Lesson
16
Vapour Absorption Refrigeration Systems Based On Ammonia-Water Pair

The specific objectives of this lesson are to:

1. Introduce ammonia-water based vapour absorption refrigeration systems (*Section 16.1*)
2. Discuss the properties of ammonia-water mixtures and introduce pressure-temperature-concentration (p-T-ξ) and enthalpy-temperature-concentration (h-T-ξ) charts (*Section 16.2*)
3. Analyze some basic steady flow processes using ammonia-water mixtures such as adiabatic and non-adiabatic mixing, throttling of solution streams and the concept of rectification (*Section 16.3*)

At the end of the lecture, the student should be able to:

1. Differentiate between water-lithium bromide and ammonia-water systems vis-à-vis their properties
2. Explain the concepts of bubble point and dew point temperatures
3. Obtain thermodynamic properties of ammonia-water mixtures using p-T-ξ and h-T-ξ charts
4. Analyze important steady flow processes involving binary mixtures

16.1. Introduction

In vapour absorption refrigeration systems based on ammonia-water pair, ammonia is the refrigerant and water is the absorbent. These systems are more versatile than systems based on water-lithium bromide as they can be used for both sub-zero (refrigeration) as well above 0°C (air conditioning) applications. However, these systems are more complex in design and operation due to the smaller boiling point temperature difference between the refrigerant and absorbent (about 133°C). Due to the smaller boiling point temperature difference the vapour generated in the generator consists of both ammonia as well as water. If water is allowed to circulate with ammonia in the refrigerant circuit, then:

i. Heat transfer in condenser and evaporator becomes non-isothermal
ii. Evaporator temperature increases
iii. Evaporation will not be complete
iv. Water may get accumulated in the evaporator leading to malfunctioning of the plant
iv. Circulation ratio increases

Since all the above effects are detrimental to the performance of the system, it is necessary to minimize the concentration of water vapour in ammonia at the inlet to the condenser. This requires additional components, namely a rectification column and a dephlegmator between generator and absorber, which increases the design complexity and cost and also reduces the system COP compared to water-lithium bromide system.

16.2. Properties of ammonia-water solutions

16.2.1. Composition

Similar to water-lithium bromide solutions, the composition of ammonia-water solution is also expressed either in mass fraction (ξ) or mole fraction (x). However, for ammonia-water solutions, the mass and mole fractions are defined in terms of ammonia. For example the mass fraction ξ is defined as the ratio of mass of ammonia to the total mass of solution, i.e.,

$$\xi = \frac{m_A}{m_A + m_W} \tag{16.1}$$

where m_A and m_W are the mass of ammonia and water in solution, respectively.

Similarly, the mole fraction of ammonia-water solution is defined as:

$$x = \frac{n_A}{n_A + n_W} \tag{16.2}$$

where n_A and n_W are the number of moles of ammonia and water in solution, respectively. The number of moles of ammonia and water can easily be obtained from their respective masses in solution and molecular weights, thus;

$$n_A = \frac{m_A}{M_A}; \text{ and } n_W = \frac{m_W}{M_W} \tag{16.3}$$

where M_A (= 17.0 kg/kmol) and M_W (= 18.0 kg/kmol) are the molecular weights of ammonia and water respectively.

16.2.2. Vapour pressure of ammonia-water solutions

Liquid ammonia and water are completely miscible in all proportions, hence can form solutions of all concentrations from 0 to 1, at normal temperatures. The effect of ammonia in water is to lower the vapour pressure of water, similarly the effect of water in ammonia is to lower ammonia's vapour pressure. Thus the total pressure over ammonia-water solutions is made up of partial pressure of ammonia and partial pressure of water vapour, and is always in between the saturation pressures of pure ammonia and water.

If Raoult's law is applied to ammonia-water mixtures, then the total pressure at any temperature, P_{total} is given by:

$$P_{total} = xP_A + (1-x)P_W \tag{16.4}$$

where x is the liquid phase mole fraction of ammonia, P_A and P_W are the saturation pressures of pure ammonia and pure water at that temperature.

However, similar to water-lithium bromide solutions, ammonia-water solutions also deviate from ideal solution behaviour predicted by Raoult's law in a negative manner, i.e., at a given temperature of the solution the actual vapour pressure will be less than that predicted by Raoult's law (activity coefficient is much smaller than 1.0).

For example, at a mass fraction of 0.4 and temperature of 40°C, Raoult's law predicts a vapour pressure of 6.47 bar, whereas the measured vapour pressure is 3.029 bar.

The vapour pressure data of ammonia-water solutions is also available in the form of Dühring and other P-T-ξ plots.

16.2.3. Composition of ammonia-water vapour

Since the vapour above ammonia-water liquid consists of both ammonia and water vapour, it is essential to distinguish between the composition in liquid phase and composition in vapour phase. The superscripts L and V will be used to distinguish between liquid and vapour phase compositions. Thus ξ^L stands for liquid phase mass fraction and ξ^V stands for vapour phase mass fraction. Though the vapour phase composition, can be obtained by assuming ideal solution behaviour, it is observed that the actual vapour composition deviates from that predicted by ideal mixture equations. Based on experimental measurements, charts have been developed for obtaining composition of ammonia-water mixture in vapour phase in equilibrium with a solution of ammonia and water at different temperatures. Figure 16.1 shows the construction of such a chart using which one can obtain the composition of mixture in vapour phase from known values of liquid phase mass fraction (ξ^L) and saturated temperature of pure ammonia or pressure.

ξ^L

P

$T_{sat,NH3}$

Mass fraction of ammonia in vapour, ξ^V
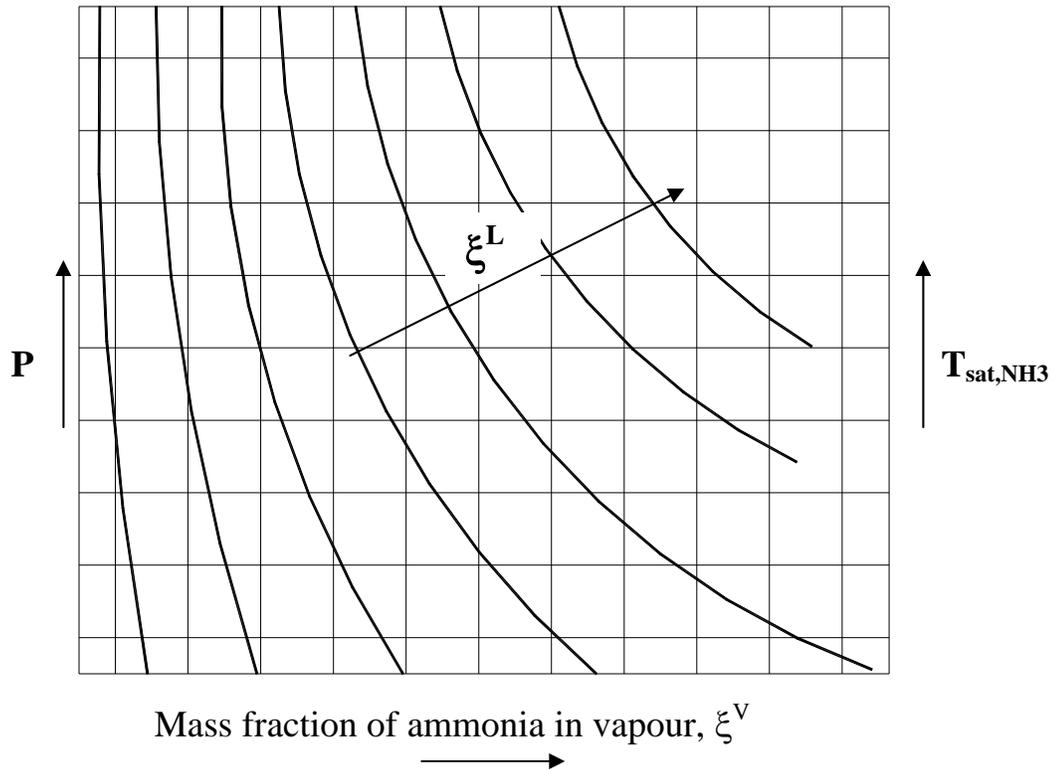
***Fig.16.1**. Vapour-liquid equilibrium chart for ammonia-water solution*

