2. MATHEMATICAL FORMULATION

2.1 System description

The vapour absorption refrigeration system, having different components and state points, is shown in Fig. 2.1. The absorbent-refrigerant solution is pumped to the generator. The affinity of the absorbent refrigerant pair is reduced at an elevated temperature and a part of the refrigerant vapourizes and condenses in the condenser. The condensate, after getting subcooled in the precooler, is throttled through TV1 to the evaporator. The refrigerant vapourizes in the evaporator and thus, cooling is produced. The subcooling in the precooler improves the performance of the system. The remaining solution mixture (weak in refrigerant) from the generator is separated and brought to the absorber through the preheater and throttle valve TV2. The solution in the absorber, maintained at a low temperature and pressure, absorbs the refrigerant vapour from the evaporator, and thus, the cycle is complete.

The volatility differential between water and ammonia is not sufficient, and hence, $\text{H}_2\text{O-\text{NH}_3}$ system needs a rectifier and an analyser to ensure high concentration of the refrigerant ammonia entering the condenser. The $\text{LiNO}_3-\text{NH}_3$, $\text{NaSCN-\text{NH}_3}$ and $\text{LiBr-H}_2\text{O}$ systems using solid absorbents, do not require any such rectification as in the
Fig. 2.1 Vapour absorption refrigeration system
Thus, pure ammonia vapour enter the condensers of the NaSCN-NH$_3$ and LiNO$_3$-NH$_3$ systems. For simplicity, it is assumed that pure ammonia vapour enter the H$_2$O-NH$_3$ system, as well.

Also, in the condenser of LiBr-H$_2$O system, pure water enters. Hence the concentration of LiBr salt in the condenser evaporator circuit is taken zero (i.e. $x = 0.0$) and the concentration of ammonia vapour in the condenser evaporator circuit is taken unity ($x = 1.0$).

The heat input to the generator in the absorption system is obtained by burning biogas or LPG, or by passing hot water from solar collectors, as the case may be. The cooling effect produced in the evaporator can be used for space cooling and the heats of condensation and absorption evolved in the condenser and the absorber can be used for space heating. In ammonia absorption cycles, toxic ammonia vapour flows in the evaporator, hence, indirect cooling using brine is preferred for the space cooling. But, with LiBr-H$_2$O system, its evaporator can be directly connected to the space, because water is non-toxic. For efficient cooling and compact system design, water cooled condensers and absorbers are preferred. Thus, the heated water after taking heat from the absorber and condenser, is sprayed in the spray pond for cooling down to about 5 K above the wet bulb temperatures of the atmospheric air, and then pumped
back to the absorber and condenser to complete the cycle. Similarly, chilled water or brine from the evaporator is sprayed in the duct for cooling and dehumidifying the space-air to be cooled.

2.2 System modelling

The mass, concentration and enthalpy equalities for the refrigerant absorbent combinations in the vapour absorption cycles, at different state points are as follows:

Mass equalities

\[ m_1 = m_2 = m_3 \] (2.1)
\[ m_4 = m_5 = m_6 = m_7 = m_8 = m_9 \] (2.2)
\[ m_{10} = m_{11} = m_{12} \] (2.3)

Concentration equalities

\[ x_1 = x_2 = x_3 \] (2.4)
\[ x_4 = x_5 = x_6 = x_7 = x_8 = x_9 \] (2.5)
\[ x_{10} = x_{11} = x_{12} \] (2.6)

Enthalpy equalities

\[ h_1 = h_2 \text{ (negligible pumping)} \] (2.7)
\[ H_6 = H_7 \text{(isenthalpic expansion)} \]  \hspace{1cm} (2.8)

\[ H_{11} = H_{12} \text{(isenthalpic expansion)} \]  \hspace{1cm} (2.9)

**Pressure equalities**

The mass transfer equilibrium implies:

\[ P_a = P_e \text{ and } P_c = P_g = P_r \]  \hspace{1cm} (2.10)

These pressures relate the refrigerant temperature to the solution temperature and concentration.

The mass and energy balance to each component as a control volume, lead to the following relations:

\[ m_1 = m_4 + m_{10} \]  \hspace{1cm} (2.11)

\[ m_1x_1 = m_4y_4 + m_{10}x_{10} \]  \hspace{1cm} (2.12)

\[ m_1/m_4 = (y_4 - x_{10})/(x_1 - x_{10}) = MR \]  \hspace{1cm} (2.13)

\[ m_{10} = m_4(y_4 - x_1)/(x_1 - x_{10}) \]  \hspace{1cm} (2.14)

\[ Q_a = m_9H_9 + m_{11}H_{11} - m_1H_1 \]  \hspace{1cm} (2.15)

\[ Q_c = m_4(H_4 - H_5) \]  \hspace{1cm} (2.16)

\[ Q_e = m_8(H_8 - H_6) \]  \hspace{1cm} (2.17)

\[ Q_g = m_4H_4 + m_{10}H_{10} - m_3H_3 + Q_r \]  \hspace{1cm} (2.18)

\[ Q_r = m_{13}H_{13} - m_4H_4 - m_{14}H_{14} \]  \hspace{1cm} (2.19)

\[ m_8 = TR \times 3600 \times 3.5/(H_8 - H_6) \]  \hspace{1cm} (2.20)
ACP = \frac{Q_a}{Q_g} \quad (2.21)

CCP = \frac{Q_c}{Q_g} \quad (2.22)

COP = \frac{Q_e}{Q_g} \quad (2.23)

HCP = \frac{(Q_a + Q_c + Q_r)}{Q_g} \quad (2.24)

