

# UNIT – 3

## Refrigerant and Refrigeration Cycles

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### Important Repeated Questions:

1. **Explain/State desirable characteristics/properties of (a good) refrigerant.**  
(S25 - Q1c, 07 marks) (S24 - Q2b) (W22 - Q2c, 07 marks) (S22 - Q3a, 03 marks)
2. **Explain designation/system of refrigerants.**  
(S25 - Q5b, 04 marks) (W23 - Q3a, 03 marks) (S23 - Q2b, 04 marks) (W22 - Q5b, 04 marks)
3. **Explain/Differentiate between Vapour Compression System and Vapour Absorption System.**  
(S24 - Q2a) (W22 - Q2b, 04 marks)
4. **Explain Li-Br Vapour Absorption System with neat sketch.**  
(S25 - Q3c, 07 marks) (W25 - Q2c, 07 marks) (S22 - Q3 OR c, 07 marks) (W22 - Q3b, 04 marks)
5. **Explain Global Warming Potential (GWP) of refrigerants.**  
(S25 - Q4b, 04 marks) (S23 - Q3a, 03 marks)
6. **Explain flash intercooling.**  
(S24 - Q3a, 03 marks) (S22 - Q3a, 07 marks)

Legends: W- Winter, S- Summer, Q- Question and 03/04/07- Marks of Question

### 3.1 Introduction to Refrigerants

- ▶ **Refrigerant:** “It is defined as any substance that absorbs heat through expansion/vaporization and loses it through condensation in a refrigeration system.”
- ▶ Refrigerants are used as working substances in refrigeration systems.
- ▶ A very large number of substances are available, which can be used as refrigerants. In fact, there is always a unique refrigerant available which is most suited for a given application and given system.

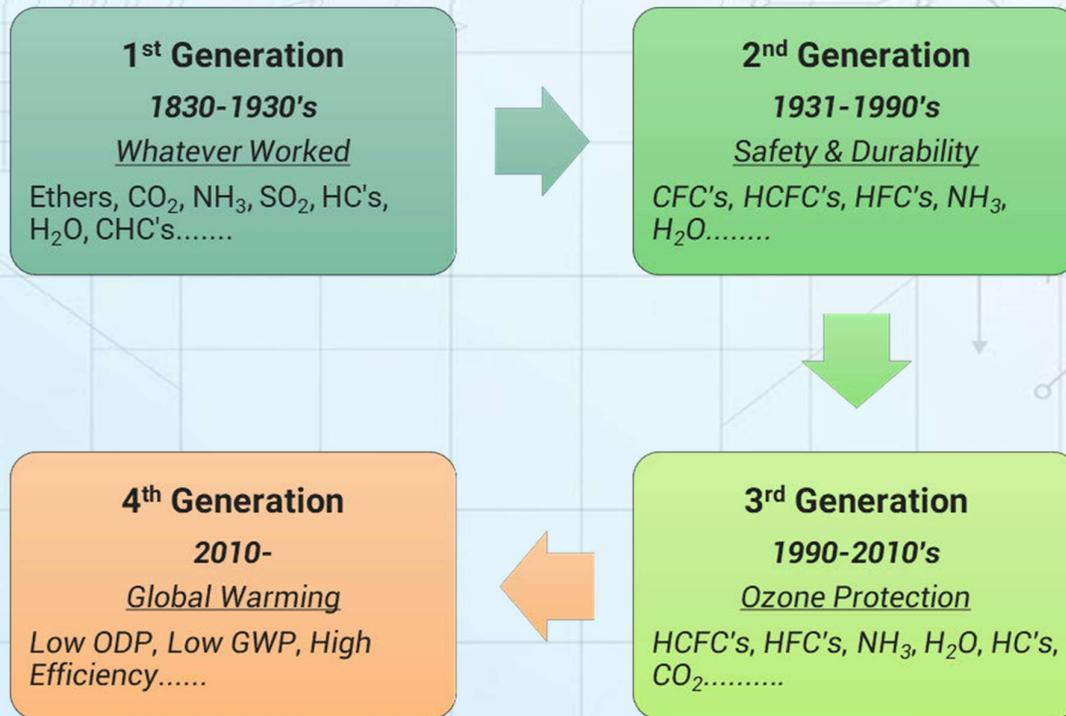


Fig.3.1 – Historical usage of refrigerants

### 3.2 Classification of Refrigerants

- ▶ Based upon the working principle, the refrigerants may be classified as follows:
  1. Primary Refrigerants
    - a) Halocarbon
    - b) Azeotrope
    - c) Hydrocarbon
    - d) Inorganic
  2. Secondary Refrigerants
    - a) Water
    - b) Brines

#### 3.2.1 Primary Refrigerants

- ▶ “The refrigerants which directly takes part in the refrigeration system (and cool the substance by the absorption of latent heat) are called primary refrigerants.”
- ▶ Based on the classification, some of the popular refrigerants are listed in table 3.1 to 3.4.

**Table 3.1 - Halocarbon Refrigerants:** A CFC or other compound in which the hydrogen of a hydrocarbon is replaced by halogens

| Refrigerant | Chemical Name                | Chemical Formula          |
|-------------|------------------------------|---------------------------|
| R-11        | Trichloro monofluoro methane | $\text{CCl}_3\text{F}$    |
| R-12        | Dichloro difluoro methane    | $\text{CCl}_2\text{F}_2$  |
| R-13        | Monochloro trifluoro methane | $\text{CClF}_3$           |
| R-14        | Carbon tetrafluoride         | $\text{CF}_4$             |
| R-21        | Dichloro monofluoro methane  | $\text{CHCl}_2\text{F}$   |
| R-22        | Monochloro difluoro methane  | $\text{CHClF}_2$          |
| R-134a      | Tetrafluoro ethane           | $\text{CH}_2\text{FCF}_3$ |

**Table 3.2 - Azeotropes:** A mixture of refrigerants whose vapour and liquid phase retain identical compositions over a wide range of temperatures and pressures

| Refrigerant Number | Chemical Name            | Chemical Formula                                 |
|--------------------|--------------------------|--|
| R-500              | 73.8% R-12 & 26.2% R-152 | $\text{CCl}_2\text{F}_2/\text{CH}_3\text{CHF}_2$ |
| R-502              | 48.8% R-22 & 51.2% R-115 | $\text{CHClF}_2/\text{CClF}_2\text{CF}_3$        |
| R-503              | 40.1% R-23 & 59.9% R-13  | $\text{CHF}_3/\text{CClF}_3$                     |
| R-504              | 48.2% R-32 & 51.8% R-115 | $\text{CH}_2\text{F}_2/\text{CClF}_2\text{CF}_3$ |

**Table 3.3 - Hydrocarbon Refrigerants:** A compound of hydrogen & carbon

| Refrigerant Number | Chemical Name | Chemical Formula          |
|--------------------|---------------|---------------------------|
| R-170              | Ethane        | $\text{C}_2\text{H}_6$    |
| R-290              | Propane       | $\text{C}_3\text{H}_8$    |
| R-600              | Butane        | $\text{C}_4\text{H}_{10}$ |
| R-600a             | Iso-butane    | $\text{C}_4\text{H}_{10}$ |
| R-1150             | Ethylene      | $\text{C}_2\text{H}_4$    |
| R-1270             | Propylene     | $\text{C}_3\text{H}_6$    |

**Table 3. 4 - Inorganic Refrigerants: A compound that do not contain Carbon & Hydrogen both**

| Refrigerant Number | Chemical Name  | Chemical Formula |
|--------------------|----------------|------------------|
| R-717              | Ammonia        | NH <sub>3</sub>  |
| R-718              | Water          | H <sub>2</sub> O |
| R-729              | Air            | -                |
| R-744              | Carbon Dioxide | CO <sub>2</sub>  |
| R-764              | Sulfur Dioxide | SO <sub>2</sub>  |

### 3.2.2 Secondary Refrigerants

- ▶ “The Refrigerants which are first cooled by primary refrigerants and then used for cooling purposes are known as secondary refrigerants.”
- ▶ They do not go under any phase change.

#### 3.2.2.1 Application of Secondary Refrigerants

- ▶ There are several applications where the direct use of a refrigerant is not possible due to safety consideration e.g.
- ▶ The toxic refrigerants cannot be used for the air conditioning of residential building.
- ▶ The amount of refrigerant for the circulation in a big cold storage would be so large so its cost will be higher.
- ▶ Under such circumstances the cheaper grade suitable cooling media such as water, brine solution of CaCl, NaCl, etc. is selected to have indirect cooling.

##### Water:

- Used when the required temperature to be maintained is above the freezing point of water.
- It is used in air-conditioning plants and industrial cooling installations

##### Brines:

- Sodium chloride (NaCl) brine solutions are most common up to about -15°C.
- Calcium chloride (CaCl) brine solutions can be used up to -50°C.
- These solutions are very corrosive to metals such as Brass, Copper, Al, etc.

#### 3.2.2.2 Advantages of Secondary Refrigerants

- ▶ It keeps the toxic refrigerant away from the load place.
- ▶ Easy to handle & control.
- ▶ The size of pipelines are considerably smaller.
- ▶ Different temperatures can be maintained in different parts of the buildings by controlling the amount of brine flowing to that part.

## 3.3 Designation of Refrigerants

- ▶ The international designation of refrigerants uses Refrigerants or R (or alternatively CFC, HCFC, HFC and HC as the case may be) as the designation followed by certain numerals.

### 3.3.1 For a fully saturated, halogenated compounds

- ▶ These halogenated compounds are derived from alkanes / hydrocarbons (C<sub>n</sub>H<sub>2n+2</sub>).

## Method – 1

- Compound derived from hydrocarbon is denoted by the chemical formula,



where

$$b + c + d = 2a + 2$$

**a** indicates the no. of Carbon (C) atoms

**b** indicates the no. of Hydrogen (H) atoms

**c** indicates no. of Fluorine (F) atoms and

**d** indicates no. of Chlorine (Cl) atoms

- The complete designation/number of the refrigerant is given by:

$$R - (a - 1)(b + 1)(c)$$

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**Example:**  $CHClF_2$  or Monochlorodifluoromethane

No. of Hydrogen (H) atoms =  $b = 1$

No. of Fluorine (F) atoms =  $c = 2$

No. of Chlorine (Cl) atoms =  $d = 1$

No. of Carbon (C) atoms =  $a = 1$  ( $\because b+c+d = 2a+2$ )

$\therefore$  The designation of  $CHClF_2$  is,

$$R-(a-1)(b+1)(c) \rightarrow R-22$$

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## Method – 2

- ▶ These refrigerants are designated by,

$$R - XYZ$$

where,

**X+1** indicates the no. of Carbon (C) atoms

**Y-1** indicates the no. of Hydrogen (H) atoms

**Z** indicates no. of Fluorine (F) atoms

The **balance** indicates no. of Chlorine (Cl) atoms

- ▶ Only **2 digits** indicates that the value of **X is Zero**.

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**Example: R-22**

Only 2 digits indicates that the value of X is Zero

$X=0 \rightarrow$  No. of Carbon (C) atoms =  $X+1 = 0+1 = 1 \rightarrow$  Derivative of Methane

$Y=2 \rightarrow$  No. of Hydrogen (H) atoms =  $Y-1 = 2-1 = 1$

$Z=2 \rightarrow$  No. of Fluorine (F) atoms = 2

The balance = No. of Chlorine (Cl) atoms =  $4 - \text{No. of (H+F) atoms} = 4 - (1+2) = 1$

$\therefore$  The chemical formula of R-22 is,



### 3.3.2 For Inorganic Refrigerants

- These are designated by number 7 followed by the molecular weight of the refrigerant (rounded-off).