16.2.4. Bubble point and dew point for ammonia-water mixtures

Figure 16.2 shows a cylinder containing mixture of ammonia and water. The pressure on the mixture is maintained constant with the help of a free-floating piston with fixed weights. Initially (State 1) the cylinder consists of subcooled solution of ammonia-water mixture. Now heat is supplied to the system and the temperature of the solution is increased steadily, the mass fraction of the solution remains constant at ξ_1 initially. At a certain temperature the first vapour bubble appears. The temperature at which the first bubble appears is called as bubble point (=T_{bubble}) of the solution at that concentration and pressure. Further heating results in increase in temperature and formation of more vapour as shown in the figure (State 2). If heating is continued further, then the temperature

increases continuously, as more liquid is converted into vapour, and finally at a particular temperature the last liquid droplet vaporizes. The temperature at which the last liquid droplet evaporates is called as dew point temperature (T_{dew}). When heating is continued further the mixture enters into superheated vapour state (State 3). It should be noted that unlike pure fluids, the temperature of the ammonia-water mixture increases continuously as the liquid undergoes vaporization. This is to say that the phase change process is characterized by a temperature glide, which is the difference between the dew point and bubble point temperatures. If this process is repeated with different initial concentrations starting from 0 (pure water) to 1 (pure ammonia) and at the same pressure, different values of bubble and dew points will be obtained. Of course when the concentration is 0 (pure water) or 1 (pure ammonia) the bubble and dew points coincide. Now if we plot the temperatures (bubble point and dew point) against concentration and join all the bubble points by a curve and all the dew points by another curve, then we would get the equilibrium Temperature vs concentration curve for ammonia-water mixtures at that pressure as shown in Fig.16.3. The loci of all the bubble points is called as bubble point line and the loci of all the dew points is known as the dew point line. The bubble point line is the saturated liquid line and the dew point line is the saturated vapour line for the mixture at that pressure. The region between the bubble and dew point lines is the two-phase region where both liquid and vapour coexist in equilibrium. Different bubble point and dew point lines will be obtained if the experiment is carried out with different pressures. For example, Figure 16.4 shows the bubble and dew point lines for two different pressures, P_1 and P_2. The same results can also be obtained if one starts the experiment initially with superheated vapour and then start cooling it. In this case, the dew point is the temperature at which the first liquid droplet forms from the vapour and the bubble point is the temperature at which the last vapour bubble condenses.
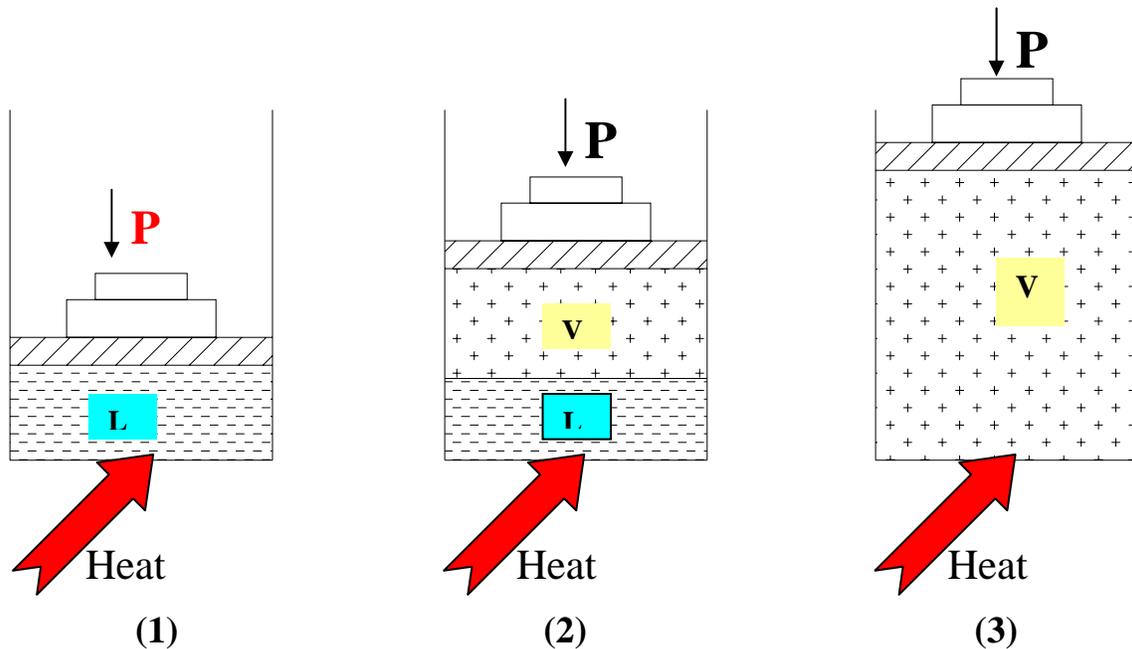
Fig.16.2: *A simple experiment illustrating the principle of bubble and dew points*
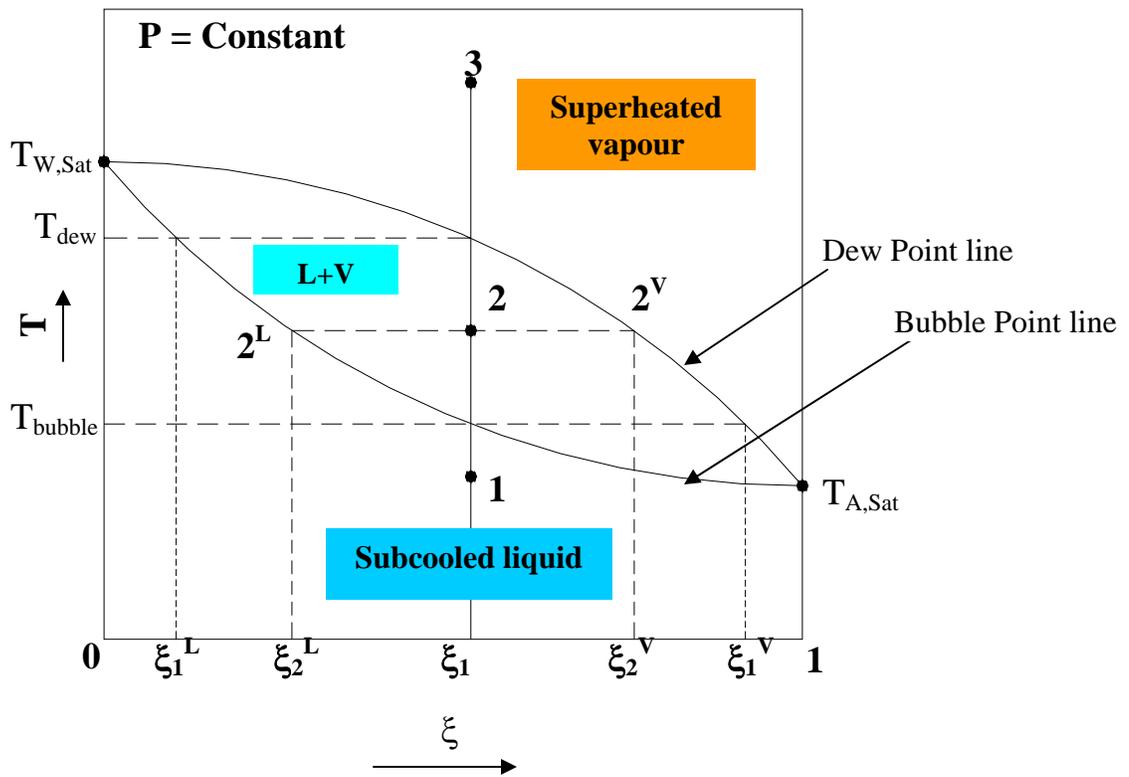
Fig.16.3: *Equilibrium temperature-concentration curve for NH$_3$-H$_2$O at a constant pressure*
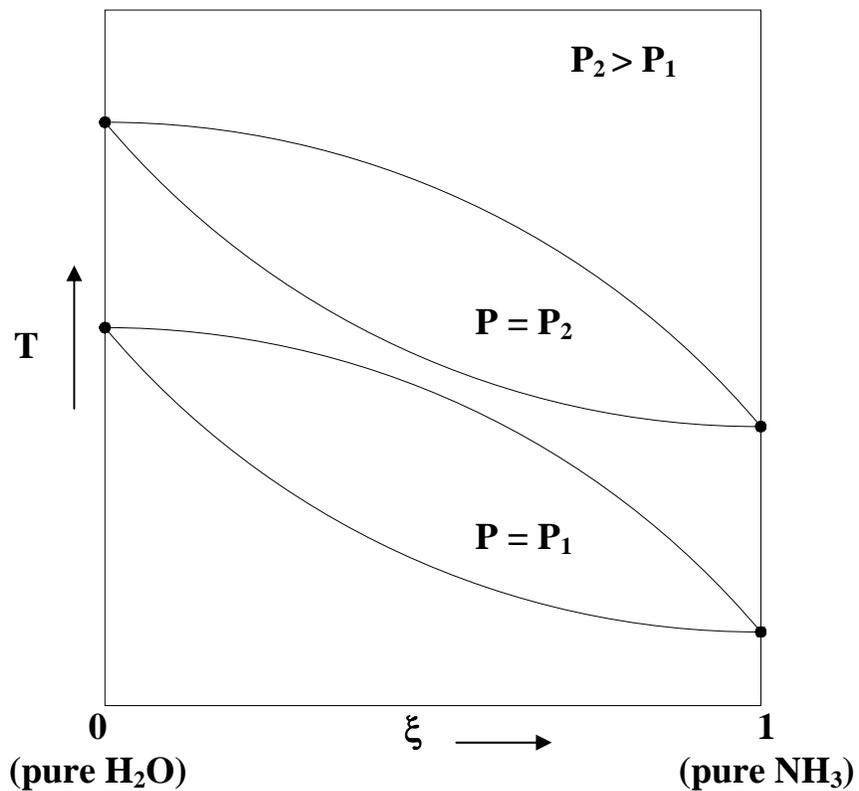
Fig.16.4: *Bubble point and dew point curves at two different pressures*