For the absorption cycles using fluids other than 
\text{H}_2\text{O}-\text{NH}_3, \ Q_r \ is \ zero. \ The \ mass \ and \ energy \ balance \ to \ the 
precooler \ and \ preheater \ lead \ to:

\[ H_g = H_8 + C_{pv}(t_c - t_e) \quad (2.25) \]

\[ H_6 = H_5 - \epsilon_c (H_9 - H_8) \quad (2.26) \]

\[ H_3 = H_1 + \frac{(m_{10}/m_1)}{\epsilon_h} (H_{10} - H_{11}) \quad (2.27) \]

\[ Q_{pc} = m_4 C_{pv}(t_g - t_e) \quad (2.28) \]

\[ Q_{ph} = m_1 C_{pl}(t_3 - t_a) \quad (2.29) \]

\[ t_g = \epsilon_c(t_c - t_e) + t_e \quad (2.30) \]

\[ t_6 = t_c - \epsilon_c \left(\frac{C_{p8}}{C_{p5}}\right)(t_c - t_e) \quad (2.31) \]

\[ t_3 = t_a + \epsilon_h \left(\frac{m_{10}/m_1}{C_{pl}/C_{p1}}\right)(t_g - t_a) \quad (2.32) \]

\[ t_{11} = t_g - \epsilon_h(t_g - t_a) \quad (2.33) \]

Similarly, mass and concentration balance on the 
rectifier, lead to the following equations:

\[ m_{13} = m_4 + m_{14} \quad (2.34) \]
\[ m_{13}y_{13} = m_4y_4 + m_{14}x_{14} \quad (2.35) \]

\[ m_{14} = m_4(y_4 - y_{13})/(y_{13} - x_{14}) \quad (2.36) \]

\[ m_{13} = m_4(y_4 - x_{14})/(y_{13} - x_{14}) \quad (2.37) \]

2.3 Thermodynamic property equations

2.3.1 Enthalpy

The equation for enthalpy in terms of temperature and concentration for LiBr-H₂O are taken from ASHRAE [73], for NaSCN-NH₃ and LiNO₃-NH₃ from Ferreira [74] as given in Appendix A1. The enthalpy equations for pure ammonia, pure water and H₂O-NH₃ mixture have been obtained using the procedure given in Ziegler and Trepp [75], and presented [66] as follows:

**Saturated enthalpy**

The reference states of zero enthalpy are taken as 0°C for saturated ammonia as well as for saturated water.

**Pure components**

\[ H_p^1 = a_0 + a_1T + a_2T^2 + a_3T^3 + (a_4 + a_5T^2)P \]
\[ + a_6P^2 \quad (2.38) \]

\[ H_p^v = b_0 + b_1T + b_2T^2 + b_3T^3 + (b_4 + b_5/T^3) \]
\[ + b_6/T^{11})P + b_7P^3/T^{11} \quad (2.39) \]
Water-ammonia mixture

\[ H_m^1 = (1-x) H_w^1 + x H_A^1 + \left[ (C_o + C_1/T + C_2/T^2) \right. \]
\[ + (C_3 + C_4P + C_5/T + C_6/T^2)(2x-1) + (C_7 \]
\[ + C_8P + C_9/T + C_{10}/T^2)(2x-1)^2 \right] x(1-x) \]  \hspace{1cm} (2.40)

where \( a_i \), \( b_i \) and \( c_i \) are constants, given in Table 2.1.

\[ H_m^V = (1-y) H_w^V + y H_A^V \]  \hspace{1cm} (2.41)

The data for the concentration of ammonia in the vapour phase is taken from Marcel Bogart [76] and correlated in terms of pressure and concentration of ammonia in the liquid phase, as follows:

\[ y = \sum_{i=0}^{6} d_i x^i + (d_7 + d_8 x) \cdot x \cdot P \]  \hspace{1cm} (2.42)

where \( d_i \), \( d_7 \) and \( d_8 \) are constants given in Table 2.2.

The saturated enthalpy equations of ammonia and water in the liquid and gas phases cover the following ranges of temperature and pressure as reported in [75]:

\[ 230 \text{ K} < T < 500 \text{ K} \quad \text{and} \quad 0.2 < P < 50 \text{ bar} \]

The enthalpy equations for \( \text{H}_2\text{O}-\text{NH}_3 \) mixture developed as above, are found to be in good agreement with the tabulated values in refs [73] up to the pressure of 20 bar. On the other hand, the polynomial form of equations developed by Jain and Gable [77] can be used only for two pressure
Table 2.1  Constants for the saturated enthalpy equations