#### Examples

| Refrigerant     | Molecular Weight | Refrigerant Number |
|-----------------|------------------|--------------------|
| -Ammonia        | 17               | R-717              |
| CO <sub>2</sub> | 44               | R-744              |
| Water           | 18               | R-718              |
| Air             | 29               | R-729              |

### 3.3.3 For Azeotropes Mixtures

- ▶ Azeotropic mixtures: 500 series

#### Example:

- R-500: Mixture of R-12 (73.8%) & R-152a (26.2%)
- R-502: Mixture of R-22 (48.8%) & R-115 (51.2%)

- ▶ Zeotropic (Non-azeotropic) mixtures: 400 series

#### Example:

- R-404A: Mixture of R-125 (44%), R143a (52%) & R134a (4%)

### 3.3.4 For Hydrocarbons

- ▶ **Saturated Hydrocarbons:** Designated same as saturated halogenated compounds

#### Example:

- Propane (C<sub>3</sub>H<sub>8</sub>): R-290
- N-butane (C<sub>4</sub>H<sub>10</sub>): R-600 (A special number is allotted)

- ▶ **Unsaturated Hydrocarbons:** Designated same as saturated halogenated compounds with an additional subscript '1' is added to XYZ.

#### Example:

- Ethylene (C<sub>2</sub>H<sub>4</sub>): R-1150
- Propylene (C<sub>3</sub>H<sub>6</sub>): R-1270

## 3.4 Desirable Properties of Refrigerants:

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- ▶ An ideal refrigerant should have the following properties:
  1. Thermodynamic and thermo-physical properties
  2. Environmental and safety properties, and
  3. Economic Properties

### 3.4.1 Thermodynamic and thermo-physical properties

#### 3.4.1.1 Suction Pressure

- ▶ At a given evaporator temperature, saturation pressure should be above atmospheric pressure for prevention of air into the system and ease of leak detection.
- ▶ Higher Suction pressure is better as the density is high & hence specific volume will be less & so the required size of the compressor will be smaller for a given mass flow rate.

#### **3.4.1.2 Discharge Pressure**

- At a given condenser temperature, the discharge pressure should be as small as possible to allow light weight construction of compressor, condenser, etc.

#### **3.4.1.3 Pressure Ratio**

- It should be as low as possible for high volumetric efficiency & low power consumption.

#### **3.4.1.4 Latent Heat of Vaporization**

- It should be as large as possible so that the required mass flow rate per unit cooling capacity will be small.

#### **3.4.1.5 Liquid Specific Heat**

- It should be small so that degree of sub-cooling will be large.

#### **3.4.1.6 Vapour Specific Heat**

- It should be large so that degree of superheating will be small.

#### **3.4.1.7 Liquid and Vapour Thermal Conductivity**

- It should high for better heat transfer.

#### **3.4.1.8 Liquid and Vapour Viscosity**

- It should be low for smaller frictional pressure drop.

#### **3.4.1.9 Boiling & Freezing point**

- ▶ At a given evaporator temperature, saturation pressure should be above atmospheric pressure for prevention of air into the system and ease of leak detectio
- ▶ Higher Suction pressure is better as the density is high & hence specific volume will be less & so the required size of the compressor will be smaller for a given mass flow rate.

### **3.4.2 Environmental & Safety Properties**

#### **3.4.2.1 Ozone Depletion Potential (ODP)**

- ▶ It should be Zero i.e. no Chlorine or Bromine atoms.

#### **3.4.2.2 Global Warming Potential (GWP)**

- ▶ It should be Low.

#### **3.4.2.3 Total Equivalent Warming Index (TEWI)**

- ▶ It should be as small as possible. It will count direct & indirect contribution of refrigerant in Global Warming.

#### **3.4.2.4 Toxicity**

- ▶ It should be non-toxic.
- ▶ Refrigerants such as R-12 & R-22 are non-toxic in the presence of air. However in the presence of an open flame they decompose & release harmful gases.

#### **3.4.2.5 Flammability**

- ▶ It should be non-flammable & non-explosive.

### 3.4.2.6 Chemical Stability

- ▶ It should be chemically stable & should not react within the system.

### 3.4.2.7 Compatibility with Common Materials

- ▶ It should not react with any material.

### 3.4.2.8 Dielectric Strength

- ▶ It should be high where refrigerant vapour comes into direct contact of electric motor windings e.g. hermetically sealed compressors

### 3.4.2.9 Ease of Leak Detection

- ▶ It should be easily detectable.

## 3.4.3 Economic Properties

### 3.4.3.1 Cost of Refrigerant

- ▶ It should be cheaper.

### 3.4.3.2 Availability

- ▶ It should be easily available

## 3.5 Common Refrigerants & its Properties

- ▶ The characteristics, properties and applications of some of the common refrigerants are discussed below:

| Refrigerant  | Properties  | Applications  |
|--|---|---|
| <p><b>R-11 (CFC)</b><br/> <math>NBP = 23.7^{\circ}C</math><br/> <math>h_{fg}</math> at <math>NBP = 182.5 \frac{kJ}{kg}</math><br/> <math>T_{cr} = 197.98^{\circ}C</math><br/> <math>ODP = 1</math><br/> <math>GWP = 3500</math></p>  | <ul style="list-style-type: none"> <li>▪ Non toxic</li> <li>▪ Non flammable</li> <li>▪ Non corrosive</li> <li>▪ Low pressure refrigerant so specific volume is very high</li> <li>▪ Need to use centrifugal compressor</li> </ul> | <ul style="list-style-type: none"> <li>▪ Large air conditioning systems</li> <li>▪ Industrial heat pumps</li> </ul>                         |
| <p><b>R-12 (CFC)</b><br/> <math>NBP = -29.8^{\circ}C</math><br/> <math>h_{fg}</math> at <math>NBP = 165.8 \frac{kJ}{kg}</math><br/> <math>T_{cr} = 112.04^{\circ}C</math><br/> <math>ODP = 1</math><br/> <math>GWP = 7300</math></p> | <ul style="list-style-type: none"> <li>▪ Non toxic</li> <li>▪ Non flammable</li> <li>▪ Non corrosive</li> <li>▪ Operating pressure is higher</li> <li>▪ Most popular</li> </ul>   | <ul style="list-style-type: none"> <li>▪ Domestic refrigerators</li> <li>▪ Small air conditioners</li> <li>▪ Small cold storages</li> </ul> |
| <p><b>R-22 (HCFC)</b><br/> <math>NBP = -40.8^{\circ}C</math><br/> <math>h_{fg}</math> at <math>NBP = 233.2 \frac{kJ}{kg}</math></p>  | <ul style="list-style-type: none"> <li>▪ Toxicity is similar to <math>CO_2</math></li> <li>▪ Water is more soluble in R22 so driers &amp; desiccants should be used</li> </ul>  | <ul style="list-style-type: none"> <li>▪ Air conditioning systems</li> <li>▪ Cold storages</li> </ul>                                       |

|   |  |   |
|---|--|---|
|   | <ul style="list-style-type: none"> <li>Discharge temperature is high</li> </ul>  |   |
| — | <ul style="list-style-type: none"> <li>Non toxic</li> <li>Non flammable</li> <li>Immiscible in mineral oils so need to use synthetic lubricating oil</li> <li>Highly hygroscopic (tending to absorb moisture from air)</li> </ul>                              | <ul style="list-style-type: none"> <li>Used as replacement of R12 in Domestic refrigerators</li> <li>Automobile A/Cs</li> </ul> |
| — | <ul style="list-style-type: none"> <li>Toxic &amp; Flammable</li> <li>Incompatible with copper</li> <li>Highly efficient</li> <li>Inexpensive &amp; easily available</li> <li>Discharge temperature is high so need to use water cooled compressors</li> </ul> | <ul style="list-style-type: none"> <li>Cold storages</li> <li>Ice plants</li> <li>Food processing</li> </ul>                    |
| — | <ul style="list-style-type: none"> <li>Non toxic</li> <li>Non flammable</li> <li>Critical temperature is very low so operate under very high pressure</li> <li>Inexpensive &amp; easily available</li> </ul>   | <ul style="list-style-type: none"> <li>Earlier used in marine applications</li> <li>Cold storages</li> </ul>                    |

### 3.6 Limitations of Single Stage Refrigeration System

- ▶ The single stage system is adequate as long as the temperature difference between condenser & evaporator (temperature lift) is small.
- ▶ However, there are many applications where the temperature lift can be quite high. The temperature lift can become large either due to the requirement of very low evaporator temperatures and/or due to the requirement of very high condensing temperatures.
- ▶ For example,
  - For low temperature (evaporator) side:**
    - In frozen food industries temperature requirement is  $-40^{\circ}\text{C}$  or lower.
    - In some chemical industries temperature requirement is as low as  $-150^{\circ}\text{C}$  required for liquefaction of gases.
  - On the high temperature (condenser) side:**
    - High condensing temperatures are required if the refrigeration system is used as a heat pump for heating applications such as process heating, drying etc.
- ▶ As the temperature lift increases the single stage systems become inefficient and impractical.

## 3.7 Multi Stage Systems

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- ▶ A multi-stage system is a refrigeration system with two or more low-side pressures.
- ▶ Multi-stage systems can be classified into:
  - a) Multi-compression systems
  - b) Multi-evaporator systems
  - c) Cascade systems, etc.

### Applications of Multi-stage systems:

- ▶ It is used when temperature lift is very high.
- ▶ Multi-stage systems are also used in applications requiring refrigeration at different temperatures.
- ▶ For example,
  - In a dairy plant refrigeration temperature may be required at  $-30^{\circ}\text{C}$  for making ice cream and at  $2^{\circ}\text{C}$  for chilling milk. In such cases it may be advantageous to use a multi-evaporator system with the low temperature evaporator operating at  $-30^{\circ}\text{C}$  and the high temperature evaporator operating at  $2^{\circ}\text{C}$ .
- ▶ Three concepts which are normally used in multi stage systems are,
  1. Flash gas removal using flash chamber
  2. Liquid Sub-cooling
  3. Intercooling
    - a. Intercooling using a water cooled heat exchanger (Water intercooler)
    - b. Intercooling using a refrigerant in a flash tank (Liquid intercooler or Flash intercooler)

### 3.7.1 Flash Gas Removal Using a Flash Chamber

- ▶ Flash gas is the vapour formed during throttling of liquid refrigerant in expansion device.
- ▶ The flash gas:
  - To be compressed to condenser pressure
  - Does not contribute to the refrigeration effect as it is already in the form of vapour, and
  - Increases the pressure drop in the evaporator.
- ▶ It is possible to improve the COP of the system if the flash gas is removed as soon as it is formed and re-compressed to condenser pressure. However, continuous removal of flash gas is difficult in practice.
- ▶ One way of improving the performance of the system is to remove the flash gas at an intermediate pressure using a flash tank.

### Working Principle of Flash Tank / Flash Chamber

- ▶ A flash tank is a pressure vessel, wherein the refrigerant liquid and vapour are separated at an intermediate pressure.
- ▶ *Fig.3.2* shows the schematic of a flash tank and *Fig.3.3 – Expansion process employing flash tank* *Fig.3.3* shows the expansion process employing flash tank on p-h diagram.
- ▶ The refrigerant from condenser is first expanded to an intermediate pressure corresponding to the pressure of flash tank,  $P_i$  using a low side float valve (process 6-7).
- ▶ The float valve also maintains a constant liquid level in the flash tank. In the flash tank, the refrigerant liquid and vapour are separated.
- ▶ The saturated liquid at point 8 is fed to the evaporator after throttling it to the required evaporator pressure,  $P_e$  (point 9) using an expansion valve.
- ▶ The saturated vapour in the flash tank (point 3) is compressed to the condenser pressure in the compressor.

