Heat and mass transfer studies on R134a bubble absorber in R134a/DMF solution based on phenomenological theory

M. Suresh, A. Mani *
Refrigeration and Airconditioning Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Madras, India

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A B S T R A C T

A phenomenological theory of heat and mass transfer is applied to model the absorption of the R134a gas bubble in liquid R134a–dimethyl formamide (DMF) solution. Required properties of R134a–DMF liquid solution namely liquid density, surface tension, diffusion coefficient, thermal conductivity, specific heat, etc., have been calculated using experimental correlations. Results have been obtained by modeling on a computer using MATLAB. The bubble dynamics during bubble growth are studied using this model. Liquid concentration, temperature, heat and mass transfer rates, local heat and mass transfer coefficients are estimated at the bubble interface. Absorption rate, coupled heat transfer rate, average heat and mass transfer coefficients over the entire bubble life span are also calculated. This model results are validated using experimental results of ammonia–water solution. The maximum bubble radius determined from this study is compared with available experimental correlations and it is found that agreement is good. Heat and mass transfer rates obtained from this model are compared with the literature experimental results. The results are in good agreement with the predictions of the model.

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1. Introduction

The absorption refrigeration technology is being viewed as one of the alternatives for the vapour compression refrigeration due to its potential for waste heat utilization. The well-known working fluid ammonia–water suffers from toxicity, corrosion and rectification requirements. Another known working pair lithium bromide–water encounters limitation of evaporator temperature, vacuum formation and the possibility of crystallization. Due to these problems, attention has been shifted to new working fluids. Among them, CFCs and HCFCs are covered by Montreal and other International Protocols and are being phased out. So R134a, a HFC refrigerant is chosen for the study. DMF (N,N-dimethyl formamide), and DMA (N,N-dimethyl acetamide) are considered as promising absorbents with R134a [19]. In this paper, analysis has been carried out using R134a/DMF combination.

Absorber is considered as one of the crucial components in vapour absorption refrigeration system. Absorption rate of the bubble type absorber is found to be always higher than that of the falling film mode [9]. Bubble type absorber provides better heat and mass transfer coefficient, also good wettability and mixing between the liquid and the vapour [9]. Hence, study of bubble absorber is attempted.

The absorption process is characterized by simultaneous heat and mass transfer phenomena. These mechanisms, though complicated, influence the system performance significantly. Elperin and Fominikh [12] studied combined heat and mass transfer mechanisms at all stages of bubble growth and rise in a bubble absorber, which can be useful in design calculations of gas–liquid absorbers. Kang et al. [11] developed an experimental correlation of mass transfer coefficient for ammonia–water bubble absorption. Kang et al. [10] also developed a correlation for initial bubble diameter, which can be used to calculate the interfacial area in the design of ammonia–water bubble absorber. Lee et al. [13] performed both the numerical and experimental analyses in the absorption process of a bubble absorber. Numerical model in these studies can be used for the optimum design of absorber. Merrall and Perez-Blanco [4] developed an analytical model to predict bubble dynamics in binary sub-cooled solutions. This model improves the understanding of bubble absorption dynamics.

Sujatha et al. [5,6] carried out numerical analysis in a vertical tubular bubble absorber working with R22 as refrigerant and five organic fluids namely DMF, DMA, DMETEG, DMEDEG and NMP as absorbents. The model is validated by comparing with the results available in the literature. Based on these results, a correlation for mass transfer coefficient has been suggested for the vertical tubular bubble absorber. Sujatha et al. [7] have also carried out experimental studies on a vertical tubular bubble absorber working with R22–DMF. The experimental pressure drop, heat transfer coefficient and mass transfer coefficient are compared with the results obtained from the numerical model.

Kang et al. [8] developed a model for a bubble absorber with a plate type heat exchanger by considering the combined heat and
mass transfer analysis in both liquid and vapour regions. All geometric variables such as distance between two plates, number of plates, and width of the plates could be selected optimally for given thermal conditions by the developed design model for ammonia–water combination.

Staicovici [1–3] used non-equilibrium phenomenological theory to evaluate gas–liquid interaction. The design of bubble absorber, based on non-equilibrium thermodynamics could be suited to a modern compact plate type construction and offer better absorption efficiency and minimum pressure loss on the gas side.

The present work is based on Staicovici’s theoretical studies on bubble interaction and presents the results of an analytical study of R134a vapour absorption in R134a–DMF solution. For validation of the model, ammonia–water is used as working fluid. Maximum bubble radius obtained from this study is compared with experimental correlations and agreement is found to be good with ±3% deviation. Heat and mass transfer rates obtained from this model are compared with the literature results and the agreement is found to be good with the deviation in the range of ±3–13.7%.

2. Model description

As shown in Fig. 1, R134a vapour coming from the evaporator of the vapour absorption refrigeration system is allowed to pass through a header, at a flow rate of \( m_b \). Vapour in the header has pressure \( p_{gb} \), temperature \( T_g \) and volume \( V_h \). From the header, the vapour is distributed and injected into R134a–DMF liquid solution at the flow rate of \( m_b \) through nozzles (diameter \( d \)) and absorbed. Pressure, temperature and mole fraction of the vapour injected into the liquid are \( p_b, T_b \) and \( y \), respectively. Pressure, temperature and mole fraction of the solution at the gas–liquid interface and at the absorber boundary surface are, respectively, \( p_l, T_l \) and \( x \) and \( p_{l∞}, T_{l∞} \) and \( x_{l∞} \).