<table>
<thead>
<tr>
<th></th>
<th>Ammonia</th>
<th>Water</th>
<th>H₂O-NH₃ mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>a₀</td>
<td>-1477.925379</td>
<td>-1296.803487</td>
<td>C₀ -2.258462E+3</td>
</tr>
<tr>
<td>a₁</td>
<td>7.979672715</td>
<td>5.6052326</td>
<td>C₁ 7.884209E+5</td>
</tr>
<tr>
<td>a₂</td>
<td>-1.584957E-2</td>
<td>-4.3682107E-3</td>
<td>C₂ -1.239222E+8</td>
</tr>
<tr>
<td>a₃</td>
<td>2.357889E-5</td>
<td>4.4796158E-6</td>
<td>C₃ 1.197489E+3</td>
</tr>
<tr>
<td>a₄</td>
<td>1.938836E-1</td>
<td>0.12685805</td>
<td>C₄ 4.686089E-2</td>
</tr>
<tr>
<td>a₅</td>
<td>-1.832123E-6</td>
<td>-3.8716726E-7</td>
<td>C₅ -9.412826E+5</td>
</tr>
<tr>
<td>a₆</td>
<td>-4.370722E-6</td>
<td>-2.3459764E-6</td>
<td>C₆ 1.797014E+8</td>
</tr>
<tr>
<td>b₀</td>
<td>780.3751592</td>
<td>1995.675063</td>
<td>C₇ -3.701820E+2</td>
</tr>
<tr>
<td>b₁</td>
<td>1.793463444</td>
<td>1.854864237</td>
<td>C₈ 2.935257E-3</td>
</tr>
<tr>
<td>b₂</td>
<td>2.438453E-4</td>
<td>-1.194269E-4</td>
<td>C₉ 5.357491E+5</td>
</tr>
<tr>
<td>b₃</td>
<td>5.887041E-7</td>
<td>3.002761E-7</td>
<td>C₁₀ -1.122989E+8</td>
</tr>
<tr>
<td>b₄</td>
<td>-5.123027E-2</td>
<td>9.858336E-2</td>
<td></td>
</tr>
<tr>
<td>b₅</td>
<td>-1.618514E+8</td>
<td>-5.850564E+8</td>
<td></td>
</tr>
<tr>
<td>b₆</td>
<td>-3.894205E+26</td>
<td>-2.566671E+28</td>
<td></td>
</tr>
<tr>
<td>b₇</td>
<td>-5.946927E+24</td>
<td>0.0</td>
<td></td>
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</tbody>
</table>
Table 2.2  Constants of equation (2.42)

<table>
<thead>
<tr>
<th>Constants</th>
<th>$0.413 \leq P \leq 3.45$</th>
<th>$3.45 &lt; P \leq 6.5$</th>
<th>$6.5 &lt; P \leq 13.5$</th>
<th>$13.5 &lt; P \leq 20.0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_0$</td>
<td>0.89793712</td>
<td>0.81351143</td>
<td>0.72752833</td>
<td>0.77097851</td>
</tr>
<tr>
<td>$d_1$</td>
<td>0.29685405</td>
<td>0.4196054</td>
<td>0.66046214</td>
<td>0.45622018</td>
</tr>
<tr>
<td>$d_2$</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>$d_3$</td>
<td>-0.39722288</td>
<td>-0.35416231</td>
<td>-0.6009903</td>
<td>-0.24143952</td>
</tr>
<tr>
<td>$d_4$</td>
<td>-0.31843513E-1</td>
<td>-0.20990156E-1</td>
<td>-0.4914533E-1</td>
<td>-0.72747812E-1</td>
</tr>
<tr>
<td>$d_5$</td>
<td>0.16958766</td>
<td>0.17765182</td>
<td>0.26705107</td>
<td>0.77452242E-1</td>
</tr>
<tr>
<td>$d_6$</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>$d_7$</td>
<td>0.14493282E-1</td>
<td>0.15354949E-1</td>
<td>0.1413030E-2</td>
<td>0.22001734E-2</td>
</tr>
<tr>
<td>$d_8$</td>
<td>-0.16365455E-1</td>
<td>-0.22806851E-1</td>
<td>-0.25908167E-2</td>
<td>-0.22307627E-2</td>
</tr>
</tbody>
</table>

for $0.25 \leq X \leq 1.0$, (with error upto 2%)

| $d_0$     | 0.23088851E-5            | 0.34794535E-4        | 0.5437887E-4         | 0.67674802E-4        |
| $d_1$     | 12.71762                 | 8.6561079            | 7.4216547            | 6.0439196            |
| $d_2$     | -45.258118               | -18.622324           | -7.005034            | 1.1659851            |
| $d_3$     | -10.311857               | -21.436794           | -43.726231           | -39.259068           |
| $d_4$     | 191.62596                | 78.931686            | -37.295422           | -26.786652           |
| $d_5$     | -259.67126               | -110.47383           | -127.05183           | -257.97452           |
| $d_6$     | 1043.3805                | 439.37634            | 1570.8754            | 1347.1125            |
| $d_7$     | -0.99521232              | -0.20546657          | -0.16737512          | -0.10000949          |
| $d_8$     | 4.0347633                | 0.63089645           | 0.72220981           | 0.31766015           |

for $0.02 < X < 0.25$, (with error upto 3%)
ranges: [3.45 to 5.52 bar] and [17.23 to 24.13 bar]

**Latent heat of vaporization**

Using the saturated enthalpy equations (2.38) and (2.39) for the pure ammonia and water, the latent heat of vaporization for ammonia and water can be obtained from:

\[ H_{LV}^P = H_{VP}^P - H_{LP}^P \]  
(2.43)

and that of the \( H_2O-NH_3 \) mixture.

\[ H_{LV}^m = H_{Vm}^m - H_{Lm}^m \]  
(2.44)

**Superheated enthalpy**

The superheated enthalpy for pure water vapour is taken from Siddiqui et al. [54], as given in the Appendix A1. The superheated enthalpy data for pure ammonia-vapour, from Arora [78], have been correlated as:

\[ H_{A}^{\text{sup}} = 2.3678756 \, t_g - 0.72779902 \, t_c + 1379.8894 \]  
(2.45)

**2.3.2 Equilibrium pressure**

The equilibrium pressure equations for LiBr-\( H_2O \) solution and pure water have been taken from ASHRAE [73]. The equilibrium pressure equation for NaSCN-NH\(_3\) solution, LiNO\(_3\)-NH\(_3\) solution and pure ammonia are taken from
Ferreira [74]. These equilibrium pressure equations taken from the different references are given in Appendix A1. Experimental equilibrium pressure data for the $\text{H}_2\text{O-NH}_3$ solution from Perry and Chilton [79] have been related as:

$$P = \exp\left[11.289381 + 0.58506864 \cdot x - \frac{2864.7202 + 1576.0613 \cdot (1-x)^3}{T}\right]$$