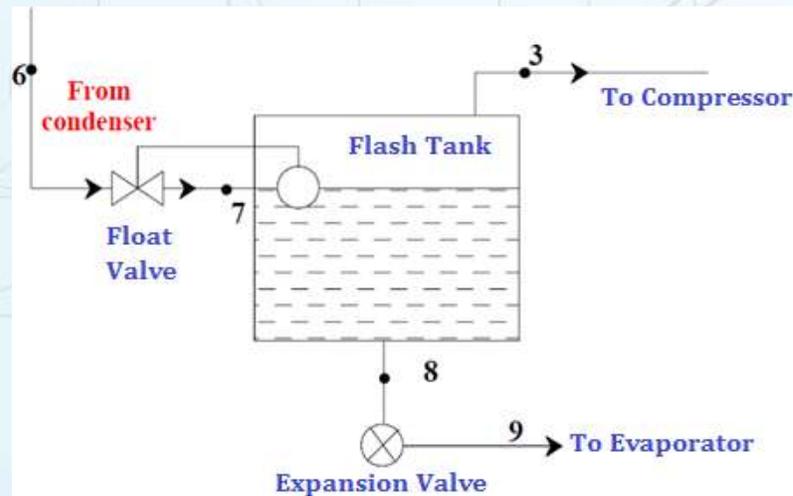


Fig.3.2 – Working principle of a flash chamber

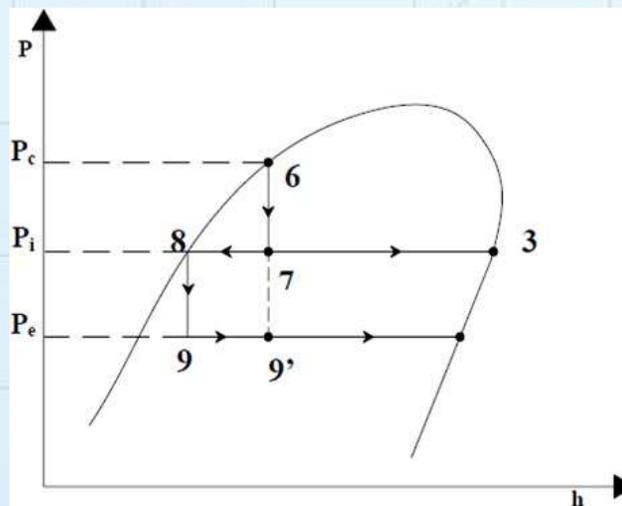


Fig.3.3 – Expansion process employing flash tank

- ▶ In the absence of flash tank, the refrigerant condition at the inlet to the evaporator would have been point 9', which has a considerably high vapour quality compared to point 9.
- ▶ As mentioned, the refrigerant liquid and vapour must get separated in the flash tank. This is possible when the upward velocity of the refrigerant vapour in the flash tank is low enough ( $< 1 \text{ m/s}$ ) for the refrigerant liquid droplets to fall back into the flash tank due to gravity.

### 3.7.2 Liquid Sub-cooling

- ▶ Since the refrigerant liquid in the flash tank is saturated, there is a possibility of vapour generation ahead of the expansion valve due to pressure drop or heat transfer in the pipelines connecting the flash tank to the expansion device.
- ▶ A Liquid Sub-cooler is used to prevent vapour entry into expansion device.

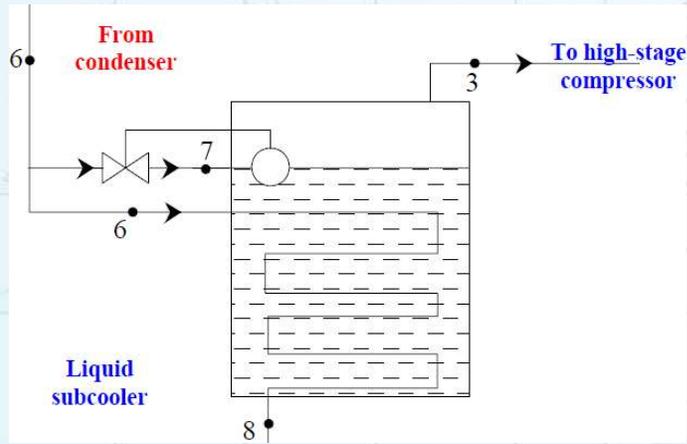


Fig.3.4 – Working principle of liquid sub-cooler

- ▶ As shown in Fig.3.4, in a liquid sub-cooler the refrigerant liquid from the condenser (at high pressure) is sub-cooled by exchanging heat with the refrigerant liquid in the flash tank (at intermediate pressure).
- ▶ As a result, a small amount of refrigerant vapour is generated in the flash tank, which needs to be compressed in the high-stage compressor.
- ▶ Compared to the earlier system, the temperature of refrigerant liquid from the sub-cooler will be higher than the saturated refrigerant temperature in the flash tank due to indirect contact heat transfer. 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.

### 3.7.3 Intercooling

- ▶ The specific work input,  $w$  in reversible, Polytropic compression of refrigerant vapour is given by:

$$w = - \int_1^2 v dp = \frac{n}{n-1} p_1 v_1 \left[ 1 - \left( \frac{p_2}{p_1} \right)^{n-1/n} \right]$$

- ▶ It can be seen that specific work input reduces as specific volume,  $v_1$  is reduced. At a given pressure, the specific volume  $v_1$  can be reduced by reducing the temperature. This is the principle behind intercooling in multi-stage compression.
- ▶ Fig.3.5 shows the process of intercooling in two-stage compression on Pressure-specific volume (P-v) and P-h diagrams.

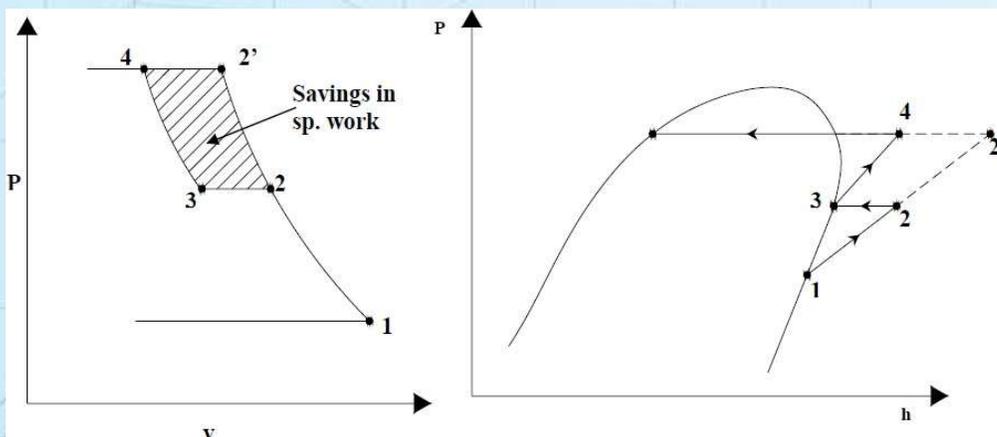
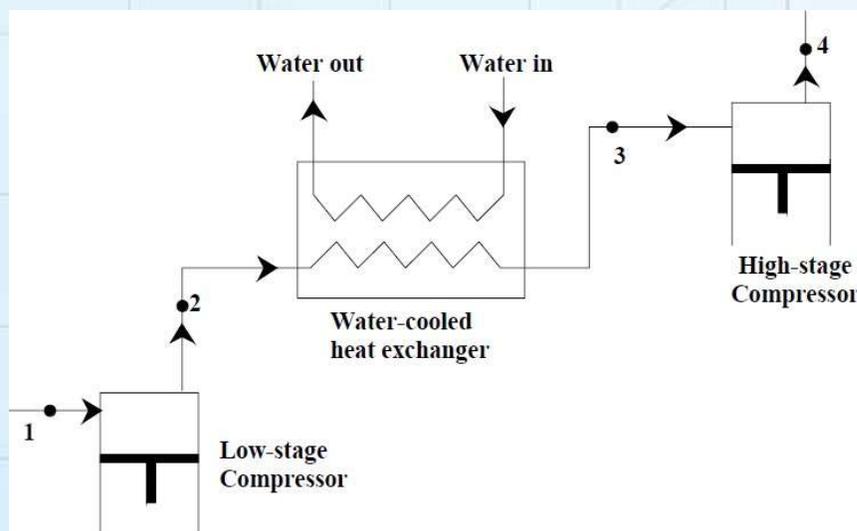


Fig.3.5 – Process of intercooling in two-stage compression on p-v and p-h diagram

- ▶ As shown in *Fig.3.5*, 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.
- ▶ Inter-cooling not only reduces the work input but also reduces the compressor discharge temperature leading to better lubrication & longer compressor life.
- ▶ Intercooling of the vapour may be achieved by using:
  - a) A water cooled heat exchanger
  - b) Refrigerant in a flash tank and
  - c) A combination of both.

### 3.7.3.1 Intercooling using a Water Cooled Heat Exchanger

- ▶ Intercooling of refrigerant vapour may be achieved by using a water cooled heat exchanger as shown in *Fig.3.6*.



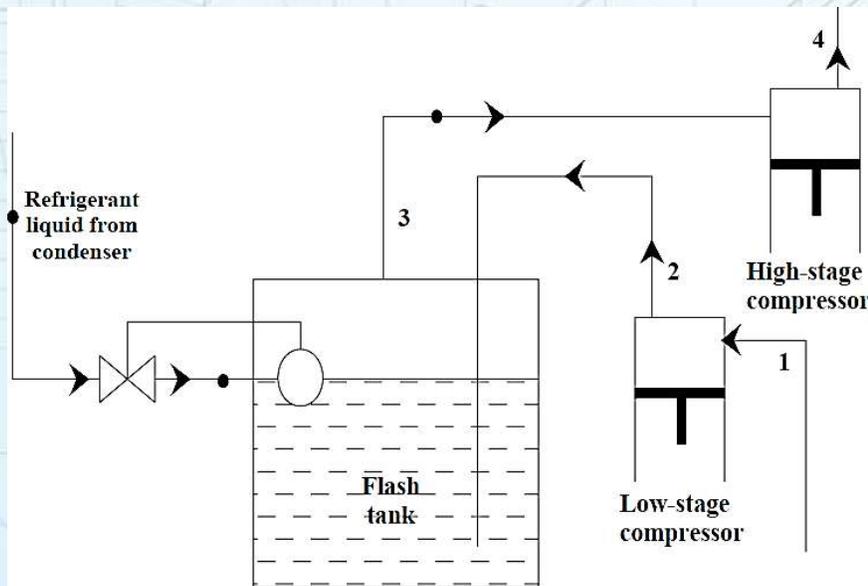
*Fig.3.6 – Intercooling by using a water cooled heat exchanger*

- ▶ Intercooling 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 because discharge temperature in air compressor is much higher.

### 3.7.3.2 Intercooling using a Refrigerant in a Flash Tank (Flash Intercooling)

- ▶ In flash intercooling, the compressed vapour from the low stage compressor is bubbled through the liquid in the flash chamber as shown in *Fig.3.7*.
- ▶ The vapours are thus cooled to the saturation temperature at the pressure of the flash chamber and a part of the liquid is evaporates, which goes to the higher stage along with the vapors from the lower stage.
- ▶ Intercooling using liquid refrigerant from condenser in the flash tank may or may not reduce the power input to the system. Because heat rejected by the refrigerant during intercooling generates additional vapour in the flash tank, which has to be compressed by the high stage compressor.

- ▶ Hence the mass flow rate of refrigerant through the high stage compressor will be more than that of the low stage compressor.



