of water-cooled heat exchanger and the refrigerant liquid in the flash tank. As a consequence of using both water cooling and flash-tank, the measure of refrigerant vapour handled by the high-stage compressor diminishes leading to lower power consumption. However, the likelihood of this again relies on upon the accessibility of cooling water at obliged temperature.

One of the outline issues in multi-stage compression is the determination of suitable intermediate pressure. For air compressors with inter cooling to the initial temperature, the theoretical work input to the framework will be minimum when the pressure ratios are rise to for all stages. This additionally brings about equivalent compressor discharge temperatures for all compressors. Thus for a two-stage air compressor with inter cooling, the optimum intermediate pressure, Pi, opt is:

$$P_{i,opt} = \sqrt{P_{low} . P_{high}}$$

Where P_{low} and P_{high} are the inlet pressure to the low-stage compressor and exit pressure from the high-stage compressor, respectively. The above relation is found to hold good for ideal gases. For refrigerants, correction factors to the above equation are suggested, for example one such relation for refrigerants is given by:

$$P_{i,opt} = \sqrt{P_e . P_c \frac{T_c}{T_e}}$$

where P_e and P_c are the evaporator and condenser pressures, and T_c and T_e are condenser and evaporator temperatures (in K).

Several combinations of multi-stage systems are used in practice. Some of them are discussed below.

1.4. Multi-stage system with flash gas removal and inter cooling

Figures 1.6(a) and (b) show a two-stage vapour compression refrigeration framework with flash gas evacuation using a flash tank, and inter cooling of refrigerant vapour by a water cooled heat exchanger and flash tank. The superheated vapour from the water cooled heat exchanger rises through the refrigerant liquid in the flash tank. It is accepted that in this process the superheated refrigerant vapour gets totally de-superheated and rises out as a soaked vapour at express 4.

However, practically speaking complete de-superheating may not be conceivable. As specified the utilization of combination of water cooling with flash tank for inter cooling decreases the vapour produced in the flash tank. The execution of this framework can be obtained effortlessly by applying mass and vitality offset comparisons to the individual parts. It is expected that the flash tank is consummately insulated and the potential and kinetic vitality changes of refrigerant over each part are negligible.

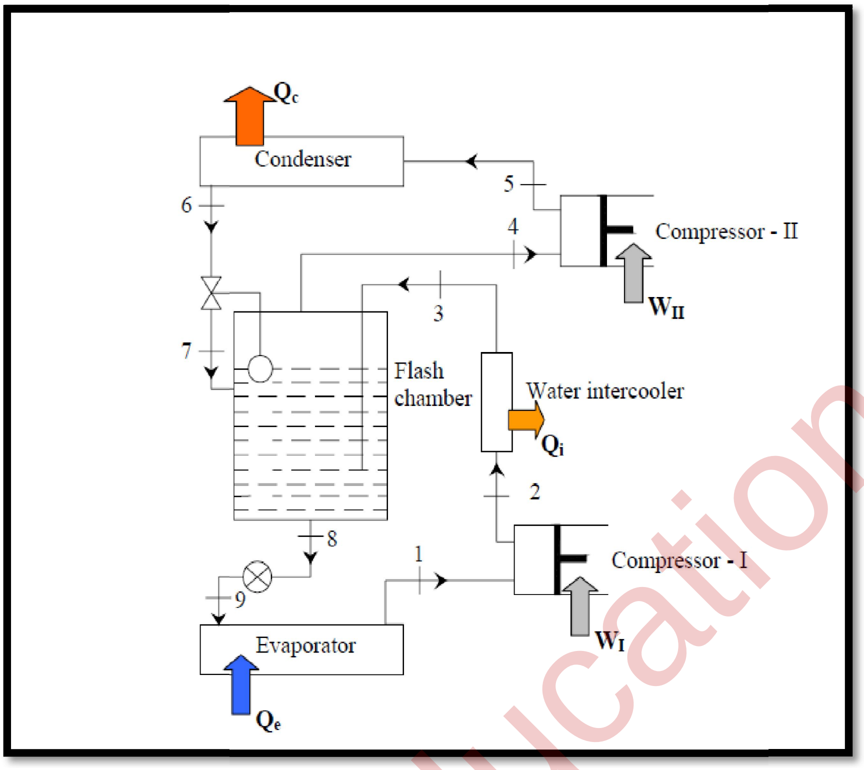


Fig.1.6(a): Two-stage vapour compression refrigeration system with flash gas removal using a flash tank and inter cooling