Now since the process is carried out in a closed system, the mass of both ammonia and water will be conserved. The concentration of subcooled liquid will be same as the concentration of superheated vapour. However, in the two-phase region in which the saturated liquid exists in equilibrium with saturated vapour, the concentration of liquid and vapour will be different. For example, at point 2 in Fig.16.3, the temperature of saturated liquid and vapour will be same as they are in equilibrium, hence, the concentration of liquid will be ξ_2^L (**intersection of constant temperature line with bubble point line**) and that of vapour will be ξ_2^V (**intersection of constant temperature line with dew point line**) as shown in the figure. Obviously the vapour formed initially will be richer in the low boiling point substance (ammonia) and the liquid remaining will be rich in high boiling point substance (water). For example, as shown in Fig.16.3, the concentration of the first vapour bubble will be ξ_1^V and the concentration of the last liquid droplet will be ξ_1^L. Since the total mass as well as mass of individual components is always conserved, we can write mass balance for total mass (m_{total}) and ammonia (m_A) mass at state 2 as:

$$m_{total} = m_2^L + m_2^V \qquad (16.5)$$

$$m_A = \xi_2^L m_2^L + \xi_2^V m_2^V = \xi_1 m_{total} \qquad (16.6)$$

where m_2^L and m_2^V are the mass of liquid and vapour at state 2, respectively.

From the above equations it can be easily shown that:

$$\frac{m_2^L}{m_2^V} = \left(\frac{\xi_2^V - \xi_1}{\xi_1 - \xi_2^L} \right), \text{ or} \qquad (16.7)$$

$$m_2^L(\xi_1 - \xi_2^L) = m_2^V(\xi_2^V - \xi_1) \qquad (16.8)$$

The above equation is called as the *mixing rule or lever rule* for the binary mixtures such as ammonia and water. It implies that the fraction of liquid and vapour in the two-phase mixture is inversely proportional to the distance between the mixture condition 2 and the saturated liquid and vapour states 2^L and 2^V, respectively.

16.2.5. Enthalpy of ammonia-water mixtures

Liquid phase:

The enthalpy of ammonia-water solution in liquid phase, h^L is calculated in a manner similar to that of water-lithium bromide solutions, i.e., by the equation:

$$h^L = \xi^L h_A^L + (1 - \xi^L) h_W^L + \Delta h_{mix} \qquad (16.9)$$

where ξ^L is the liquid phase mass fraction of ammonia, $h_A{}^L$ and $h_W{}^L$ are liquid phase enthalpies of pure ammonia and water respectively. Δh_{mix} is the heat of mixing, which is negative (exothermic) similar to water-lithium bromide mixtures.

Using the above equation one can calculate the specific enthalpy of ammonia-water solutions at any concentration and temperature provided the heat of mixing is known from measurements. Thus enthalpy charts for solution are plotted as a field of isotherms against mass fraction by taking suitable reference values for enthalpy of ammonia and water. Since pressure does not have a significant effect on liquid enthalpy (except at critical point), normally pressure lines are not shown on typical solution enthalpy charts. Also **enthalpy of subcooled liquid is generally assumed to be equal to the saturated enthalpy at that temperature without loss of much accuracy**.

Vapour phase:

Evaluation of enthalpy of a mixture of vapours of ammonia and water is more complicated compared to liquid phase enthalpy. This is due to the dependence of vapour enthalpy on both temperature and pressure. However, to simplify the problem, it is generally assumed that ammonia and water vapour mix without any heat of mixing. Then the enthalpy of the vapour mixture, h^V is given by:

$$h^V = \xi.^V h_A{}^V + (1 - \xi^V) h_W{}^V \qquad (16.10)$$

where $\xi.^V$ is the vapour phase mass fraction of ammonia and $h_A{}^V$ and $h_W{}^V$ are the specific enthalpies of ammonia vapour and water vapour respectively at the temperature of the mixture. However, since vapour enthalpies depend on temperature as well as pressure, one has to evaluate the vapour enthalpy at suitable pressure, which is not equal to the total pressure. An approximate, but practically useful method is to evaluate the vapour enthalpies of ammonia and water at pressures, P_A and P_W given by:

$$P_A = y P_{total}$$
$$\qquad (16.11)$$
$$P_W = (1 - y) P_{total}$$

where y is the vapour phase mole fraction of ammonia and P_{total} is the total pressure. It should be noted that P_A and P_W are equal to the partial pressures of ammonia and water only if they behave as ideal gases. However since ammonia and water vapour may not approach the ideal gas behaviour at all temperatures and pressures, in general P_A and P_W are not equal to the partial pressures. Using this method enthalpies of ammonia-water mixtures in vapour phase have been obtained as functions of temperature and mass fraction.