*Fig.3.7 – Intercooling using a refrigerant in a flash tank*

- ▶ Total power input to the system decreases or not depends on whether the increased power consumption due to higher mass flow rate is compensated by reduction in specific work of compression or not.
- ▶ For ammonia, the power input usually decreases with intercooling by liquid refrigerant, because ammonia has large latent heat of vaporization, so amount of vapour generated is less compared to other refrigerants.
- ▶ Flash intercoolers are, therefore, commonly used in multistage ammonia plants.
- ▶ However, for refrigerants such as R12, R22, the power input marginally increases, thus intercooling using liquid refrigerant is not effective for R12 and R22.

### 3.8 Types of Compound Vapour Compression Systems

- ▶ Following combinations for compound vapour compression systems can be possible:
  - a) Two stage compression with Flash Chamber
  - b) Two stage compression with Liquid Intercooler/Flash Intercooling
  - c) Two stage compression with Water Intercooler
  - d) Two stage compression with Liquid Sub-cooler
  - e) Two stage compression with Flash Gas Removal, Water & Flash Intercooler
  - f) Two stage compression with Water Intercooler & Liquid Sub-cooler
  - g) Two stage compression with Water Intercooler, Liquid Sub-cooler and Flash Intercooler

#### 3.8.1 Two Stage Compression with Flash Chamber

- ▶ The arrangement of a two stage compression with flash chamber is shown in *Fig.3.8* with schematic & p-h diagram.
- ▶ The various processes in the system are as follows:
  - The saturated vapour refrigerant at the evaporator pressure ( $p_e$ ) enters to low stage compressor at state 1, where it is compressed isentropically from the evaporator pressure ( $p_e$ ) to flash chamber pressure or intermediate pressure ( $p_i$ ) as shown by the curve 1-2 in *Fig.3.8*.

- o The superheated vapour refrigerant leaving the low stage compressor at state 2 is now mixed with the saturated vapour refrigerant produced in the flash chamber (state 3). The condition of refrigerant after mixing is shown by state 4, which is in superheated state.

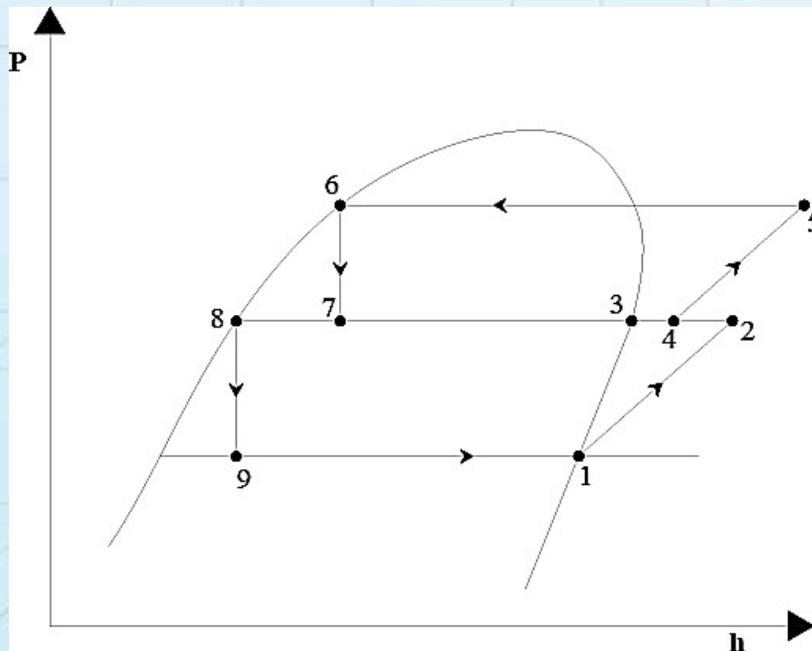
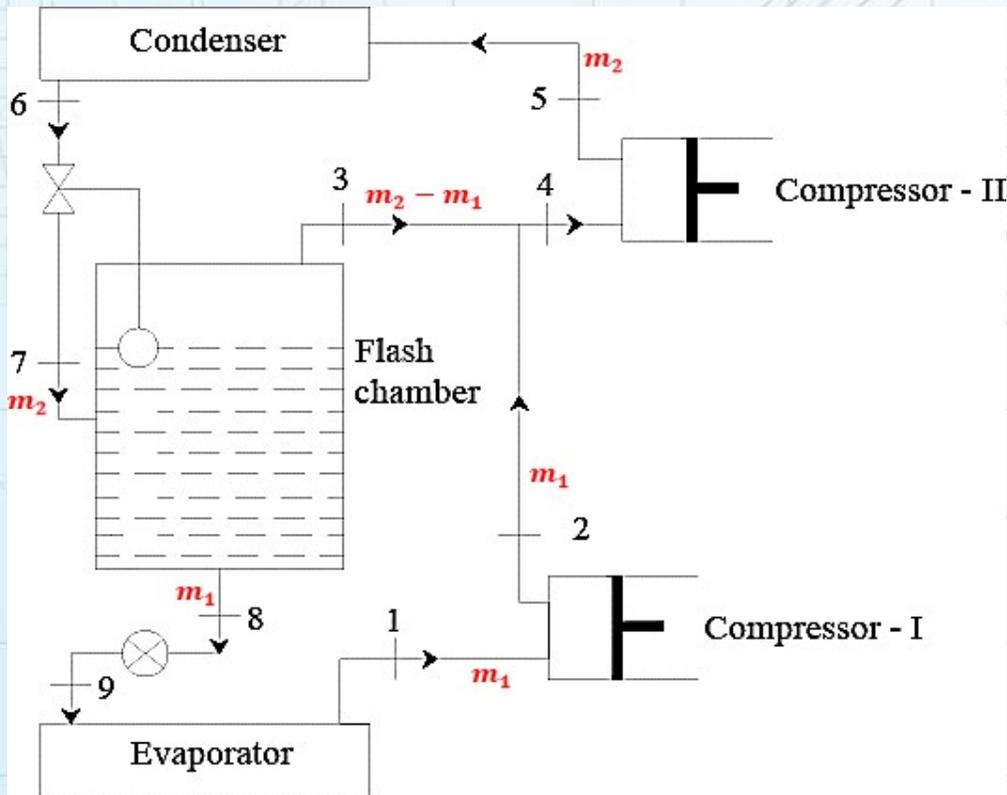


Fig.3.8 – Schematic and p-h diagram of two stage compression with flash chamber

- The superheated refrigerant at state 4 is now compressed isentropically in high stage compressor from intermediate pressure ( $p_i$ ) to condenser pressure ( $p_c$ ), as shown by the curve 4-5.
- The superheated vapour leaving the high stage compressor at pressure ( $p_c$ ) is passed through the condenser at constant pressure as shown by the horizontal line 5-6, where it is condensed.
- The saturated liquid at pressure ( $p_c$ ) is now expanded in a float valve to an intermediate pressure which is equals to the flash chamber pressure, shown by the line 6-7.
- The expanded refrigerant, which is a mixture of liquid and vapour at state 7 is now enters to a flash chamber. Flash chamber separates the liquid and vapour refrigerant at intermediate pressure ( $p_i$ ).
- The saturated vapour refrigerant from the flash chamber at state 3 is now mixed with the refrigerant from the low stage compressor (state 2).
- The liquid refrigerant from the flash chamber at state 8 is further expanded in an expansion valve up to an evaporator pressure ( $p_e$ ), as shown by the line 8-9.
- The refrigerant leaving the expansion valve is evaporated in the evaporator by absorbing the latent heat from the colder region as shown by the curve 9-1.

### Cycle Analysis:

▶ Let,

$m_1$  = Mass of refrigerant passing through the evaporator

$m_2$  = Mass of refrigerant passing through the condenser

$m_3 = m_2 - m_1$  = Mass of vapour refrigerant formed in the flash chamber

- Now consider flash chamber is an insulated vessel, there is no heat exchange between the flash chamber and atmosphere. From mass and energy balance in the flash chamber, the heat taken and given to the flash chamber is same.

$\therefore$  Heat taken by the flash chamber = Heat given by the flash chamber

$$\therefore m_2 h_7 = m_1 h_8 + m_3 h_3$$

$$\therefore m_2 h_7 = m_1 h_8 + (m_2 - m_1) h_3$$

▶ The refrigerating effect of the system,

$$Q_{RE} = m_1(h_1 - h_9)$$

▶ The work done in low pressure compressor,

$$W_{c1} = m_1(h_2 - h_1)$$

▶ The work done in high pressure compressor,

$$W_{c2} = m_2(h_5 - h_4)$$

▶ Heat rejected in the condenser,

$$Q_c = m_2(h_5 - h_6)$$

▶ COP of the system,

$$COP = \frac{Q_{RE}}{W_{c1} + W_{c2}}$$

$$\therefore COP = \frac{m_1(h_1 - h_9)}{m_1(h_2 - h_1) + m_2(h_5 - h_4)}$$

### 3.8.2 Two Stage Compression with Liquid Intercooler / Flash Intercooling

- ▶ The arrangement of a two stage compression with flash intercooling is shown in Fig.3.9 with schematic & p-h diagram.

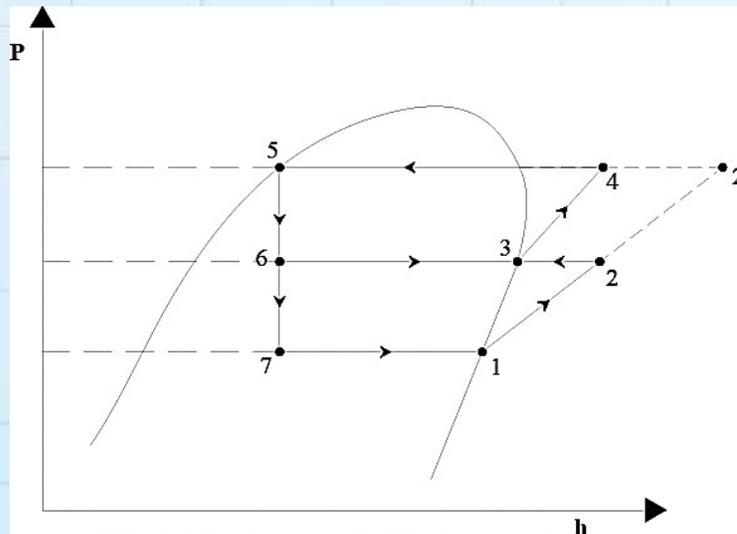
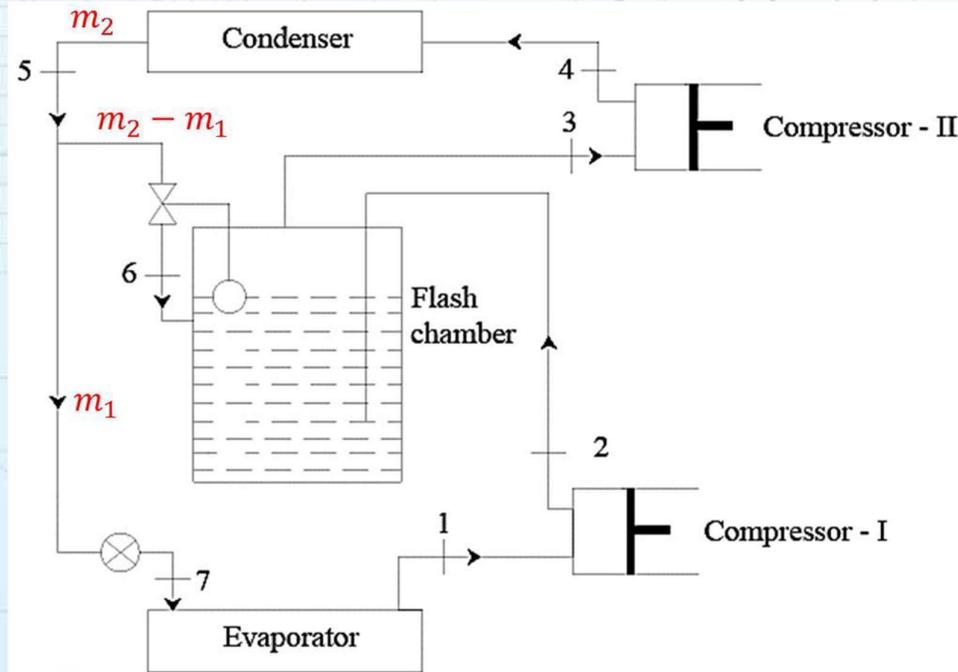


Fig.3.9 – Schematic and p-h diagram of two stage compression with flash intercooling

- ▶ The various processes in the system are as follows:
  - The saturated vapour refrigerant at the evaporator pressure, ( $p_e$ ) is enters to low stage compressor at state 1, where it is compressed isentropically from the evaporator pressure ( $p_e$ ) to flash chamber or intermediate pressure ( $p_i$ ) as shown by the curve 1-2 in Fig.3.9.
  - The superheated vapour refrigerant leaving the low stage compressor at state 2 is now cooled at constant pressure in a liquid intercooler or flash chamber with the help of liquid refrigerant from condenser.
  - The refrigerant leaving the liquid intercooler is in saturated vapour state (State 3).