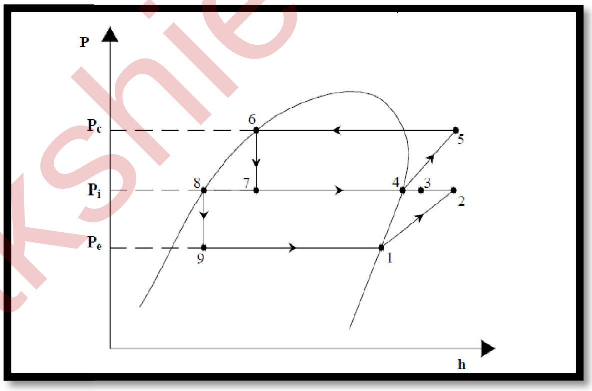


Fig.1.6(b): Two-stage vapour compression refrigeration system with flash gas removal using a flash tank and inter cooling – P-h diagram

From mass and energy balance of the flash tank:

$$\dot{m}_7 + \dot{m}_3 = \dot{m}_8 + \dot{m}_4$$

$$\dot{m}_7 h_7 + \dot{m}_3 h_3 = \dot{m}_8 h_8 + \dot{m}_4 h_4$$

From mass and energy balance across expansion valve,

$$\dot{m}_8 = \dot{m}_9$$
$$h_8 = h_9$$

From mass and energy balance across evaporator:

$$\dot{m}_9 = \dot{m}_1$$

$$Q_e = \dot{m}_1(h_1 - h_9)$$

From mass and energy balance across low-stage compressor, Compressor-I:

$$\dot{m}_9 = \dot{m}_1 = \dot{m}_I$$

$$W_I = \dot{m}_I(h_2 - h_1)$$

where $\dot{m}_I$ is the mass flow rate of refrigerant through Compressor-I.

From mass and energy balance across water-cooled intercooler:

$$\dot{m}_2 = \dot{m}_3 = \dot{m}_I$$

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

Where Q_I is the heat transferred by the refrigerant to the cooling water in the intercooler.

From mass and energy balance across high-stage compressor, Compressor-II:

$$\dot{m}_4 = \dot{m}_5 = \dot{m}_{II}$$

$$W_{II} = \dot{m}_{II}(h_5 - h_4)$$

where $\dot{m}_{II}$ is the mass flow rate of refrigerant through Compressor-II.

Finally, from mass and energy balance across condenser:

$$\dot{m}_5 = \dot{m}_6 = \dot{m}_{II}$$

$$Q_c = \dot{m}_{II}(h_5 - h_6)$$

Finally, from mass and energy balance across the float valve:

$$\dot{m}_6 = \dot{m}_7 = \dot{m}_{II}$$
$$h_6 = h_7$$

From the above set of equations, it can be easily shown that for the flash tank:

$$\dot{m}_7 = \dot{m}_4 = \dot{m}_{II}$$

$$\dot{m}_3 = \dot{m}_8 = \dot{m}_I$$

$$\dot{m}_{II} = \dot{m}_I\left[\frac{h_3 - h_8}{h_4 - h_7}\right]$$

It can be seen from the above expression that the refrigerant flow through the high stage compression can be reduced by reducing the enthalpy of refrigerant vapour entering into the flash tank, h_3 from the water-cooled intercooler.

The amount of additional vapour generated due to de-superheating of the refrigerant vapour from the water-cooled intercooler is given by:

$$\dot{m}_{gen} = \dot{m}_I \left[\frac{h_3 - h_4}{h_4 - h_8} \right]$$

Thus the vapour generated m_{gen} will be zero, if the refrigerant vapour is completely de-super heated in the water-cooled intercooler itself. However, this may not be possible in practice.