16.2.6. The complete enthalpy-composition diagram for ammonia-water mixtures:

Normally, charts of enthalpy-temperature-mass fraction are available which give both liquid phase as well as vapour enthalpy of mixtures. Figure 16.5 shows one such chart. Figure 16.6 shows the enthalpy-composition diagram at a constant pressure P. In the figure point **a** represents the condition of saturated liquid mixture at a temperature T with a liquid phase mass fraction of ξ^L. The liquid phase enthalpy corresponding to this condition is given by h^L. The composition and enthalpy of vapour mixture in equilibrium with the liquid mixture at temperature T and pressure P are obtained by drawing a vertical line from **a** upto the auxiliary line and then drawing a horizontal line to the right from the intersection of the vertical line with the auxiliary line. The intersection of this horizontal line with the dew point line **a'** gives the vapour phase mass fraction ξ^V and the vapour phase enthalpy h^V as shown in the figure. The isotherm T in the two-phase region is obtained by joining points **a** and **a'** as shown in the figure. Point **b** in the figure lies in the two-phase region. The specific enthalpy of this point h_b is given by:

$$h_b = (1 - \psi_b)h^L + \psi_b h^V \tag{16.12}$$

where ψ_b is the quality or dryness fraction of the two-phase mixture at b. Since points a, a' and b are co-linear, the dryness fraction ψ_b is given by:

$$\psi_b = \frac{\xi_b - \xi^L}{\xi^V - \xi^L} \tag{16.13}$$

In actual enthalpy-composition diagrams the isotherms are not shown in two-phase region as a different set of them exist for each pressure.

It is important to note that it is not possible to fix the state of the mixture (subcooled, saturated, two-phase or superheated) just from temperature and mass fraction alone, though one can calculate enthalpy of the mixture from temperature and mass fraction. This is due to the reason that at a given mass fraction and temperature, depending upon the pressure the point can be subcooled or saturated or superheated.

For example, a liquid mixture with a mass fraction of 0.4 and temperature of 80°C has an enthalpy of 210 kJ/kg, and it will be in subcooled condition if the pressure is 4.29 bar and saturated if the pressure is 8.75 bar.
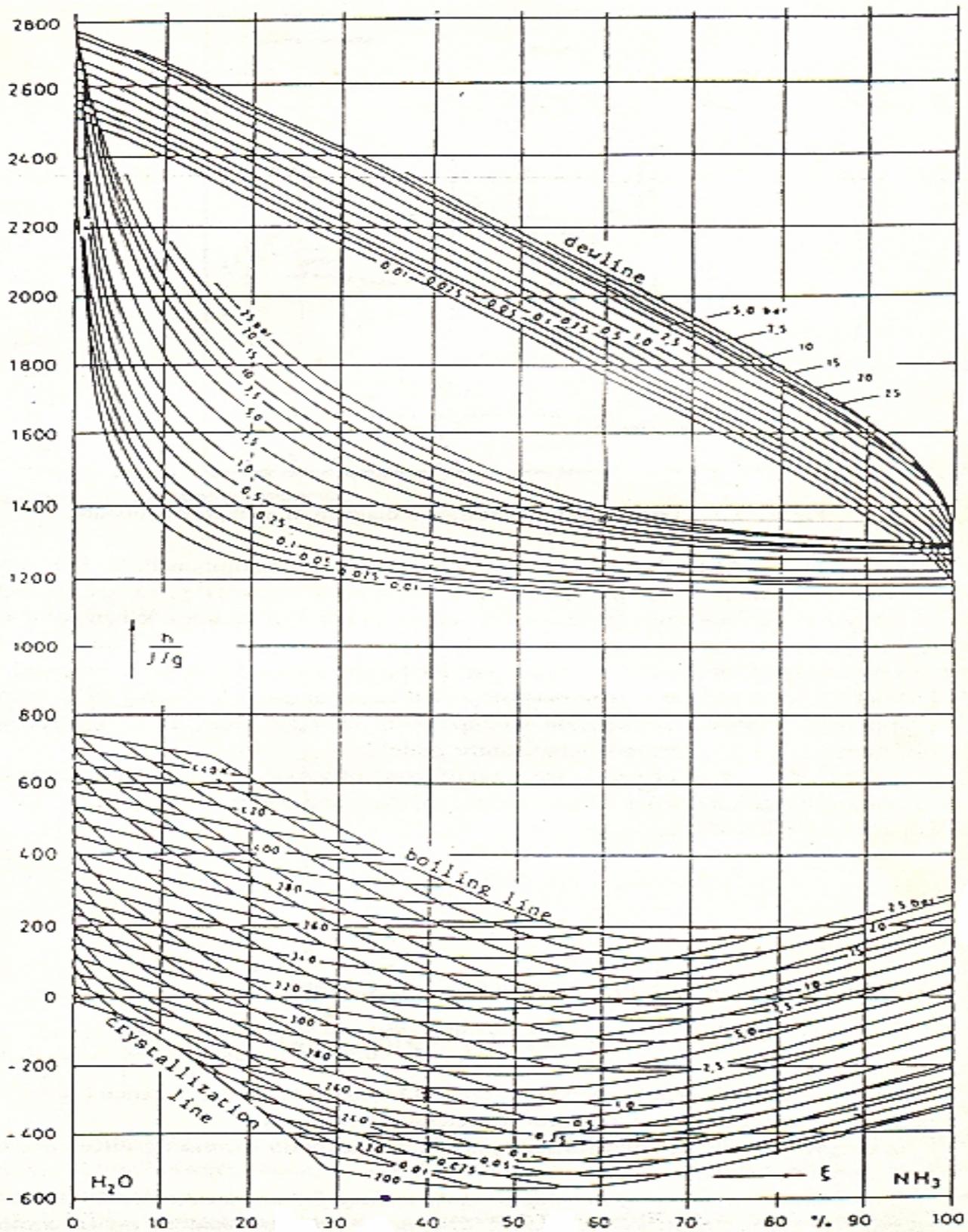
Fig.16.5: *h-T-ξ chart for ammonia-water solution*
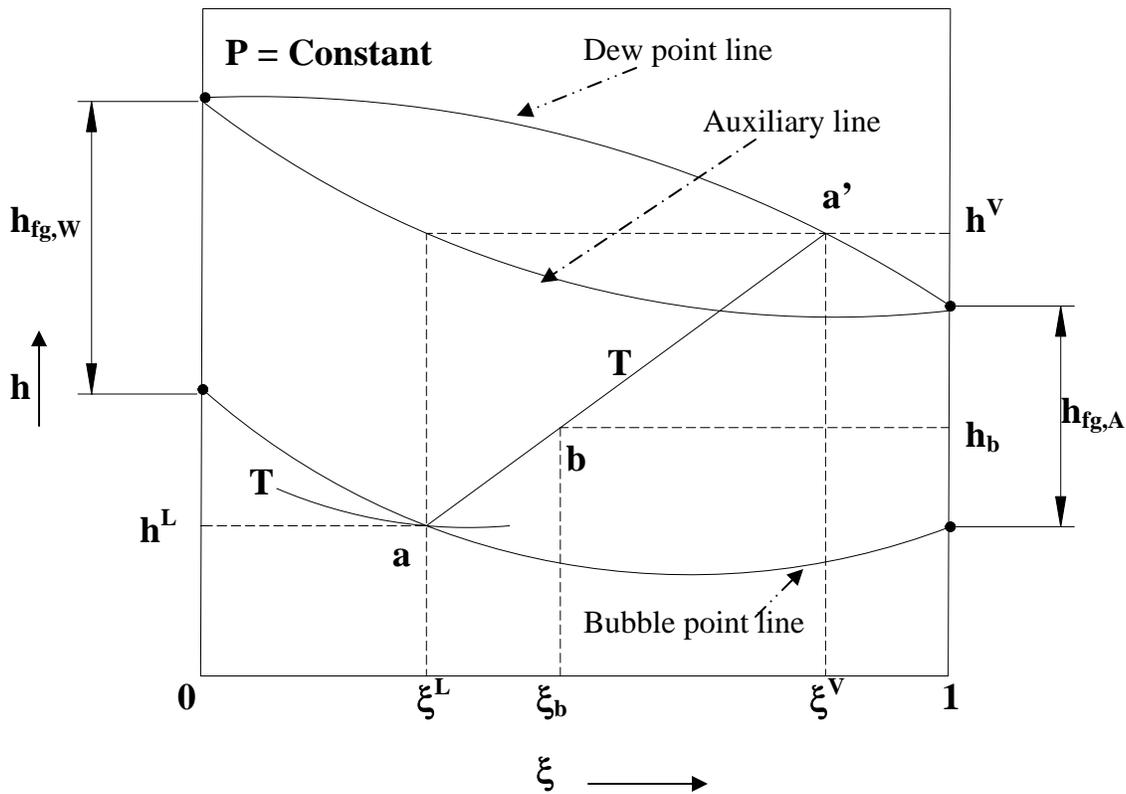
Fig.16.6: Enthalpy-composition diagram of NH₃-H₂O at a constant pressure P