- The dry & saturated vapour refrigerant at state 3 is now compressed isentropically in high stage compressor from intermediate pressure ( $p_i$ ) to condenser pressure ( $p_c$ ), as shown by the curve 3-4.
- The superheated vapour refrigerant leaving the high stage compressor at pressure ( $p_c$ ) is passed through the condenser at constant pressure as shown by the horizontal line 4-5, where it is condensed.
- Heat rejected by the refrigerant during intercooling (process 2-3) generates additional vapour in the flash tank. To maintain a constant liquid level in the flash tank some of the saturated liquid refrigerant ( $m_2 - m_1$ ) kg at pressure  $p_c$  is now expanded in a float valve to an intermediate pressure which is equals to the flash chamber pressure, while rest of the liquid refrigerant ( $m_1$  kg) is expanded in an expansion valve up to the evaporator pressure ( $p_e$ ), shown by the line 5-7.
- The refrigerant leaving the expansion valve (state 7) is evaporated in the evaporator by absorbing the latent heat from the colder region as shown by the curve 7-1.
- ▶ Total power input to the system decreases or not depends on whether the increased power consumption due to higher mass flow rate is compensated by reduction in specific work of compression or not.
- ▶ For ammonia, the power input usually decreases with intercooling by liquid refrigerant, because ammonia has large latent heat of vaporization, so amount of vapour generated is less compared to other refrigerants.
- ▶ Flash intercoolers are, therefore, commonly used in multistage ammonia plants.

### Cycle Analysis

- ▶ Let,

$m_1$  = Mass of refrigerant passing through the evaporator

$m_2$  = Mass of refrigerant passing through the condenser

$m_3 = m_2 - m_1$  = Mass of the liquid refrigerant evaporated in the flash chamber

- ▶ Now consider flash chamber is an insulated vessel, there is no heat exchange between the flash chamber and atmosphere. From mass and energy balance in the flash chamber, the heat taken and given by the flash chamber is same.

$\therefore$  Heat taken by the flash chamber = Heat given by the flash chamber

$$\therefore m_1 h_2 + (m_2 - m_1) h_6 = m_2 h_3$$

- ▶ The refrigerating effect of the system,

$$Q_{RE} = m_1(h_1 - h_7)$$

- ▶ The work done in low pressure compressor,

$$W_{c1} = m_1(h_2 - h_1)$$

- ▶ The work done in high pressure compressor,

$$W_{c2} = m_2(h_4 - h_3)$$

- ▶ Heat rejected in the condenser,

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

- ▶ COP of the system,

$$COP = \frac{Q_{RE}}{W_{c1} + W_{c2}}$$

$$\therefore COP = \frac{m_1(h_1 - h_7)}{m_1(h_2 - h_1) + m_2(h_4 - h_3)}$$

### 3.8.3 Two Stage Compression with Water Intercooler

- ▶ The arrangement of a two stage compression with water intercooler is shown in Fig.3.10 with schematic & p-h diagram.

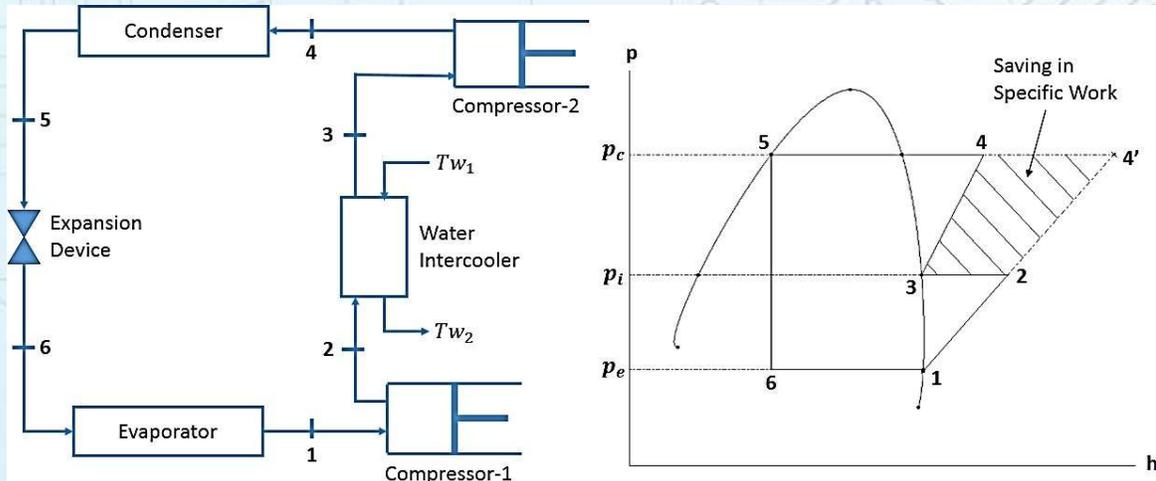


Fig.3.10 – Schematic and p-h diagram of two stage compression with water intercooler

- ▶ The various processes in the system are as follows:
  - The saturated vapour refrigerant at the evaporator pressure, ( $p_e$ ) is enters to low stage compressor at state 1, where it is compressed isentropically from the evaporator pressure ( $p_e$ ) to water intercooler pressure or intermediate pressure ( $p_i$ ) as shown by the curve 1-2 in Fig.3.10.
  - The superheated vapour refrigerant leaving the low stage compressor at state 2 is now cooled at constant pressure in a water intercooler with the help of cold water.
  - The refrigerant leaving the water intercooler is in saturated vapour state (State 3).
  - The dry & saturated vapour refrigerant at state 3 is now compressed isentropically in high stage compressor from intermediate pressure ( $p_i$ ) to condenser pressure ( $p_c$ ), as shown by the curve 3-4.
  - The superheated vapour refrigerant leaving the high stage compressor at pressure ( $p_c$ ) is passed through the condenser at constant pressure as shown by the horizontal line 4-5, where it is condensed.
  - The saturated liquid refrigerant at pressure  $p_c$  is now expanded in an expansion valve to an evaporator pressure ( $p_e$ ), shown by the line 5-6.
  - The refrigerant leaving the expansion valve (state 6) is evaporated in the evaporator by absorbing the latent heat from the colder region as shown by the curve 6-1.
- ▶ Intercooling 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 because discharge temperature in air compressor is much higher.

### Cycle Analysis

- ▶ Let,

$m_R$  = Mass of refrigerant circulating through the system

$m_W$  = Mass of water circulating through the water intercooler

$Cp_w$  = Specific heat of water

- ▶ From mass and energy balance in the water intercooler, the heat rejected from the refrigerant and gained by the water is same.

$\therefore$  Heat rejected from refrigerant = Heat gained by water

$$\therefore m_R(h_2 - h_3) = m_W Cp_w(t_{w2} - t_{w1})$$

- ▶ The refrigerating effect of the system,

$$Q_{RE} = m_R(h_1 - h_6)$$

- ▶ The work done in low pressure compressor,

$$W_{c1} = m_R(h_2 - h_1)$$

- ▶ The work done in high pressure compressor,

$$W_{c2} = m_R(h_4 - h_3)$$

- ▶ Heat rejected in the condenser,

$$Q_c = m_R(h_4 - h_5)$$

- ▶ COP of the system,

$$COP = \frac{Q_{RE}}{W_{c1} + W_{c2}}$$

$$\therefore COP = \frac{m_R(h_1 - h_6)}{m_R(h_2 - h_1) + m_R(h_4 - h_3)}$$

$$\therefore COP = \frac{(h_1 - h_6)}{(h_2 - h_1) + (h_4 - h_3)}$$

### 3.8.4 Two Stage Compression with Liquid Sub-cooler

- ▶ A Liquid Sub-cooler is used to prevent vapour entry into expansion device.
- ▶ The arrangement of a two stage compression with liquid Sub-cooler is shown in Fig.3.11 with schematic & p-h diagram.
- ▶ The various **processes** in the system are as follows:
  - The saturated vapour refrigerant at the evaporator pressure, ( $p_e$ ) is enters to low stage compressor at state 1, where it is compressed isentropically from the evaporator pressure ( $p_e$ ) to an intermediate pressure ( $p_i$ ) as shown by the curve 1-2 in Fig.3.11.
  - The superheated vapour refrigerant leaving the low stage compressor at state 2 is now mixed with the saturated vapour refrigerant produced in the liquid sub-cooler (state 3). The condition of refrigerant after mixing is shown by state 4, which is in superheated state.
  - The superheated refrigerant at state 4 is now compressed isentropically in high stage compressor from intermediate pressure ( $p_i$ ) to condenser pressure ( $p_c$ ), as shown by the curve 4-5.

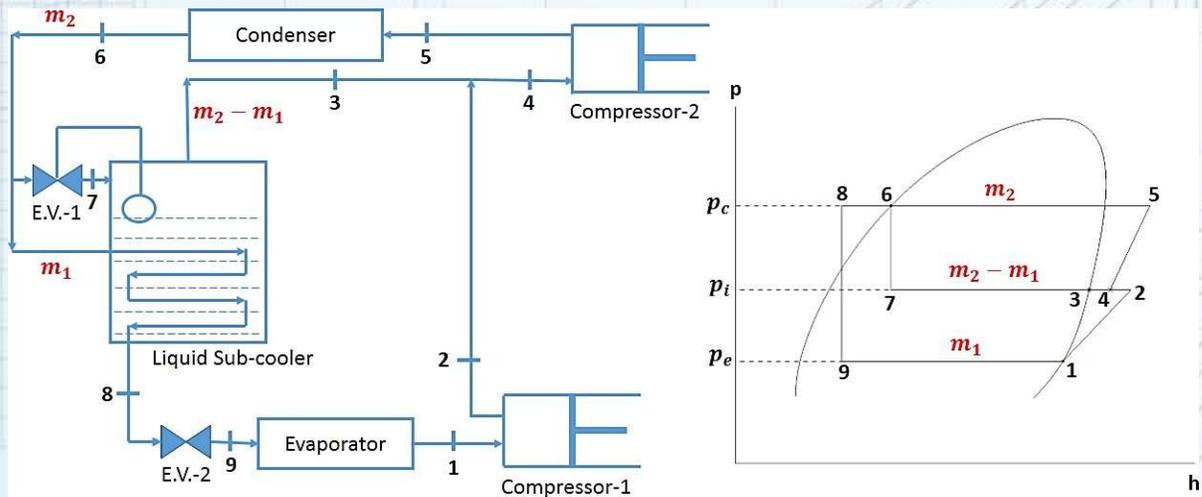


Fig.3.11 – Schematic and p-h diagram of two stage compression with Liquid Sub-cooler

- The superheated vapour leaving the high stage compressor at pressure ( $p_c$ ) is passed through the condenser at constant pressure as shown by the horizontal line 5-6, where it is condensed.
- As shown in Fig.3.11, in a liquid sub-cooler the refrigerant liquid from the condenser (at high pressure  $p_c$ ) is sub-cooled by exchanging heat with the refrigerant liquid in the flash tank (at intermediate pressure  $p_i$ ), shown by the line 6-8.
- As a result, a small amount of refrigerant vapour is generated in the liquid intercooler, which needs to be compressed in the high-stage compressor (state 3).
- To maintain a constant liquid level in the flash tank some of the saturated liquid refrigerant ( $m_2 - m_1$  kg) at pressure  $p_c$  is now expanded in a float valve to an intermediate pressure (Process 6-7), while rest of the liquid refrigerant ( $m_1$  kg) is passing through the liquid sub-cooler.
- The refrigerant leaving the liquid sub-cooler (state 8) is expanded in an expansion valve up to the evaporator pressure ( $p_e$ ), shown by the line 8-9.
- The refrigerant leaving the expansion valve (state 9) is evaporated in the evaporator by absorbing the latent heat from the colder region as shown by the curve 9-1.