For the above system, the COP is given by:.

$$COP = \frac{Q_e}{W_I + W_{II}} = \frac{\dot{m}_I (h_1 - h_9)}{\dot{m}_I (h_2 - h_1) + \dot{m}_{II} (h_5 - h_4)}$$

The above system offers several advantages,

a) Quality of refrigerant entering the evaporator reduces thus giving rise to higher refrigerating effect, lower pressure drop and better heat transfer in the evaporator
b) Throttling losses are reduced as vapour generated during throttling from P_c to P_i is separated in the flash tank and recompressed by Compressor-II.
c) Volumetric efficiency of compressors will be high due to reduced pressure ratios.
d) Compressor discharge temperature is reduced considerably.

However, one drawback of the above framework is that since refrigerant liquid in the flash tank is soaked, there is a probability of liquid flashing ahead of the expansion valve because of pressure drop or heat move in the pipelines connecting the flash tank to the expansion gadget. At times this issue is handled by using a framework with a liquid sub cooler. As shown in Fig.1.7, in a liquid sub cooler the refrigerant liquid from the condenser is sub cooled by exchanging heat with the refrigerant liquid in the flash tank.

Thus, a little measure of refrigerant vapour is produced in the flash tank, which needs to be compressed in the high-stage compressor. Contrasted with the before framework, the temperature of refrigerant liquid from the sub cooler will be higher than the soaked refrigerant temperature in the flash tank because of indirect contact heat exchange. However, since the refrigerant at the inlet to the expansion valve is at high pressure and is sub cooled, there is less chance of flashing of liquid ahead of expansion valve.

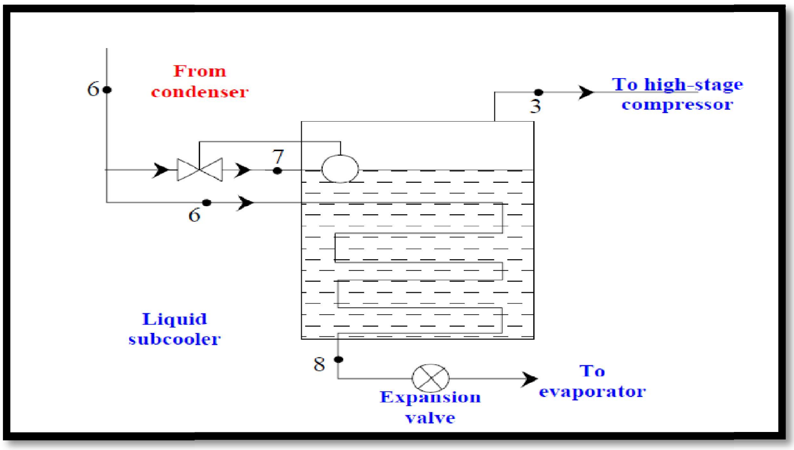
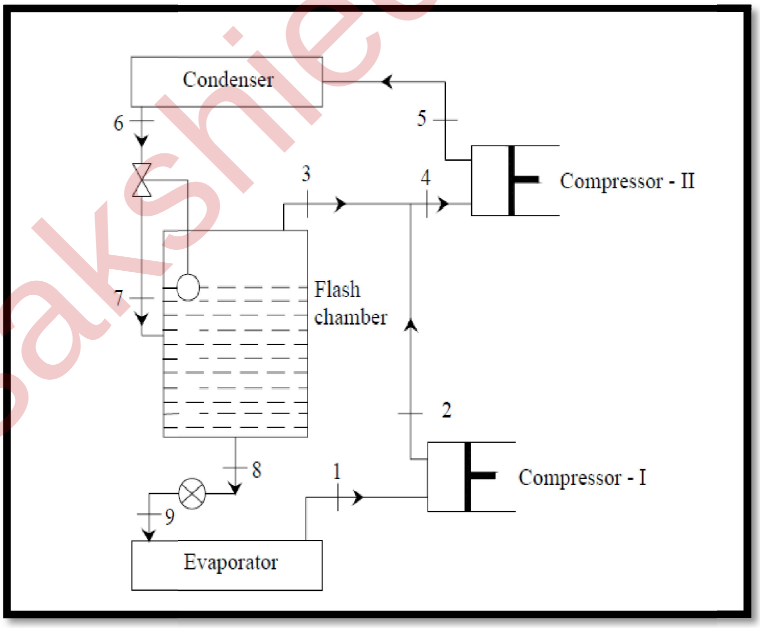