Determination of temperature of mixture in two-phase region:

A trial-and-error method has to be used to determine the temperature of a point in two-phase region if its enthalpy, liquid phase mass fraction and pressure are known. The trial-and-error method can be graphical or numerical. Figure 16.7 shows a graphical method for finding the temperature of point x in the two-phase region which is at a known pressure P_x, liquid phase mass fraction ξ_x and enthalpy h_x. To start with, point a' is obtained as shown in the figure by drawing a vertical line from point x upto the auxiliary line and then drawing a horizontal line from the intersection point a'' upto the dew point line, the intersection of which gives a'. Then a straight line a'-x-a is drawn as shown. Next point b' is obtained by drawing a vertical line upto the auxiliary line and then drawing a horizontal line from b'' upto the dew point line to get b'. Then line b'-x-b is drawn passing through x. This procedure is repeated until convergence is obtained.

Numerically the temperature can be obtained from the equation, which needs to be satisfied for each end of the isotherm passing through x, i.e.,

$$\frac{h^V - h_x}{\xi^V - \xi_x} = \frac{h_x - h^L}{\xi_x - \xi^L} \tag{16.14}$$

To start with guess values of h^L and ξ^L are assumed by taking some point on the bubble point line. Then saturated vapour properties h^V and ξ^V are obtained from the enthalpy-composition charts using the guess values of h^L and ξ^L. Then using the above equation,

new values of h^L and ξ^L are obtained. Then these new values are used to obtain next set of h^V and ξ^V. This procedure is repeated till the values converge. Once the converged values of h^L and ξ^L are obtained then the temperature is read from the enthalpy-composition chart.

***Fig.16.7**: A graphical method for finding temperature of liquid-vapour mixture*

16.3. Basic steady-flow processes with binary mixtures

<u>a) Adiabatic mixing of two streams:</u> When two streams of ammonia-water solutions are mixed adiabatically as shown in Fig.16.8, one can write mass and energy balance equations as:

$$m_1 + m_2 = m_3 \tag{16.15}$$
$$m_1 \xi_1 + m_2 \xi_2 = m_3 \xi_3 \tag{16.16}$$
$$m_1 h_1 + m_2 h_2 = m_3 h_3 \tag{16.17}$$

From the above equations, the mass fraction and enthalpy of the mixture at 3 are given by:

$$\xi_3 = \xi_1 + \frac{m_2}{m_3}(\xi_2 - \xi_1) \qquad\qquad (16.18)$$

$$h_3 = h_1 + \frac{m_2}{m_3}(h_2 - h_1) \qquad\qquad (16.19)$$
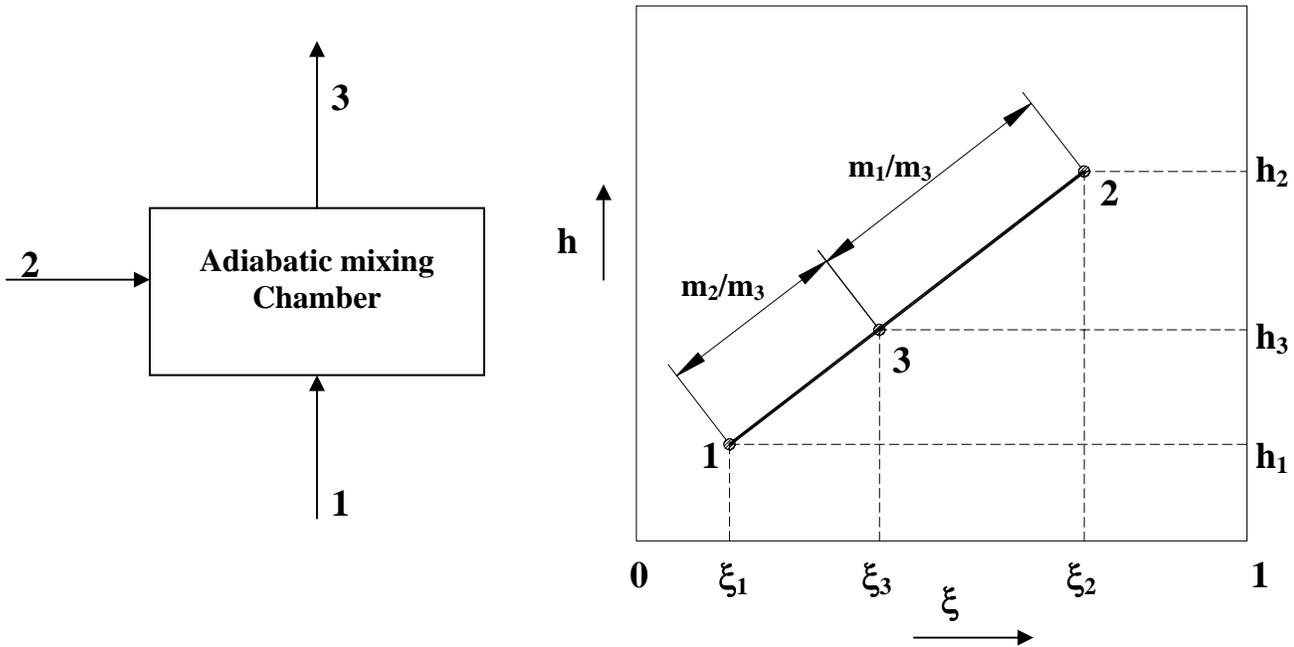
Fig.16.8: Adiabatic mixing of two solution streams