### Cycle Analysis

□ Let,

$m_1$  = Mass of refrigerant passing through the evaporator

$m_2$  = Mass of refrigerant passing through the condenser

$m_3 = m_2 - m_1$  = Mass of vapour refrigerant formed in the liquid sub-cooler

▶ The refrigerating effect of the system,

$$Q_{RE} = m_1(h_1 - h_9)$$

▶ The work done in low pressure compressor,

$$W_{c1} = m_1(h_2 - h_1)$$

▶ The work done in high pressure compressor,

$$W_{c2} = m_2(h_5 - h_4)$$

▶ Heat rejected in the condenser,

$$Q_c = m_2(h_5 - h_6)$$

► COP of the system,

$$COP = \frac{Q_{RE}}{W_{c1} + W_{c2}}$$

$$\therefore COP = \frac{m_1(h_1 - h_9)}{m_1(h_2 - h_1) + m_2(h_5 - h_4)}$$

### 3.8.5 Two Stage Compression with Flash Gas Removal, Water & Flash Intercooler

► Fig.3.12 shows a schematic and p-h diagram of two stage vapour compression refrigeration system with flash gas removal using flash tank and intercooling of vapour refrigerant by water and flash intercooler.

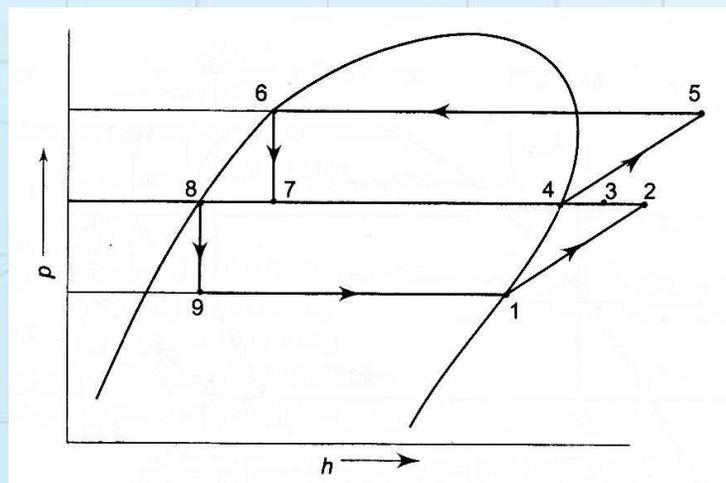
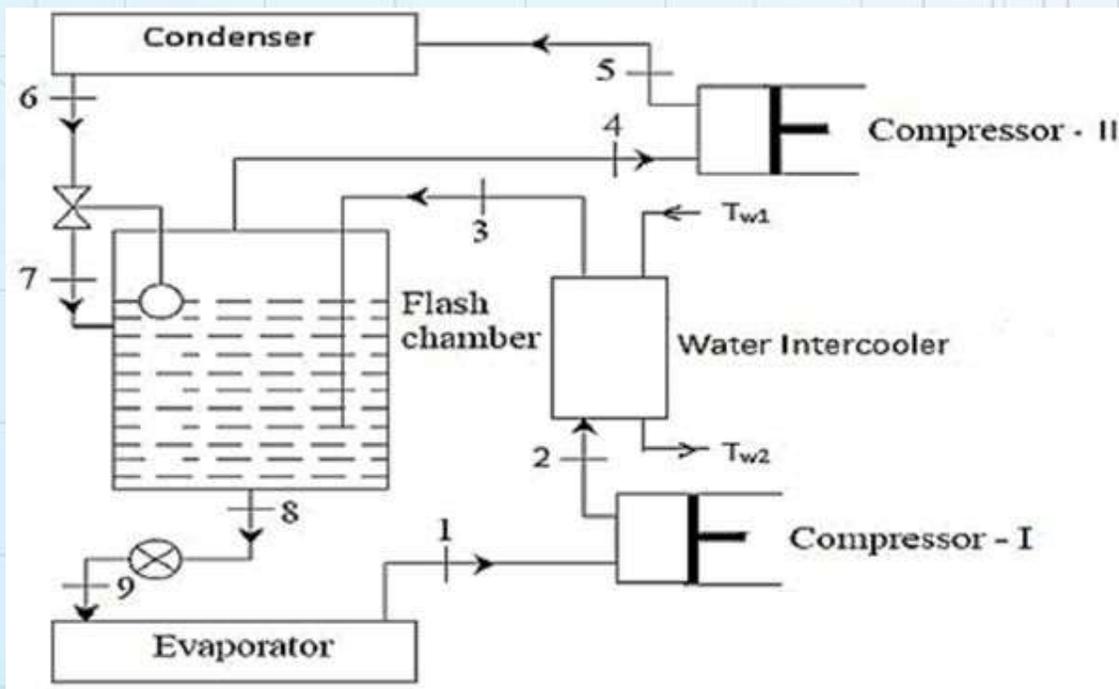


Fig.3.12 – Schematic and p-h diagram of two stage compression with Liquid Sub-cooler

► The various **processes** in the system are as follows:

- The saturated vapour refrigerant at the evaporator pressure, ( $p_e$ ) is enters to low stage compressor at state 1, where it is compressed isentropically from the evaporator pressure ( $p_e$ ) to an intermediate pressure ( $p_i$ ) as shown by the curve 1-2 in Fig.3.12.
- The superheated vapour refrigerant leaving the low stage compressor at state 2 is now cooled at constant pressure in a water intercooler with the help of cold water. The refrigerant leaving the water intercooler is still remains in the superheated state (State 3), which is further cooled at constant pressure in a liquid intercooler or flash intercooler with the help of liquid refrigerant from condenser.
- The refrigerant leaving the flash intercooler is in saturated vapour state (State 4).
- The dry & saturated vapour refrigerant at state 4 is now compressed isentropically in high stage compressor from intermediate pressure ( $p_i$ ) to condenser pressure ( $p_c$ ), as shown by the curve 4-5.
- The superheated vapour leaving the high stage compressor at pressure ( $p_c$ ) is passed through the condenser at constant pressure as shown by the horizontal line 5-6, where it is condensed.
- The saturated liquid at pressure  $p_c$  is now expanded in a float valve to an intermediate pressure which is equals to the flash chamber pressure, shown by the line 6-7.
- The expanded refrigerant, which is a mixture of liquid and vapour at state 7 is now enters to a flash chamber. Flash chamber separates the liquid and vapour refrigerant at intermediate pressure ( $p_i$ ).
- The liquid refrigerant from the flash chamber at state 8 is further expanded in an expansion valve up to an evaporator pressure ( $p_e$ ), as shown by the line 8-9.
- The refrigerant leaving the expansion valve is evaporated in the evaporator by absorbing the latent heat from the colder region as shown by the curve 9-1.

### Cycle Analysis

□ Let,

$m_1$  = Mass of refrigerant passing through the evaporator

$m_2$  = Mass of refrigerant passing through the condenser

$m_w$  = Mass of water circulating through the water intercooler

$Cp_w$  = Specific heat of water

▶ The work done in low pressure compressor,

$$W_{c1} = m_1(h_2 - h_1)$$

▶ From mass and energy balance in the water intercooler, the heat rejected from the refrigerant and gained by the water is same.

*∴ Heat rejected from refrigerant = Heat gained by water*

$$∴ m_1(h_2 - h_3) = m_w Cp_w(t_{w2} - t_{w1})$$

▶ Now consider flash chamber is an insulated vessel, there is no heat exchange between the flash chamber and atmosphere. From mass and energy balance in the flash chamber, the heat taken and given to the flash chamber is same.

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

$$∴ m_2 h_7 + m_1 h_3 = m_1 h_8 + m_2 h_4$$

- ▶ The work done in high pressure compressor,

$$W_{c2} = m_2(h_5 - h_4)$$

- ▶ The refrigerating effect of the system,

$$Q_{RE} = m_1(h_1 - h_9)$$

- ▶ Heat rejected in the condenser,

$$Q_c = m_2(h_5 - h_6)$$

- ▶ COP of the system,

$$COP = \frac{Q_{RE}}{W_{c1} + W_{c2}}$$

$$\therefore COP = \frac{m_1(h_1 - h_9)}{m_1(h_2 - h_1) + m_2(h_5 - h_4)}$$

### 3.8.6 Two Stage Compression with Water Intercooler & Liquid Sub-cooler

- ▶ The arrangement of a two stage compression with water intercooler and liquid sub-cooler is shown in Fig.3.13 with its p-h diagram.

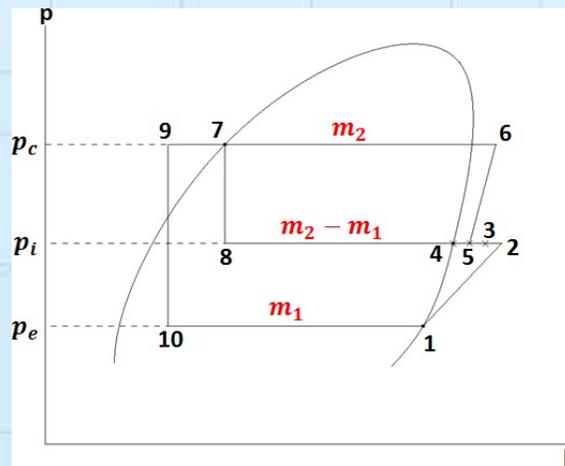
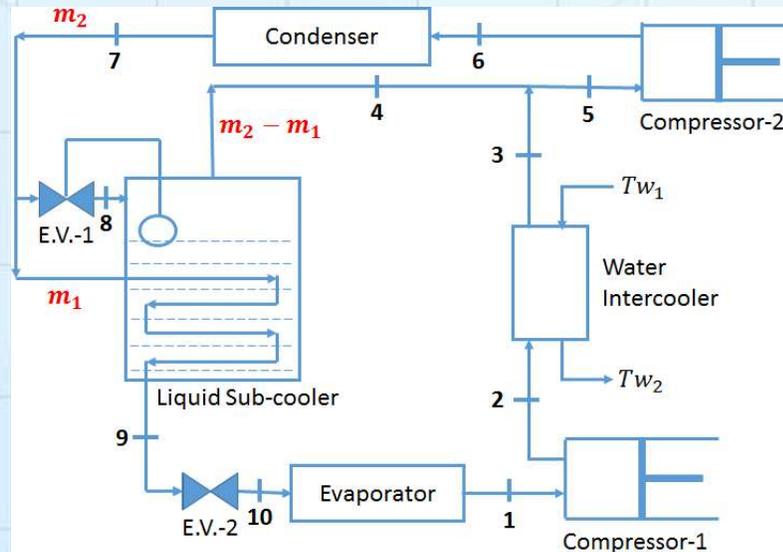