Range: $0.2 < x < 1.0$ and $273.16 < T < 393.16 \text{ K}$  \hspace{1cm} (2.46)

### 2.3.3 Solution refrigerant temperatures

Equating the equilibrium pressure equations for the refrigerant-absorbent solutions with the equilibrium pressure equations for the refrigerants, the solution temperatures can be represented in terms of the refrigerant temperatures as follows:

#### Lithium nitrate-ammonia

$$T_s = \frac{s_3 + s_4(1-x)^3}{A - s_1 - s_2(1-x)^3}$$  \hspace{1cm} (2.47)

#### Sodium thiocyanate-ammonia

$$T_s = \frac{s_7 + s_8(1-x)^3}{A - s_5 - s_6x}$$  \hspace{1cm} (2.48)

#### Water-ammonia

$$T_s = \frac{s_{11} + s_{12}(1-x)^3}{A - s_9 - s_{10}x}$$  \hspace{1cm} (2.49)
\[ A = s_{13} + s_{14}/T_r + s_{15}/T_r^2 \] (2.50)

Lithium bromide-water

\[ T_s = B(T_r - 255.382) + C \]

where,

\[ B = \sum_{i=0}^{3} u_i \, x^i \text{ and } C = \sum_{i=0}^{3} w_i \, x^i \] (2.51)

Range: \( 273.16 \leq T_r \leq 383.16 \, \text{K} \), \( 278.15 \leq T_s \leq 449.16 \, \text{K} \)

and \( 45 \leq x \leq 70\% \) (2.52)

where,

\( T_s \) = solution temperature (Kelvins)

\( T_r \) = refrigerant temperature (Kelvins)

where \( s_i \), \( u_i \) and \( w_i \) are constants given in Table A1.1 of the Appendix A1.

2.3.4 Density

The equations for density in terms of temperature and concentration for NaSCN-NH\(_3\) and LiNO\(_3\)-NH\(_3\) solutions are taken from Ferreira [74], as given in Appendix A1. The experimental density data for LiBr-H\(_2\)O solution taken from ASHRAE [2], for H\(_2\)O-NH\(_3\) solution from Bogart [76], for pure
water and pure ammonia from refs [78], and for aqueous solution of CaCl$_2$ from Ch. 12-45 of Perry Handbook [80], have been correlated as follows:

**Lithium bormide-water**

\[ \rho_m^1 = [1.459029 + 0.27687598 E - 2 x \\
+ (-0.22666074 E-1 + 0.42907626 E-3 x) \\
(T-273.16)] \times 10^3 \]  \hspace{1cm} (2.53)

**Water-ammonia**

\[ \rho_m^1 = 1075.7596 + 0.32246832 E-1 T \times (-10.049441 \\
- 13.265566 x) + 0.90928949 E-1 T^2 \\
(0.52290183 E-3 - 0.24832278 E-1 x) \]

Range: \(0.0 < x < 0.5\), (with error upto 0.2 to 2%) \hspace{1cm} (2.54)

\[ \rho_m^1 = 1000.5831 - 482.84528 x + 1.8901175 T \\
- 0.54252692 E-2 T^2 \]

Range: \(0.5 < x < 1.0\), (with error upto 2%) \hspace{1cm} (2.55)

**Saturated water**

\[ \rho_p^1 = 924.93884 - 0.26103808 E+2 P + 0.466373 T \\
- 0.77185873 E-3 T^2 \]

Range: \(273.16 \leq T \leq 400\) K, (with error upto 0.77%) \hspace{1cm} (2.56)
\[ p_v^{\nu} = 0.21245214 \times 10^3 \frac{P}{T} + 0.97735799 \times 10^{-4} + 631.07294/T^3 + 0.27735754 \times 10^{23}/T^{11} + 0.37691151 \times 10^{27}/T^{11} \]

Range: \(273.16 \leq T \leq 400\) K, (with error upto 0.6%) \(2.57\)

**Saturated ammonia**

\[ p_p^l = 700.94647 - 6.260643 P - 0.22460699 T + 0.44655363 \times 10^{-3} T^2, \text{(with error upto 2%)} \]

\[ p_v^{\nu} = 0.21388012 + 287.55188 \frac{P}{T} - 1906151.5/T^3 + 0.27928234 \times 10^{26}/T^{11} - 0.255 \times 10^{26} \frac{P^2}{T^{11}}, \]

(with error upto 1.5%) \(2.59\)

**Liquid water (at one atmosphere)**

\[ p_p^l = 1000.1885 - 0.52829016 \times 10^{-1}(T-273.16) - 0.34998786 \times 10^{-2}(T-273.16)^2 \]

Range: \(273.16 \leq T \leq 413.16\) K, (with error upto 0.7%) \(2.60\)

**Aqueous solution of CaCl\textsubscript{2}**

\[ p_m^l = 905.0 + 386.63 \times (0.4 \times 10^{-1} + 0.2135 \times 10^{-4} T) - 116.25 \times 10^{-1} x^2 (0.388 \times 10^{-2} + 0.366 \times 10^{-4} T) \]

\(2.61\)
2.3.5 Viscosity

The equations for the viscosities of NaSCN-NH₃ and LiNO₃-NH₃ solution are taken from [74] and given in Appendix A1. The viscosity data for the other solutions and pure components, are correlated and presented below:

Lithium bromide-water

The viscosity data of ASHRAE [2] are related in terms of concentration and temperature as follows:

\[ \mu_m^1 = \left( \frac{(1.7650152 + 0.32196343 \times 10^{-2} x - 0.33326805 \times 10^{-3} x^2 + 0.12705402 \times 10^{-4} x^3)}{\exp(-0.027(T-273.16)) + 0.0178 x}} \right) \times 10^{-3} \]

Range: 10 ≤ x ≤ 30% and 273.16 ≤ T ≤ 350.16 K,
(with error upto 7%) (2.62)

\[ \mu_m^1 = \left( \frac{(2.3587019 - 0.23850093 \times 10^{-1} x - 0.43801876 \times 10^{-3} x^2 + 0.41959618 \times 10^{-4} x^3)}{\exp(-0.03(T-273.16)) + 0.0132 x}} \right) \times 10^{-3} \]

Range: 30 ≤ x ≤ 50% and 273.16 ≤ T ≤ 350.16 K,
(with error upto 6%) (2.63)

\[ \mu_p^1 = \left( \frac{(1.9709527 + 0.10996455 \times 10^{-1} x - 0.59088085 \times 10^{-4} x^3 + 0.31119022 \times 10^{-7} x^5)}{\exp(-0.029(T-273.16)) + 0.021 x}} \right) \times 10^{-3} \]
Range: \( 50 \leq x \leq 60\% \) and \( 273.16 \leq T \leq 350.16 \) K, (with error upto 8\%) \hspace{1cm} (2.64)

**Water-ammonia**

For a binary mixture of two liquids the equation given in Ch. 3-282 of Perry Handbook [80] is used, which is written in terms of the viscosities of liquid ammonia and water as:

\[
\ln \mu_{m}^{1} = x \ln \mu_{A}^{1} + (1-x) \ln \mu_{W}^{1} + 2x(1-x)G_{12} \hspace{1cm} (2.65)
\]

where \( G_{12} \) is an adjustable parameter normally obtained from experimental data. The above equation can correlate for both polar and non-polar liquid mixture viscosities upto about 15\% error.

The viscosities of aqueous ammonia given in terms of temperature at 26\% concentration, are taken from Ch. 3-252 of Perry Handbook [80] and using the viscosity equations of pure water and ammonia, values of \( G_{12} \) are calculated and correlated as:

\[
G_{12} = 1.8424034 - 0.99686859 \times 10^{-2} (T-273.15) \hspace{1cm} (2.66)
\]

Using the above relation for \( G_{12} \), the values of \( \mu_{m}^{1} \) were compared with the experimental data given in International Critical Table V.5:20 [81] at 25\(^\circ\)C for the different
concentrations; and were found in good agreement.

Saturated water

The viscosity data for saturated water taken from refs [78] are related as:

\[
\mu_p^l = 1.4679906 \times 10^{-3} \exp(-0.0261 (T-273.16)) - 0.15948702 \times 10^{-3}
\]

Range: \(273.16 \leq T \leq 423.16\) K, (with error upto 3%) \((2.67)\)

\[
\mu_p^v = 15.8361 \times 10^{-6} \exp(2.9178 \frac{P}{T}) + 66.816 \times 10^{-6} \frac{P}{T} - 0.597/T^2
\]

Range: \(273.16 \leq T \leq 450\) K, (with error upto 2%) \((2.68)\)

Saturated liquid ammonia

The viscosity data taken from refs [82] are related as:

\[
\mu_p^l = 0.98 \times 10^{-3} \exp(-0.67065 \times 10^{-2} T) + 0.78536 \times 10^{-4}
\]

Range: \(223.16 \leq T \leq 323.16\) K, (with error upto 2.5%) \((2.69)\)

Ammonia vapour

The viscosity data of ammonia gas at atmospheric pressure are taken from Ch. 3-248 of Perry Handbook [80] and correlated as:

\[
\mu_p^v
\]
\[ \mu_p^V = 5.2342 \times 10^{-6} \exp(0.2398 \times 10^{-2} T) \\
+ 449.381 \times 10^{-6}/T - 1.76581 \times 10^{-1}/T^2 \]

Range: 253 < T < 500 K, (with error upto 1%) \hspace{1cm} (2.70)

**Aqueous solution of CaCl\textsubscript{2}**

The viscosity data taken from Ch. 12-44 of Perry Handbook [80] have been related as:

\[ \mu_m^1 = (0.414266 - 0.444 \times 10^{-3} x - 0.137 \times 10^{-4} T^2 \\
+ 0.312 \times 10^{-7} T^3) \cdot \exp(-0.1298 \times 10^{-1} T \\
+ 0.86 \times 10^{-1} x) \hspace{1cm} (2.71) \]

### 2.3.6 Thermal conductivity

The equations for thermal conductivity of NaSCN-NH\textsubscript{3} and LiNO\textsubscript{3}-NH\textsubscript{3} solutions taken from Ferreira [74] are given in Appendix A1. The equations for thermal conductivity of the other solutions and pure components, used in the present study, are given below:

**Lithium bromide-water**

The thermal conductivity data taken from the refs [83] are related as follows:

\[ K_m^1 = [(11.945 - 0.94 \times 10^{-1} T + 0.15987 \times 10^{-3} T^2) x \\
+ 573.22833] \times 10^{-3} \]
Range: 273.16 \leq T \leq 398 \text{ K}, (with error upto 2\%) \quad (2.74)

\begin{align*}
K^V_P &= [25.78 \exp(-7.25 P/(T-273.16)) \\
&\quad - 720.03418 P/(T-273.16) \\
&\quad + 607388 P/(T-273.16)^2 - 0.161 E+9/ \\
&\quad (T-273.16)^3].1.0 E-3
\end{align*}

Range: 273.16 \leq T \leq 398 \text{ K}, (with error upto 2\%) \quad (2.75)