Figure 16.9 shows the adiabatic mixing process with the mixture state 3 lying in two-phase region on the enthalpy-composition diagram. The mixture state in two-phase region implies that some vaporization has occurred during adiabatic mixing of the two inlet streams 1 and 2. The enthalpy and composition of the two-phase mixture at 3 can be obtained by using the equations given above. However, since this is in two-phase region, the mixture consists of saturated liquid and vapour. The dryness fraction and temperature of the mixture (T_3) have to be obtained by trial-and-error method by applying mixing rules. The fraction of the vapour in the mixture at 3 is then given by:

$$\frac{m_3{}^V}{m_3} = \frac{\xi_3 - \xi_3{}^L}{\xi_3{}^V - \xi_3{}^L} = \frac{\overline{3\,3L}}{\overline{3V\,3L}} \qquad\qquad (16.20)$$

b) Mixing of two streams with heat transfer: The process of mixing of two streams with heat transfer takes place in absorber and generator of absorption refrigeration systems. For example, Fig.16.10 shows the mixing of saturated refrigerant vapour (state 1) with saturated solution of refrigerant-absorbent (state 2) in the absorber. The resulting mixture is a solution that is rich in refrigerant (state 3). Since the process is exothermic, heat (Q) is released during this process. Mass and energy balance equations for this process can be written as:
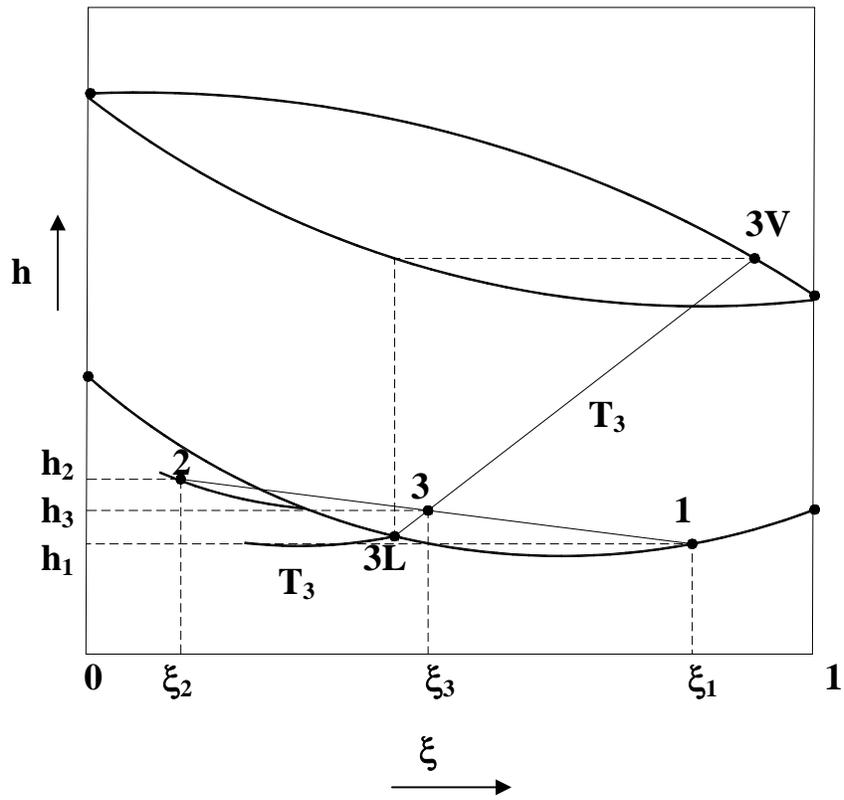
Fig.16.9*: Adiabatic mixing of two streams on h-T-ξ diagram*

$$m_1 + m_2 = m_3 \qquad (16.21)$$

$$m_1\xi_1 + m_2\xi_2 = m_3\xi_3 \qquad (16.22)$$

$$m_1 h_1 + m_2 h_2 = m_3 h_3 + Q \qquad (16.23)$$

From the above equations, the enthalpy of the mixture at 3 is given by:

$$h_3 = h_1 + \frac{m_2}{m_3}\left(h_2 - h_1\right) - \frac{Q}{m_3} \qquad (16.24)$$

Thus with heat transfer from the mixing chamber, the exit state lies at a vertical distance of (Q/m_3) below the state which would result without heat transfer (point 3'). The exit point would lie above the state without heat transfer if heat is transferred to the mixing chamber.

c) Throttling process: Throttling or isenthalpic expansion of ammonia-water solution takes place in the solution expansion valve of the absorption refrigeration system. Figure 16.11 shows the throttling process on enthalpy-composition diagram. Since both mass and energy are conserved during this process, and there is neither work nor heat transfer, we obtain:

$$\xi_1 = \xi_2 \qquad (16.25)$$

$$h_1 = h_2 \qquad (16.26)$$
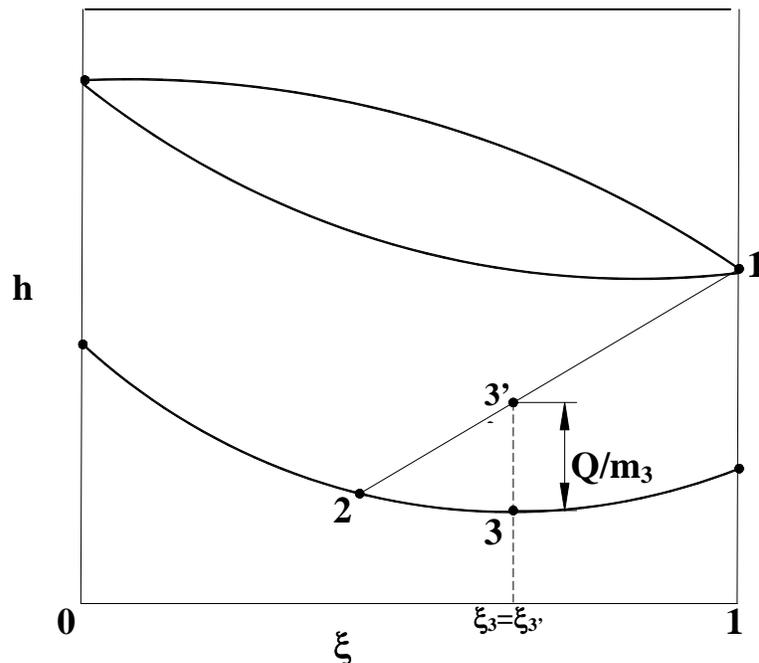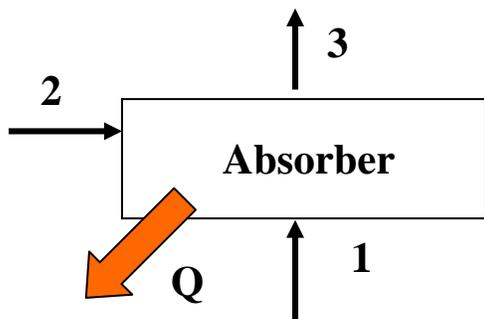
Fig.16.10: Mixing of two streams with heat transfer