Fig.3.13 – Schematic and p-h diagram of two stage compression with Water Intercooler & Liquid Sub-cooler

- ▶ The various **processes** in the system are as follows:

- The saturated vapour refrigerant at the evaporator pressure, ( $p_e$ ) is enters to low stage compressor at state 1, where it is compressed isentropically from the evaporator pressure ( $p_e$ ) to an intermediate pressure ( $p_i$ ) as shown by the curve 1-2 in Fig.3.13.
- The superheated vapour refrigerant leaving the low stage compressor at state 2 is now cooled at constant pressure in a water intercooler with the help of cold water. The refrigerant leaving the water intercooler is still remains in the superheated state (State 3).
- The superheated vapour refrigerant leaving the intercooler at state 3 is now mixed with the saturated vapour refrigerant produced in the liquid sub-cooler (state 4). The condition of refrigerant after mixing is shown by state 5, which is in superheated state.
- The superheated refrigerant at state 5 is now compressed isentropically in high stage compressor from intermediate pressure ( $p_i$ ) to condenser pressure ( $p_c$ ), as shown by the curve 5-6.
- The superheated vapour leaving the high stage compressor at pressure ( $p_c$ ) is passed through the condenser at constant pressure as shown by the horizontal line 6-7, where it is condensed.
- As shown in Fig. 4.17, in a liquid sub-cooler the refrigerant liquid from the condenser (at high pressure  $p_c$ ) is sub-cooled by exchanging heat with the refrigerant liquid in the flash tank (at intermediate pressure  $p_i$ ), shown by the line 7-9.
- As a result, a small amount of refrigerant vapour is generated in the liquid sub-cooler.
- To maintain a constant liquid level in the flash tank / liquid sub-cooler some of the saturated liquid refrigerant ( $m_2 - m_1$  kg) at pressure  $p_c$  is now expanded in a float valve to an intermediate pressure (Process 7-8), while rest of the liquid refrigerant ( $m_1$  kg) is passing through the liquid sub-cooler.
- The refrigerant leaving the liquid sub-cooler (state 9) is expanded in an expansion valve up to the evaporator pressure ( $p_e$ ), shown by the line 9-10.
- The refrigerant leaving the expansion valve is evaporated in the evaporator by absorbing the latent heat from the colder region as shown by the curve 10-1.

### Cycle Analysis

□ Let,

$m_1$  = Mass of refrigerant passing through the evaporator

$m_2$  = Mass of refrigerant passing through the condenser

$m_3 = m_2 - m_1$  = Mass of vapour refrigerant formed in the liquid sub-cooler

$m_w$  = Mass of water circulating through the water intercooler

$Cp_w$  = Specific heat of water

▶ The work done in low pressure compressor,

$$W_{c1} = m_1(h_2 - h_1)$$

▶ From mass and energy balance in the water intercooler, the heat rejected from the refrigerant and gained by the water is same.

$$\therefore \text{Heat rejected from refrigerant} = \text{Heat gained by water}$$

$$\therefore m_1(h_2 - h_3) = m_w Cp_w(t_{w2} - t_{w1})$$

- ▶ Now consider liquid intercooler is an insulated vessel, there is no heat exchange between the flash chamber and atmosphere. From mass and energy balance in the liquid intercooler, the heat taken and given to the liquid intercooler is same.

$\therefore$  Heat taken by the liquid intercooler = Heat given by the liquid intercooler

$$\therefore m_1(h_7 - h_9) + (m_2 - m_1)h_8 = (m_2 - m_1)h_4$$

- ▶ The work done in high pressure compressor,

$$W_{c2} = m_2(h_6 - h_5)$$

- ▶ The refrigerating effect of the system,

$$Q_{RE} = m_1(h_1 - h_{10})$$

- ▶ Heat rejected in the condenser,

$$Q_c = m_2(h_6 - h_7)$$

- ▶ COP of the system,

$$COP = \frac{Q_{RE}}{W_{c1} + W_{c2}}$$

$$\therefore COP = \frac{m_1(h_1 - h_{10})}{m_1(h_2 - h_1) + m_2(h_6 - h_5)}$$

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

- ▶ The arrangement of a two stage compression with water intercooler, liquid sub-cooler and flash intercooler is shown in *Fig.3.14* with its p-h diagram.

- ▶ The various **processes** in the system are as follows:

- The saturated vapour refrigerant at the evaporator pressure, ( $p_e$ ) is enters to low stage compressor at state 1, where it is compressed isentropically from the evaporator pressure ( $p_e$ ) to an intermediate pressure ( $p_i$ ) as shown by the curve 1-2 in *Fig.3.14*.
- The superheated vapour refrigerant leaving the low stage compressor at state 2 is now cooled at constant pressure in a water intercooler with the help of cold water. The refrigerant leaving the water intercooler is still remains in the superheated state (State 3).
- The superheated vapour refrigerant leaving the water intercooler at state 3 is now passed through the liquid intercooler or flash chamber which cools it to saturated vapour refrigerant as shown by the line 3-4. The cooling is done with the help of liquid refrigerant from condenser.
- The dry & saturated vapour refrigerant leaving the flash intercooler at state 4 is now compressed isentropically in high stage compressor from intermediate pressure ( $p_i$ ) to condenser pressure ( $p_c$ ), as shown by the curve 4-5.
- The superheated vapour leaving the high stage compressor at pressure ( $p_c$ ) is passed through the condenser at constant pressure as shown by the horizontal line 5-6, where it is condensed.
- As shown in *Fig. 4.18*, in a liquid sub-cooler the refrigerant liquid from the condenser (at high pressure  $p_c$ ) is sub-cooled by exchanging heat with the refrigerant liquid in the flash tank (at intermediate pressure  $p_i$ ), shown by the line 6-8.
- As a result, a small amount of refrigerant vapour is generated in the liquid sub-cooler.
- To maintain a constant liquid level in the flash tank / liquid sub-cooler some of the saturated liquid refrigerant ( $m_2 - m_1$  kg) at pressure  $p_c$  is now expanded in a float valve to an

intermediate pressure (Process 6-7), while rest of the liquid refrigerant ( $m_1$  kg) is passing through the liquid sub-cooler.

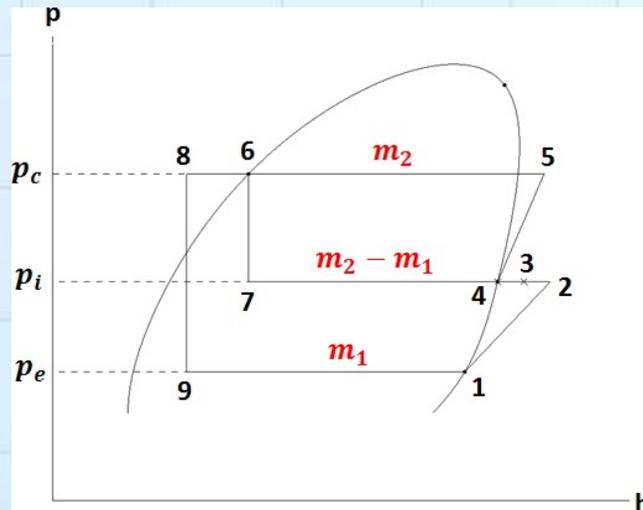
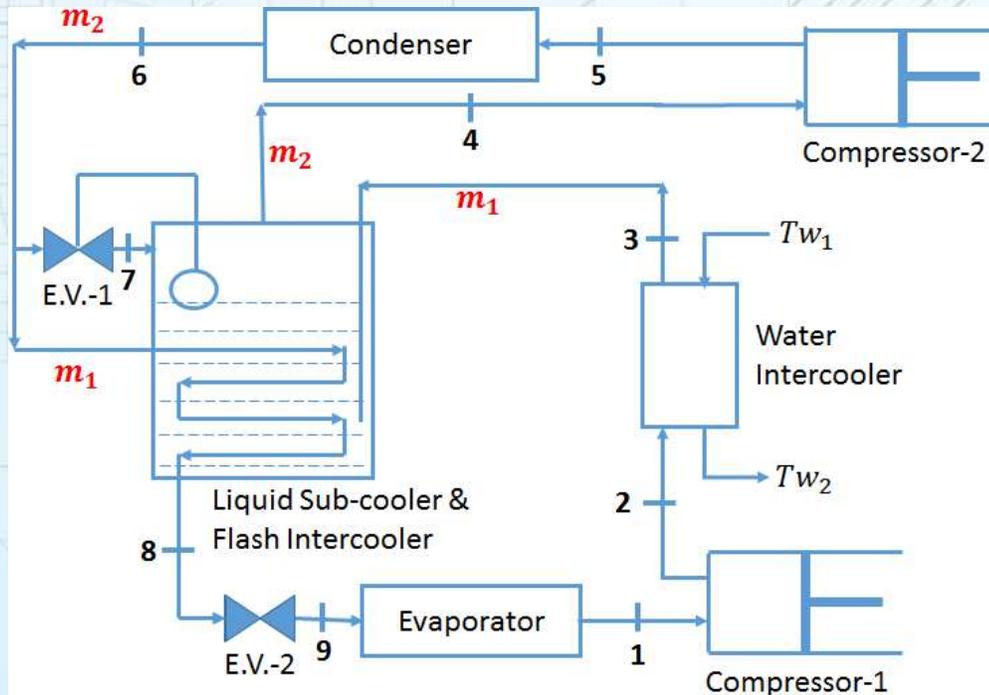


Fig.3.14 – Schematic and p-h diagram of two Stage Compression with Water Intercooler, Liquid Sub-cooler and Flash Intercooler

- The refrigerant leaving the liquid sub-cooler (state 8) is expanded in an expansion valve up to the evaporator pressure ( $p_e$ ), shown by the line 8-9.
- The refrigerant leaving the expansion valve is evaporated in the evaporator by absorbing the latent heat from the colder region as shown by the curve 9-1.

### Cycle Analysis

□ Let,

$m_1$  = Mass of refrigerant passing through the evaporator

$m_2$  = Mass of refrigerant passing through the condenser

$m_w$  = Mass of water circulating through the water intercooler

$Cp_w$  = Specific heat of water

- ▶ The work done in low pressure compressor,

$$W_{c1} = m_1(h_2 - h_1)$$

- ▶ From mass and energy balance in the water intercooler, the heat rejected from the refrigerant and gained by the water is same.

$\therefore$  Heat rejected from refrigerant = Heat gained by water

$$\therefore m_1(h_2 - h_3) = m_w Cp_w(t_{w2} - t_{w1})$$

- ▶ Now consider flash intercooler is an insulated vessel, there is no heat exchange between the flash chamber and atmosphere. From mass and energy balance in the flash intercooler, the heat taken and given to the flash intercooler is same.

$\therefore$  Heat taken by the flash intercooler = Heat given by the flash intercooler

$$\therefore m_1(h_6 - h_8) + (m_2 - m_1)h_7 + m_1h_3 = m_2h_4$$

- ▶ The work done in high pressure compressor,

$$W_{c2} = m_2(h_5 - h_4)$$

- ▶ The refrigerating effect of the system,

$$Q_{RE} = m_1(h_1 - h_9)$$

- ▶ Heat rejected in the condenser,

$$Q_c = m_2(h_5 - h_6)$$

- ▶ COP of the system,

$$COP = \frac{Q_{RE}}{W_{c1} + W_{c2}}$$

$$\therefore COP = \frac{m_1(h_1 - h_9)}{m_1(h_2 - h_1) + m_2(h_5 - h_4)}$$

### 3.9 Vapour Absorption Refrigeration (VAR) System

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- ▶ The simple vapour absorption refrigeration cycle is similar to the vapor compression cycles in many ways however differ in two important respects:
  - One is the nature of the compression process. Instead of compressing a vapor between the evaporator and the condenser, the refrigerant of an absorption system is absorbed by a secondary substance, called an **absorbent**, to form a liquid solution. The liquid solution is then pumped to the higher pressure. Because the specific volume of the liquid solution is much less than that of the refrigerant vapor, significantly less work is required.
  - The other main difference between absorption and vapor-compression systems is that some means must be introduced in absorption systems to recover the refrigerant vapor from the liquid solution before the refrigerant enters the condenser. This involves heat transfer from a relatively high-temperature source
- ▶ Vapour Absorption Refrigeration System becomes economically attractive when there is a source of inexpensive thermal energy at a temperature of 100 to 200°C is available at a relatively low price. Some

examples of inexpensive thermal energy sources include geothermal energy, solar energy, and waste heat from cogeneration or process steam plants and even natural gas.