**Saturated liquid ammonia**

The thermal conductivity data from refs [82] are related as:

\begin{align*}
K^l_P &= 0.4354446 \exp(-0.27864 E-3 T) + 24.39/T \\
&\quad + 2310.8552/T^2
\end{align*}

Range: 223.16 \leq T \leq 323.16 \text{ K}, (with error upto 3\%) \quad (2.76)

**Ammonia gas**

The data taken from Ch. 3-314 of Perry Handbook [80] for the ammonia gas at one atmosphere, are correlated as follows:

\begin{align*}
K^V_P &= 88.5605 E-3 \exp(-1.6464483 E+5/T^2) \\
&\quad + 0.643407/T + 553.64/T^2 + 3.9735 E+4/T^3
\end{align*}

Range: 253 \leq T \leq 513 \text{ K}, (with error upto 2\%) \quad (2.77)
Aqueous solution of CaCl$_2$

The data taken from Ch. 12-45 of Perry Handbook [80] are related as:

$$K_m^1 = 0.635 - 0.157648 \times 10^{-2} T - 0.14071 \times 10^{-2} x + 0.4919 \times 10^{-5} T^2$$

(2.78)

2.3.7 Specific heat

The equations for specific heat of NH$_3$-NaSCN and NH$_3$-LiNO$_3$ solutions are taken from Ferreira [74] as given in Appendix A1. The equations for the various solutions and pure components are given below:

**Lithium bromide-water**

The specific heat data for LiBr-H$_2$O solution taken from ASHRAE [2] are related in terms of LiBr salt concentration as:

$$C_m^1 = 4.259 - 0.053843 x + 2.307 \times 10^{-4} x^2$$

(2.79)

**Water-ammonia**

The specific heat data taken from International Critical Table V.5:115 [81] and Perry Handbook [80] are correlated as follows:
\[ C_m^1 = 4.1519 - 0.43165688 \times 10^{-2} x + (0.30345 \times 10^{-3} x + 0.23896 \times 10^{-4})(T-273.15) - 0.349 \times 10^{-6} x(T-273.15)^2 \]

Range: \(0.0 \leq x \leq 0.4\) and \(275.55 \leq T \leq 334.15\) \(\text{(2.80)}\)

**Saturated water**

The specific heat data of saturated liquid water and water vapour are taken from refs [78] and related as:

\[ C_L^1 = 4.2686 - 0.3538 \times 10^{-2} (T-273.16) + 0.255 \times 10^{-4}(T-273.16)^2 \]

Range: \(273.16 \leq T \leq 573.16\) K, (with error upto 2%) \(\text{(2.81)}\)

\[ C_V^1 = 7.636 - 0.3715 \times 10^{-1} T + 0.5965 \times 10^{-4} T^2 - 0.27293817 \times 10^{-6} P.T^2 \]

Range: \(273.16 \leq T \leq 450\) K, (with error upto 2%) \(\text{(2.82)}\)

**Saturated liquid ammonia [82]**

\[ C_L^1 = 4.444544 - 0.5064 \times 10^{-2} T + 0.21567 \times 10^{-4} T^2 \]

Range: \(223.16 \leq T \leq 323.16\) K, (with error upto 1.6%) \(\text{(2.83)}\)

**Ammonia gas at one atmosphere [80]**

\[ C_V^1 = 1.9556 + 0.789 \times 10^{-4} T + 0.4032684 \times 10^{-4} T^{1.5} \]
Range: $253 \leq T \leq 513$ K, (with error upto 1%) (2.84)

Aqueous solution of CaCl$_2$ [80]

$$c_m^1 = 36.824 - 0.697 x - (0.12366 + 0.1248 \times 10^{-2} x) T + 0.1398 \times 10^{-4} T^2 x$$ (2.85)

2.3.8 Surface tension

Saturated water

The data for surface tension of saturated water at the liquid vapour interface, are taken from refs [84] and related in terms of pressure and temperature as given below:

$$\sigma_p = \left[6.64332 - (235.80637 P - 13.735 P^2)/T + 0.3661916 E^{-9} T^2/P\right] 1.0 \times 10^{-2}$$

Range: $273.16 \leq T \leq 450$ K, (with error upto 3%) (2.86)

Saturated ammonia

The surface tension data for ammonia at the liquid vapour interface, taken from V.4:442, 447 of refs [81], are related as:

$$\sigma_p = 15.5863/T - 0.54614477 \times 10^{-4} T - 16.310587 \times 10^{-3}$$
Range: $233 \leq T \leq 398$ K, (with error upto 5\%) \hspace{1cm} (2.87)

### 2.3.9 Thermal coefficient of expansion

#### Pure water

The coefficient of expansion data for water have been taken from refs [85] and related in the following mathematical form:

$$
\beta_p = 0.23174 \times 10^{-2} - 0.297332/T - 87.617157/T^2 \hspace{1cm} (2.88)
$$

#### Pure ammonia

The value of $\beta$ for ammonia is found to be constant in the temperature range of -50 to 50\(^\circ\)C [85] and is,

$$
\beta_p = 2.45 \times 10^{-3} \hspace{1cm} (2.89)
$$

The average value of $\beta$ for a mixture of H\(_2\)O-NH\(_3\) solution is roughly estimated to be

$$
\beta_m = \beta_w(1-x) + \beta_a x \hspace{1cm} (2.90)
$$

### 2.3.10 Crystallization line

The equations for concentration of LiNO\(_3\) and NaSCN salt in the absorbent circuit (absorber, preheater and generator side), which may lead to crystallization because of temperature changes in each component, have been taken from Ferreira [74] and presented in Appendix A1. The
concentrations leading to crystallization for LiBr salt are taken from Bogart [76] and related as:

$$X_c = 9.8459 \times 10^{-2} (T-273.15) + 59.7995$$ (2.91)

in the range $300 \leq T \leq 375$ K. The upper limit for the concentration of LiBr salt is 70%.