Hence the inlet and outlet states, points 1 and 2 are identical on enthalpy-composition diagram as shown in the figure. However, as there is possibility of vapour generation due to flashing, the exit condition may be a mixture of saturated liquid and vapour at the outlet pressure P_2 then the exit temperature T_2 will be much lower than the inlet temperature T_1. Taking point 2 as in the two-phase region corresponding to the outlet pressure P_2, one can get the vapour fraction and exit temperature T_2 by trial-end-error method as discussed earlier.
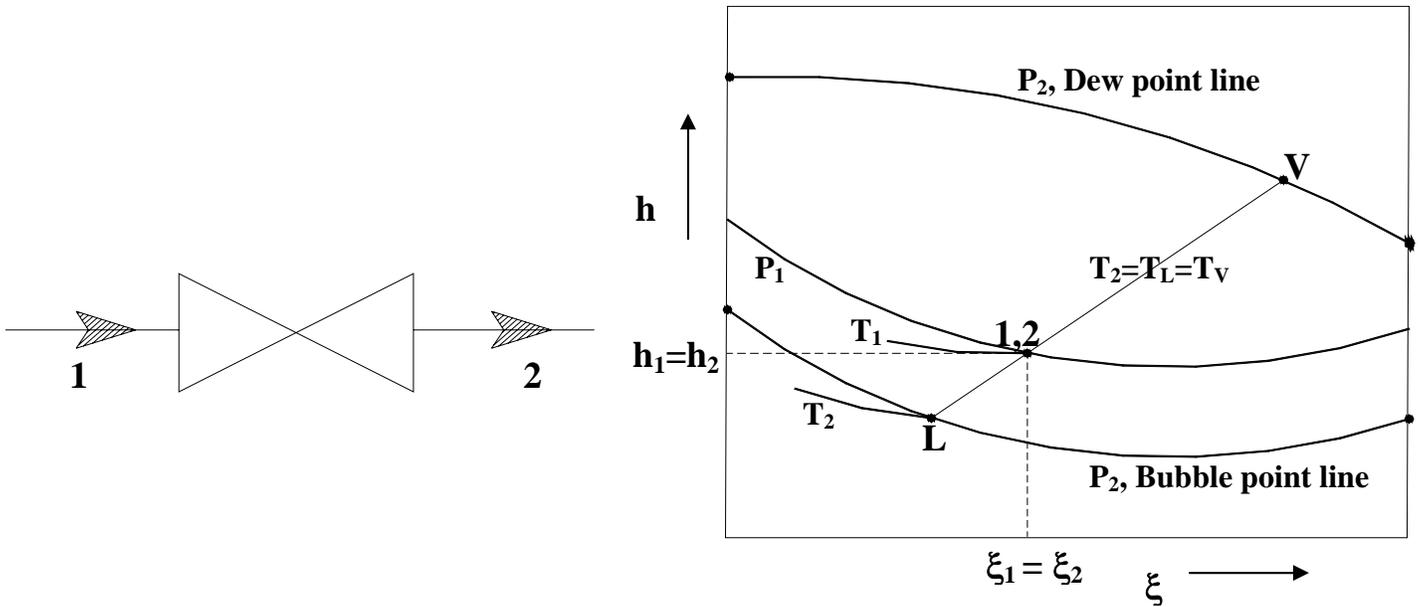
Fig.16.11: Throttling of ammonia-water solution

d) Heating and cooling process – concept of rectification: Figure 16.12 shows an arrangement wherein an initially subcooled solution (state 1) is heated in a heat exchanger A (HX A) in such a way that the exit condition 2 lies in the two-phase region. This two-phase mixture then flows into an adiabatic separator (SEP A) where the saturated liquid (state 3) and saturated vapour (state 4) are separated. The saturated vapour at state 4 is then cooled to state 5 in another heat exchanger B (HX B) by rejecting heat $_4Q_5$. The resulting two-phase mixture is then fed to another adiabatic separator B (SEP B), where again the saturated liquid (state 6) and saturated vapour (state 7) are separated. It is assumed that the entire process takes place at a constant pressure and is a steady-flow process.
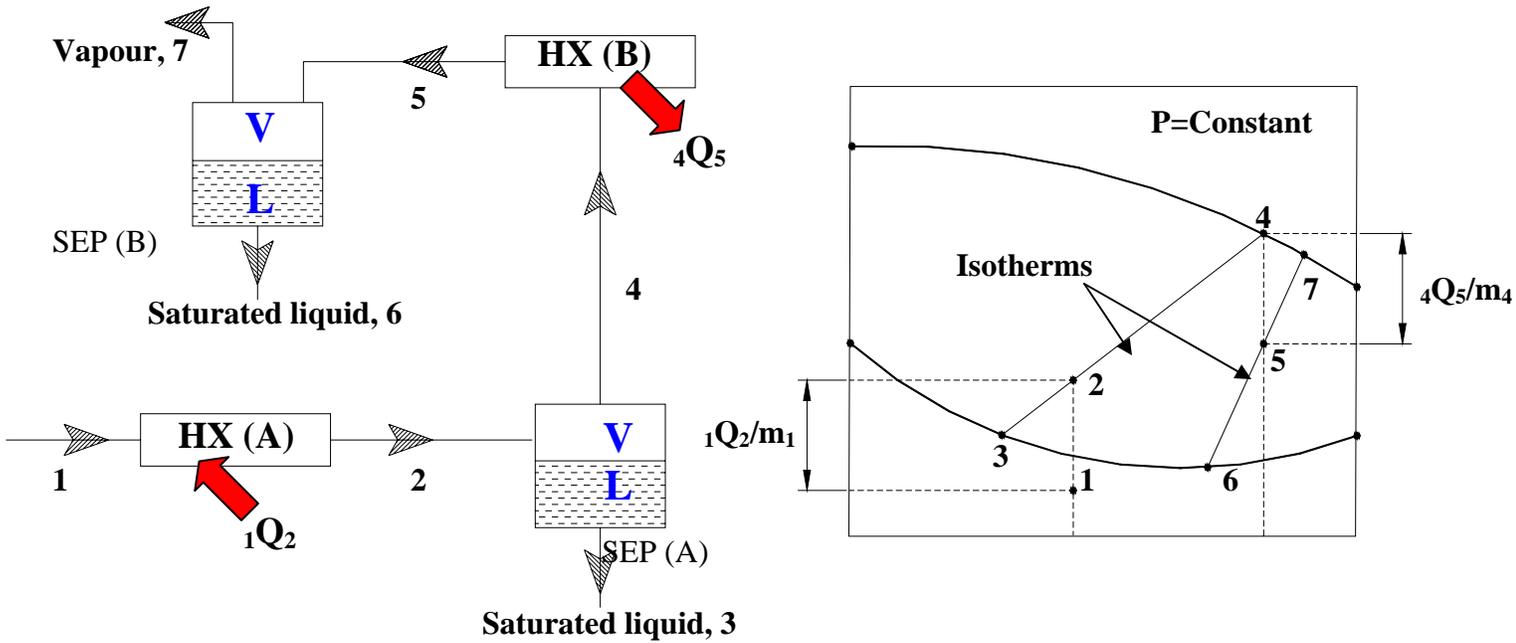
Fig.16.12: *Heating and cooling of NH₃-H₂O solution – concept of rectification*

Now mass and energy balances are applied to each of the components as shown below:

Heat exchanger A:

Mass balance:

$$m_1 = m_2 \qquad (16.27)$$
$$\xi_1 = \xi_2 \qquad (16.28)$$

Energy balance:

$$_1Q_2 = m_1(h_2 - h_1) \qquad (16.29)$$

Separator A:

Mass balance:

$$m_2 = m_3 + m_4 \qquad (16.30)$$

$$m_2\xi_2 = m_3\xi_3 + m_4\xi_4 \qquad (16.31)$$

Energy balance:

$$m_2 h_2 = m_3 h_3 + m_4 h_4 \qquad \text{(16.32)}$$

from the above equations:

$$\frac{m_3}{m_2} = \frac{\xi_4 - \xi_2}{\xi_4 - \xi_3} = \frac{h_4 - h_2}{h_4 - h_3} = \frac{\text{length } 4-2}{\text{length } 4-3} \qquad \text{(16.33)}$$

$$\frac{m_4}{m_2} = \frac{\xi_2 - \xi_3}{\xi_4 - \xi_3} = \frac{h_2 - h_3}{h_4 - h_3} = \frac{\text{length } 2-3}{\text{length } 4-3} \qquad \text{(16.34)}$$

Similar equations can be obtained for heat exchanger B and separator B. The entire process is also shown on enthalpy-composition diagram in Fig.16.12.