- ▶ The most widely used absorption refrigeration system is the **ammonia–water system**, where ammonia ( $\text{NH}_3$ ) serves as the refrigerant and water ( $\text{H}_2\text{O}$ ) as the absorbent.
- ▶ Other absorption refrigeration systems include water–lithium bromide and water–lithium chloride systems, where water serves as the refrigerant. These two systems are limited to applications such as air-conditioning where the minimum temperature is above the freezing point of water.

### 3.10 Desirable Properties of Refrigerant-Absorbent Combinations

- ▶ The refrigerant should exhibit high solubility with solution in the absorbent.
- ▶ There should be large difference in the boiling points of refrigerant and absorbent, so that only refrigerant is boiled-off in the generator.
- ▶ There should be no crystallization or solidification inside the system.
- ▶ The mixture should be safe, chemically stable, non-corrosive, inexpensive and should be available easily.
- ▶ The refrigerant-absorbent mixture should have high thermal conductivity and low viscosity for high performance.

### 3.11 Simple $\text{H}_2\text{O} - \text{NH}_3$ Vapour Absorption Refrigeration System

- ▶ The principal components of a simple vapour absorption refrigeration system are shown schematically in Fig. 3.15. In this case, ammonia is the refrigerant and water is the absorbent.

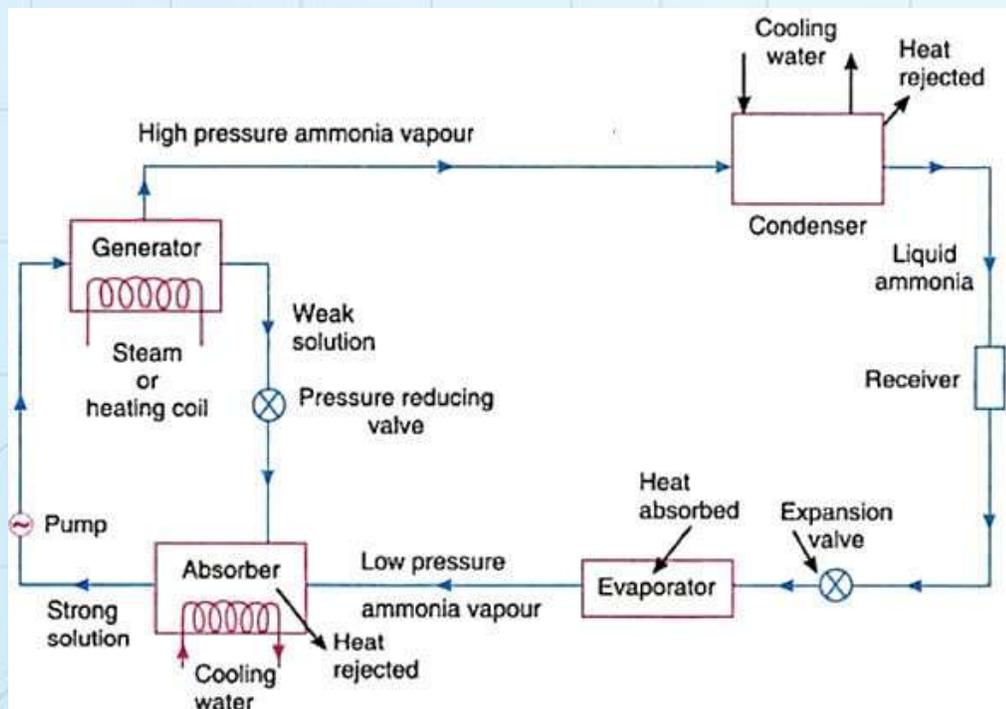


Fig.3.15 – Schematic of Simple Aqua-Ammonia Vapour Absorption Refrigeration System

- ▶ Ammonia circulates through the condenser, expansion valve, and evaporator as in a vapour-compression system. However, the **compressor is replaced by the absorber, pump, generator, and expansion valve** as shown on the left side of the diagram.

- ▶ In the **absorber**, ammonia vapour coming from the evaporator is absorbed by liquid water. The formation of this liquid solution is exothermic and hence heat is to be released. The solvency of ammonia in the water decreases as temperature increases. Thus the cooling water is circulated around the absorber to remove the energy released due to absorption of ammonia in the water.
- ▶ The strong ammonia – water solution leaves the absorber and enters the pump, where its pressure is increased to that of the generator.
- ▶ In the **generator**, heat transfer from a high temperature source drives ammonia vapour out of the solution (an endothermic process), leaving a weak ammonia – water solution in the generator. The ammonia vapour liberated passes to the condenser and the remaining weak solution flows back to the absorber through an expansion valve.
- ▶ The high pressure ammonia vapour from the generator is condensed in the condenser to a high pressure liquid ammonia. This liquid ammonia is passed to the expansion valve through the receiver and then supplied to the evaporator where it absorbs the heat from the cooling region.
- ▶ The only work input is the power required to operate the pump, and this is small in comparison to the work that would be required to compress refrigerant vapour between the same pressure levels.
- ▶ However, costs associated with the heat source and extra equipment not required by vapour-compressor systems can cancel the advantage of a smaller work input.
- ▶ **COP** of the vapour absorption cycle is defined as:

$$COP_{absorption} = \frac{\text{Desired Output}}{\text{Required Input}} = \frac{Q}{Q_{gen} + W_{pump}} = \frac{Q_L}{Q_{gen}}$$

### 3.12 Lithium-Bromide Absorption Refrigeration System

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- ▶ In Li-Br absorption refrigeration system water is used as refrigerant and a solution of lithium bromide in water is used as absorbent.
- ▶ The lithium bromide solution has a strong affinity for water vapour because of its very low vapour pressure.
- ▶ Since water is used as refrigerant, these systems are used only in applications requiring refrigeration at temperatures above 0°C.
- ▶ Hence, Vapour absorption refrigeration systems using water-lithium bromide pair are extensively used in large capacity air conditioning systems.
- ▶ Since lithium bromide solution is corrosive, therefore inhibitors (e.g. Lithium Chromate) should be added in order to protect the metal parts of the system.
- ▶ Fig.3.16 shows a Li-Br vapour absorption system. In this system, the absorber and the evaporator are placed in one shell which operates at the same low pressure of the system.
- ▶ The generator and condenser are placed in another shell which operates at the same high pressure of the system.

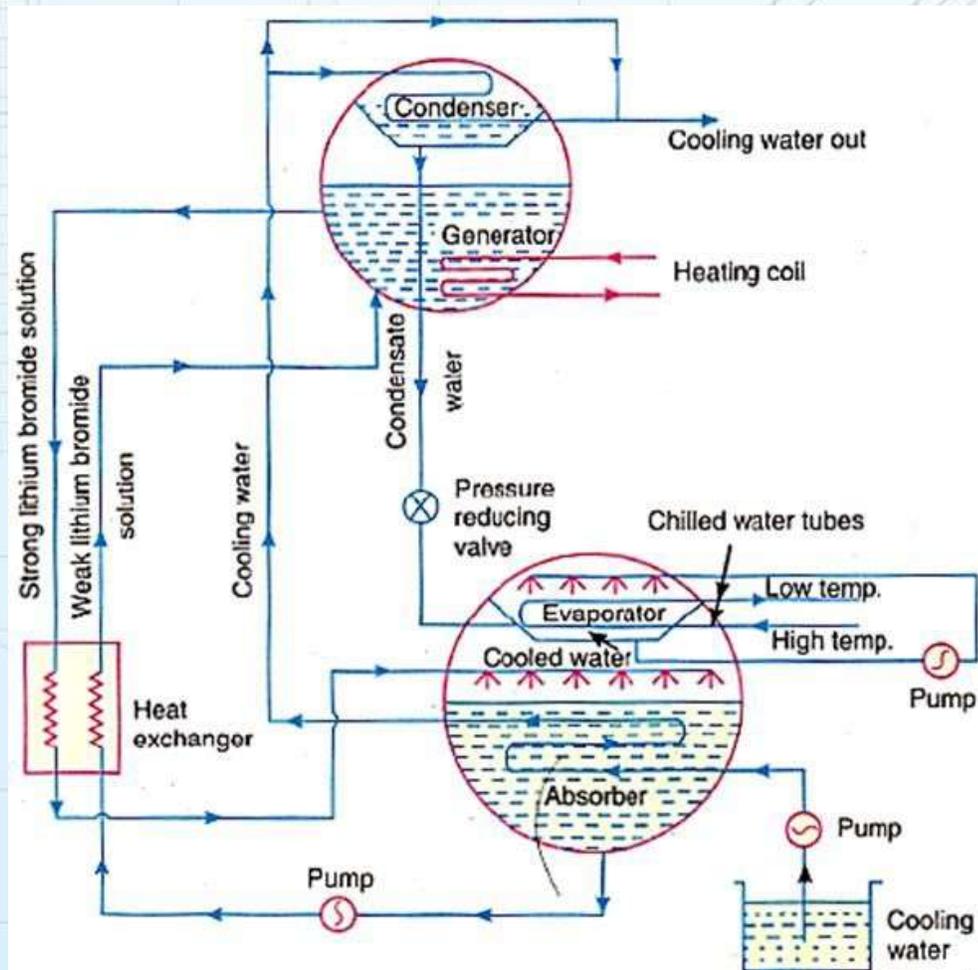


Fig.3.16 – Li-Br Vapour Absorption System

### Working:

- ▶ The water for the process requirement or air conditioning coil is chilled as it is pumped through the chilled water tubes in the evaporator by giving up heat to the refrigerant water sprayed over the tubes.
- ▶ Since the pressure inside the evaporator is maintained very low, therefore the refrigerant water evaporates.
- ▶ The water vapour thus formed will be absorbed by the strong lithium bromide solution which is sprayed in the absorber and the solution becomes weak.
- ▶ This weak solution (weak in Li-Br) is pumped to a generator, where it is heated by a heating coil.
- ▶ A portion of water is evaporated by the heat and the solution becomes strong in Li-Br. This strong solution is passed through the heat exchanger and then sprayed in the absorber as discussed above.
- ▶ The weak solution of lithium bromide from the absorber to the generator is also passed through the heat exchanger. This weak solution gets heat from the strong solution in the heat exchanger, thus reducing the quantity of heat in the generator.
- ▶ The refrigerant water vapour formed in the generator due to heating of solution are passed to the condenser where they are cooled and condensed by the cooling water flowing through the condenser water tubes.
- ▶ The cooling water for condensing is pumped from the cooling water pond or tower. This cooling water first enters the absorber where it takes away the heat of condensation and dilution.

- ▶ The condensate from the condenser is supplied to the evaporator to compensate the water vapour formed in the evaporator. The pressure reducing valve reduces the pressure of condensate from the condenser pressure to the evaporator pressure.
- ▶ The cooled water from the evaporator is pumped and sprayed in the evaporator in order to cool the water for air-conditioning flowing through the chilled tubes. This completes the cycle.