Fig.1.7: Refrigeration system with liquid sub cooler

1.5. Use of flash tank for flash gas removal

Inter cooling of refrigerant vapour using water-cooled heat exchangers are conceivable in ammonia systems because of high discharge temperature of ammonia. However, this is for the most part unrealistic in systems using refrigerants such as R 12 or R 134a because of their low discharge temperatures. In these systems, instead of passing the refrigerant vapour from the low-stage compressor through the flash tank, vapour from the flash tank is blended with the vapour coming from the low-stage compressor. Thus, the inlet condition to the high-stage compressor will be slightly superheated. A two-stage compression framework with flash tank for flash gas evacuation for refrigerants such as R 134a is shown in Fig. 1.8 (a). Figure 1.8 (b) shows the corresponding P-h chart.



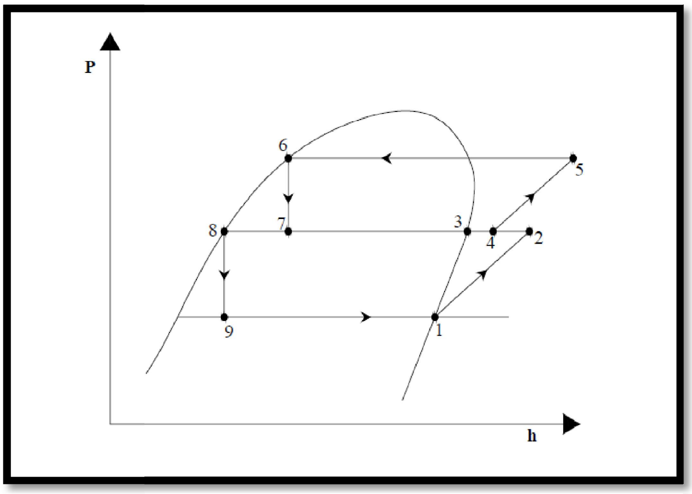
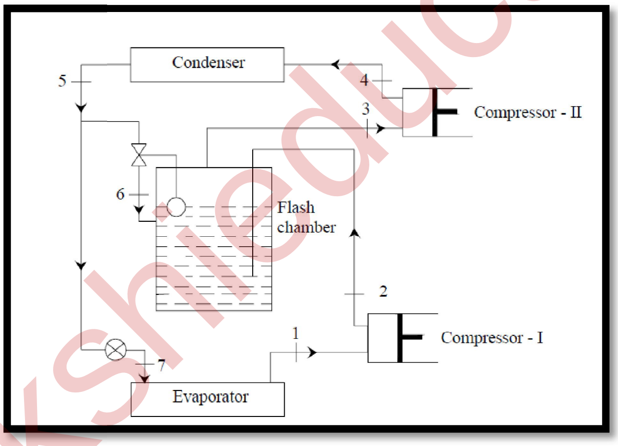


Fig.1.8: A two-stage compression system with flash tank for flash gas removal only (a) System schematic; (b) Cycle on P-h diagram

1.6. Use of flash tank for inter cooling only

Sometimes the flash tank is used for inter cooling of the refrigerant vapour between the low and high-stage compressors. It is not used for flash gas removal. Figures 1.9 (a) and (b) show the system schematic and P-h diagram of a two-stage compression system where the flash tank is used for inter cooling only.



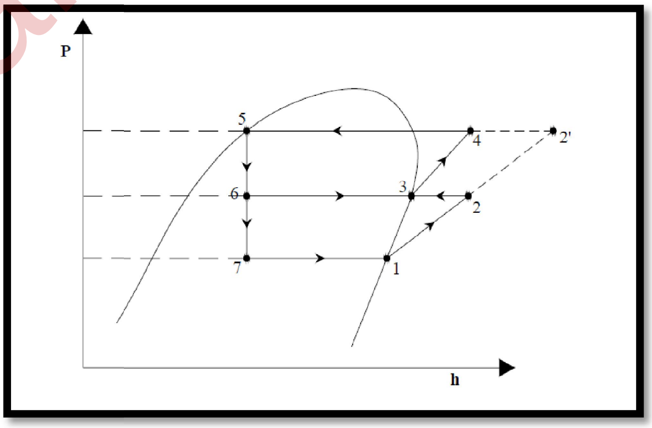


Fig.1.9: A two-stage compression system with the flash tank used for inter cooling only (a) System schematic (b) Cycle on P-h diagram