It may be noted that from the above arrangement consisting of heating, cooling and separation, one finally obtains a vapour at state 7 that is rich in ammonia. That is the combination of heat exchangers with separators is equivalent to the process of rectification. Heat exchanger A plays the role of generator, while heat exchanger B plays the role of dephlegmator. To improve the process of rectification in actual vapour absorption refrigeration systems, a rectifying column is introduced between the generator and dephlegmator. In the rectifying column, the vapour from the separator A comes in contact with the saturated liquid coming from separator B. As a result, there will be heat and mass transfer between the vapour and liquid and finally the vapour comes out at a much higher concentration of ammonia.

The practical ammonia-water based vapour absorption refrigeration system incorporating rectifying column and dephlegmator in addition to the basic components will be discussed in the next lesson.

Questions and Answers:

1. Presence of water vapour in the refrigerant circuit of a NH_3-H_2O system:

a) Decreases evaporator temperature
b) Increases evaporator temperature
c) Increases circulation ratio
d) Leads to non-isothermal heat transfer in evaporator and condenser

Ans. b), c) and d)

2. Compared to H_2O-LiBr systems, a NH_3-H_2O system:

a) Requires additional components due to the requirement of rectification
b) Yields higher COP
c) Yields lower COP
d) Increases design complexity and system cost

Ans. a), c) and d)

3. Which of the following statements regarding the definition of concentration are TRUE:

a) A strong solution of H_2O-LiBr implies a solution rich in refrigerant
b) A strong solution of H_2O-LiBr implies a solution weak in refrigerant
c) A strong solution of NH_3-H_2O implies a solution rich in refrigerant
d) A strong solution of NH_3-H_2O implies a solution weak in refrigerant

Ans. b) and c)

4. Which of the following statements regarding NH_3-H_2O solution are TRUE:

a) The bubble point temperature is always higher than dew point temperature
b) The bubble point temperature is always lower than dew point temperature
c) At a given pressure, the bubble point and dew point temperatures are higher than the saturation temperature of NH_3 but lower than the saturation temperature of H_2O
d) At a given pressure, the bubble point and dew point temperatures are lower than the saturation temperature of NH_3 but higher than the saturation temperature of H_2O

Ans.: b) and c)

5. For NH_3-H_2O solution at equilibrium, which of the following statements are FALSE:

a) The concentration of liquid phase is lower than the concentration of vapour phase
b) The enthalpy of subcooled solution is a function of temperature and pressure
c) The enthalpy of superheated vapour is a function of temperature only
d) The state of the mixture can be uniquely determined by temperature and concentration

Ans.: b) and d)

6. When a binary solution of NH_3-H_2O is throttled adiabatically:

a) Temperature always remains constant
b) Temperature may decrease
c) Temperature may increase
d) Enthalpy always remains constant

Ans.: b) and d)

7. A binary mixture of NH_3 - H_2O is at a temperature of **40°C** and a liquid phase mole fraction x of **0.5**. Find the vapour pressure of the solution, if the activity coefficient of the solution is **0.65**. The saturation pressures of ammonia and water at 40°C are 1557 kPa and 7.375 kPa, respectively.

Ans.: From Raoult's law, the vapour pressure is given by:

$$P_{v,Raoult} = x.P_{sat,NH_3} + (1-x).P_{sat,H_2O} = 782.19 \text{ kPa}$$

Using the definition of activity coefficient, a; the actual vapour pressure P_v is given by:

$$P_{v,act} = a.P_{v,Raoult} = 0.65 \times 782.19 = 508.42 \text{ kPa} \qquad \textbf{(Ans.)}$$

8. A binary vapour mixture consisting of ammonia and water is at a mole fraction of 0.9 and 10°C. If the partial pressures of ammonia and water vapour in the mixture are 616.25 kPa and 1.227 kPa, respectively; and the specific vapour enthalpies of ammonia and water are 1471.57 kJ/kg and 2519.9 kJ/kg, respectively, find a) the vapour pressure of the mixture, and b) the specific enthalpy of the mixture.

Ans.:

a) Assume the vapour mixture to behave as a mixture of ideal gases, then the total pressure of the mixture P_v is given by:

$$P_v = y.P_{NH_3} + (1-y).P_{H_2O} = 554.75 \text{ kPa} \qquad \textbf{(Ans.)}$$

b) The mass fraction of the mixture ξ^V is given by:

$$\xi^V = \frac{m_A}{m_A + m_W} = \frac{n_A.M_A}{n_A.M_A + n_W.M_W} = \frac{17n_A}{17n_A + 18n_W}$$

Since the mole fraction of the vapour mixture is $0.9 \Rightarrow \mathbf{n_A = 9\ n_W}$

Substituting this in the expression for mass fraction, we find that $\mathbf{\xi^V = 0.895}$

Again assuming the vapour mixture to behave as a mixture of ideal gases; the enthalpy of the mixture is given by:

$$\mathbf{h^V = \xi^V.h_A + (1-\xi^V)h_W = 1581.64 \text{ kJ/kg}} \qquad \textbf{(Ans.)}$$

9. Find the dryness fraction (quality) and specific enthalpy of the two-phase (liquid & vapour) of ammonia-water mixture using the following data:

Liquid phase mass fraction, ξ^L = **0.30**
Vapour phase mass fraction, ξ^V = **0.87**
Mass fraction of 2-phase mixture, ξ = **0.50**
Specific enthalpy of saturated liquid, h^L = **340 kJ/kg**
Specific enthalpy of saturated vapour, h^V = **1640 kJ/kg**

Ans.:

$$\text{Dryness fraction, } \psi = \frac{m^V}{m^V + m^L} = \frac{\xi - \xi^L}{\xi^V - \xi^L} = 0.351 \qquad \textbf{(Ans.)}$$

Enthalpy of the two-phase mixture is given by:

$$h = (1 - \psi)h^L + \psi h^V = 796.3 \text{ kJ/kg} \qquad \textbf{(Ans.)}$$

9. Two solution streams are mixed in a steady flow device. A heat transfer rate of **24 kW** takes place from the device. Find the exit concentration and enthalpy using the data given below:

Stream 1:   Mass flow rate, m_1 = 0.1 kg/s
             Concentration, ξ_1 = 0.7
             Enthalpy, h_1 = 110 kJ/kg

Stream 2:   Mass flow rate, m_2 = 0.3 kg/s
             Concentration, ξ_2 = 0.4
             Enthalpy, h_2 = 250 kJ/kg

Ans.:

From mass balance of solution and ammonia, the exit concentration is given by ξ_3 :

$$\xi_3 = \frac{(m_1\xi_1 + m_2\xi_2)}{(m_1 + m_2)} = 0.475 \qquad \textbf{(Ans.)}$$

From energy balance of solution and ammonia, the exit concentration is given by h_3:

$$h_3 = \frac{\left[(m_1 h_1 + m_2 h_2) - Q\right]}{(m_1 + m_2)} = 155 \text{ kJ/kg} \qquad \textbf{(Ans.)}$$