2.4 Equations of state for computer simulation

The properties of the refrigerant-absorbent solutions, the pure refrigerants and the other fluids used in the various components of the absorption cycles, have been calculated by using the property equations in the form of SUBROUTINES. These properties, at different state points in the cycles, depend upon the temperature, pressure and concentration of the working fluids. For computer simulation, the equations of state around the different components have been presented below in a general form. For a specific fluid, the property equations are modified according to those given in section 2.3. For example, the viscosity equation of water vapour is related in terms of temperature and pressure, whereas, the viscosity equation of ammonia vapour is in terms of temperature only. In such cases, the dependents in the equations, will have to be changed.
Absorber

\[ P_a = P_e = P(T_e) \]

\[ x_a = x(T_a, P_a) \]

\[ x_l = x_a \]

\[ H_1 = H_{m}^{1}(T_a, P_a, x_a) \]

\[ \rho^v_{p} = \rho^v(T_a, P_a) \]

\[ \rho^l_{p} = \rho^l(T_a, P_a) \]

\[ \rho^m_{m} = \rho^m(T_a, x_a) \]

\[ \mu^v_{p} = \mu^v(T_a, P_a) \]

\[ \mu^l_{m} = \mu^l(T_a, x_a) \]

\[ C^m = C^l(T_a, x_a) \]

\[ C_{pl} = C^m \]

\[ k^m = k^l(T_a, x_a) \]

\[ \sigma = \sigma_{p}(T_a, P_a) \]

---

Tube

\[ T_{wa} = [T_{wi} + T_a + \Delta t_a/2]/2 \]

\[ \Delta t_m = \Delta t_a/\ln[(T_a - T_{wi})/(T_a - T_{wi} - \Delta t_a)] \]

Shell

\[ \rho^w = \rho^w_{p}(T_{wa}) \]

\[ \mu^w = \mu^w_{p}(T_{wa}) \]

\[ \mu^w_{m} = \mu^w_{p}(T_{ao}) \]

\[ c^w = c^w_{p}(T_{wa}) \]

\[ k^w = k^w_{p}(T_{wa}) \]
Condenser

Shell

\[ P_c = P(T_c); \ T_c \text{ is assigned} \]

\[ T_{wc} = [T_{wi} + T_c + \frac{\Delta t_c}{2}] \]

\[ H_5 = H^1_p(T_c, P_c) \]

\[ \Delta t_m = \Delta t_c / \ln[(T_c - T_{wi})/(T_c - T_{wi} - \Delta t_c)] \]

\[ H^1_v = H^1_v(T_c, P_c) \]

\[ \rho^v = \rho^v_p(T_c, P_c) \]

\[ \rho^l = \rho^l_p(T_c, P_c) \]

\[ \mu^v = \mu^v_p(T_c, P_c) \]

\[ \mu^l = \mu^l_p(T_c) \]

\[ c^l = c^l_p(T_c) \]

\[ c_{p5} = c^l \]

\[ K^l = K^l_p(T_c) \]

\[ H^1_v = H^1_v_c + 0.68 \ C^l(t_c - t_{co}) \]

Tube

\[ \rho^w = \rho^1_p(T_{wc}) \]

\[ \mu^w = \mu^1_p(T_{wc}) \]

\[ c^w = c^1_p(T_{wc}) \]

\[ \rho^w = \rho^1_p(T_{wc}) \]

\[ \mu^w = \mu^1_p(T_{ci}) \]

\[ c^w = c^1_p(T_{wc}) \]

\[ K^w = K^1_p(T_{wc}) \]

\[ \beta^w = \beta^1_p(T_{wc}) \]
**Evaporator**

<table>
<thead>
<tr>
<th>Tube</th>
<th>Shell</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_e = P(T_e)$</td>
<td>$T_{we} = [T_{el} + T_e + \Delta t_e/2]/2$</td>
</tr>
<tr>
<td>$H_0 = H^V_p(T_e, P_e)$</td>
<td>$\Delta t_m = t_e/\ln([T_{el} - T_e + \Delta t_e]/(T_{el} - T_e))$</td>
</tr>
<tr>
<td>$H_{f1} = H^1_p(T_e, P_e)$</td>
<td>Water, if $t_e &gt; 5^\circ C$</td>
</tr>
<tr>
<td>$h^{1V} = H^{1V}_p(T_e, P_e)$</td>
<td>$\rho^V = \rho^V_p(T_e, P_e)$</td>
</tr>
<tr>
<td></td>
<td>$\rho^1 = \rho^1_p(T_e, P_e)$</td>
</tr>
<tr>
<td></td>
<td>$\mu^V = \mu^V_p(T_e, P_e)$</td>
</tr>
<tr>
<td></td>
<td>$\mu^1 = \mu^1_p(T_e)$</td>
</tr>
<tr>
<td></td>
<td>$C^V = C^V_p(T_e, P_e)$</td>
</tr>
<tr>
<td></td>
<td>$C^1 = C^1_p(T_e)$</td>
</tr>
<tr>
<td></td>
<td>$C_{p8} = C^V$</td>
</tr>
<tr>
<td></td>
<td>$\kappa^1 = \kappa^1_p(T_e)$</td>
</tr>
<tr>
<td>$\sigma = \sigma_p(T_e, P_e)$</td>
<td>$\rho^b = \rho^1(T_{we})$</td>
</tr>
<tr>
<td></td>
<td>$\mu^b = \mu^1(T_{we})$</td>
</tr>
<tr>
<td></td>
<td>$\mu_w = \mu^1(T_{eo})$</td>
</tr>
<tr>
<td></td>
<td>$C^b = C^1(T_{we})$</td>
</tr>
</tbody>
</table>
Rectifier

Shell

\[ P_r = P_c \]

\[ x_4 = 0.0 \text{ (for LiBr-H}_2\text{O)} \]

\[ = 1.0 \text{ (for ammonia cycles)} \]

\[ x_r = x_4 \]

\[ \gamma_r = \gamma_4 \]

\[ x_r = \gamma_r \]

\[ T_r = T(T_c, x_r) \]

\[ x_{14} = x(T_r, P_r) \]

\[ H_4 = H_m^\text{sup}(t_g, t_c) \]

\[ H_4 = H_m^V(T_r, P_r, x_r), \]

\[ (\text{for NH}_3-\text{H}_2\text{O}) \]

\[ H_{14} = H_m^V(T_r, x_{14}) \]

\[ H_{14}^V = H_m^V(T_r, P_r, x_r, y_r) \]

\[ \rho^V = \rho_p^V(T_r, P_r) \]

Tube

\[ T_{wr} = \frac{(T_{wi} + T_r + \Delta t_r/2)/2}{\Delta t_m = \Delta t_r/\ln[(T_r - T_{wi})/ (T_r - T_{wi} - t_r)]} \]

\[ \rho^w = \rho_p^1(T_{wr}) \]

\[ \mu^w = \mu_p^1(T_{wr}) \]

\[ \mu^w = \mu_p^1(T_{ri}) \]

\[ C^w = C_p^1(T_{wr}) \]

\[ K^w = K_p^1(T_{wr}) \]

\[ p^w = p_p^1(T_{wr}) \]
\[ P^m = P^1(T_r, x_r) \]
\[ \mu^v = \mu^1(T_r, P_r) \]
\[ \mu^m = \mu^1(T_r, x_r) \]
\[ C^m = C^1(T_r, x_r) \]
\[ K^m = K^1(T_r, x_r) \]
\[ H^1v = H^1v + 0.68 C^m(t_r - t_{ro}) \]

**Generator**

**Shell**

\[ P_g = P_c \]
\[ x_{10} = \frac{MR \cdot x_1 - y_4}{MR - 1.0} \]
\[ x_g = x_{10} \]
\[ Y_{13} = y(P_g, x_g) \]
\[ T_g = T_s(T_c, x_g) \]

**Tube**

**Solar**

\[ \Delta t_m = \frac{\Delta t_{gc}}{\ln \left( \frac{t_{sol} - t_g}{t_{sol} - t_g - \Delta t_{gc}} \right)} \]

The properties of hot fluid from the storage tank of the solar collectors are evaluated at the temperature \( t_{gcl} \), defined by equation (3.118).
The temperature $T_{gs}$ is defined by equation (3.116) and (3.117).
Preheater

Shell

\[ T_{hs} = \frac{(T_{g} + T_{ll})}{2} \]

\[ \Delta t_{m} = \frac{(T_{g} - T_{3}) - (T_{ll} - T_{a})}{\ln\left(\frac{\left(T_{g} - T_{3}\right)}{\left(T_{ll} - T_{a}\right)}\right)} \]

\[ H_{ll} = H_{m}^{l}(T_{a}, P_{a}, x_{a}) \]

\[ \rho_{s}^{m} = \rho_{m}^{l}(T_{hs}, x_{g}) \]

\[ \mu_{s}^{m} = \mu_{m}^{l}(T_{hs}, x_{g}) \]

\[ C_{s}^{m} = C_{m}^{l}(T_{hs}, x_{g}) \]

\[ K_{s}^{m} = K_{m}^{l}(T_{hs}, x_{g}) \]

Tube

\[ T_{ht} = \frac{(T_{a} + T_{3})}{2} \]

\[ T_{wh} = \frac{(T_{ht} + T_{hs})}{2} \]

\[ \rho_{t}^{m} = \rho_{m}^{l}(T_{ht}, x_{a}) \]

\[ \mu_{t}^{m} = \mu_{m}^{l}(T_{ht}, x_{a}) \]

\[ C_{t}^{m} = C_{m}^{l}(T_{ht}, x_{a}) \]

\[ K_{t}^{m} = K_{m}^{l}(T_{ht}, x_{a}) \]

\[ \beta_{t}^{m} = \beta_{m}(T_{ht}) \]
Precooler

\[
\begin{align*}
T_{ps} &= \frac{(T_6 + T_c)}{2} \\
T_{pt} &= \frac{(T_9 + T_e)}{2} \\
\Delta t_m &= \frac{[(T_c - T_9) - (T_6 - T_e)]}{\ln[(T_c - T_9)/(T_6 - T_e)]} \\
H_9 &\text{ is defined by Eq. (2.25)}
\end{align*}
\]

\[
\begin{align*}
H_9 &\text{ is defined by Eq. (2.26)} \\
\rho_s &= \rho_p(T_{ps}, P_c) \\
\mu_s &= \mu_p(T_{ps}) \\
C_s &= C_p(T_{ps}) \\
K_s &= K_p(T_{ps}) \\
\rho_t &= \rho_p(T_{pt}, P_e) \\
\mu_t &= \mu_p(T_{pt}, P_e) \\
C_t &= C_p(T_{pt}, P_e) \\
K_t &= K_p(T_{pt}, P_e) \\
\beta_t &= \beta_p(T_{pt})
\end{align*}
\]