3. Governing equations

Problem is formulated from the dynamics of a single bubble, namely a spherical symmetry flow and uniformity of gas pressure in the bubble. For a spherically symmetric extension of a gas bubble in an infinite viscous fluid and for homobaric approximation (gas pressure is uniform in the bubble), only the motion of outer
liquid is of interest. Moreover, the following assumptions are considered for the liquid and gas medium: (a) the liquid gravitational forces are neglected; liquid is Newtonian, viscous and incompressible fluid; (b) the refrigerant vapour in the header and bubble is considered as an ideal gas; as the bubble evolves the temperature of refrigerant vapour in the header and bubble remains constant and does not involve in the heat transfer process; the gas–liquid interaction is an evolitional phenomenon, deemed to be an open system.

In the liquid phase, continuity, Navier–Stokes, heat and mass transfer equations are considered. In the gas phase, First law of thermodynamics and Bernoulli’s equation are considered. In the gas–liquid interface, equations of motion, energy equation, gas mass balance and liquid mass balance equations are considered.

Staicovici [3] has assumed the physical and thermo-physical properties of liquid medium as constants with respect to time. In this work, these properties (thermal conductivity, specific heat, density, surface tension and diffusion coefficient) are considered as functions of liquid temperature and used as variables in the numerical study.

3.1. Liquid phase equation

The equations describing the liquid motion in the spherical coordinates have the following forms [16]:

\[ \frac{\partial}{\partial t}(\rho^2 \mathbf{v}) = 0 \]  
(1)

\[ \text{Navier–Stokes equation for laminar flow is} \]

\[ \rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\frac{\partial \mathbf{p}}{\partial t} + 2\mu \nabla^2 \mathbf{v} \]  
(2)

3.2. Interface equations

The following governing equations are arrived at the interface [13]:

**Motion**

\[ p_{l,x} = p_h \left( \frac{2\sigma}{R} \right) + p_h \left( v_g - v_{l-x} \right) \left( v_g - \frac{\partial R}{\partial t} \right) \]  
(3)

**Gas mass balance**

\[ j_t \rho_l \frac{\partial V}{\partial t} + j_r \rho_h \left( v_h - \frac{\partial R}{\partial t} \right) S = 0 \]  
(4)

\[ \frac{\partial V}{\partial t} = 4\pi R^2 \frac{\partial h}{\partial t} \]  
(5)

**Liquid mass balance**

\[ j_t \rho_l \frac{\partial V}{\partial t} + j_r \rho_h \left( v_h - \frac{\partial R}{\partial t} \right) S = \rho_l \left( \frac{\partial V}{\partial t} \right) \]  
(6)

where \( \rho_l \) is the concentration gradient in the radial direction, \( \partial x \) is the actual increase of the liquid molar fraction \( x \) at interface.

**Energy balance**

\[ j_t \rho_l \frac{\partial V}{\partial t} C + K \frac{\partial T_l}{\partial t} S = \rho_l \left( \frac{\partial V}{\partial t} \right) c_p \partial T_l \]  
(7)

where \( \frac{\partial T_l}{\partial t} \) is the temperature gradient in the radial direction, \( \partial T_l \) is the actual increase of the liquid temperature at interface and \( C \) is the local thermal capability of the binary mixture [11].

3.3. Gas phase equations

Applying First law of thermodynamics for the gas in the header

\[ (m_h - nm_h)h_g = \frac{\partial p_{gh}}{\partial t} V_h \]  
(8)

Applying Bernoulli equation to the gas flow in the header

\[ m_h = A \sqrt{\rho_h (p_{gh} - p_g)} \]  
(9)

**Mass balance in the bubble**

\[ m_h - j_r \rho_l \frac{\partial V}{\partial t} = \rho_h \frac{\partial V}{\partial t} \]  
(10)

3.4. Phenomenological equations

**Reduced mass transfer rate**

\[ j_r = \frac{p_g}{\rho_l c_p T_g} \]  
(11)

**Reduced thermodynamic force**

\[ TF_r = \left[ (s_{gr} - s_{lr}) - (g - x) \left( \frac{\partial s_{gr}}{\partial x} \right) \right] + \frac{1}{T_{gr} - T_{lr}} \]  
(12)

**Reduced phenomenological coefficient**

\[ L_r = \frac{j_r}{TF_r} \]  
(13)

Initial values of \( j_r \) and \( TF_r \) are calculated using Eqs. (11) and (12) and \( L_r \) is found using Eq. (13). Keeping \( L_r \) constant for the entire absorption process, \( TF_r \) can be expressed in implicit form in Eq. (12) and determined by an iterative procedure for each time step. Subsequently \( j_r \) can also be calculated from Eq. (13) for each time step.

4. Model equations

The solution to Eq. (1), by integration results in

\[ V = \frac{\partial R}{\partial T} \left( \frac{R^2}{T} \right)^2 \]  
(14)

Solving Navier–Stoke’s equation by neglecting viscous term and using liquid mass balance at the interface, results in

\[ \frac{\partial R}{\partial T} = \left[ \left( p_{gh} - \frac{m_h^2}{A^2 \rho_h} - 2\sigma \right) \frac{1}{\rho_l} \left( \frac{\partial V}{\partial t} \right)^2 \left( j_r \rho_h - 1 \right) \right] \frac{1}{T(1 - j_r)} \]  
(15)

From Eq. (8).

\[ \frac{\partial p_{gh}}{\partial t} = (m_h - nm_h) \frac{h_g}{V_h} \]  
(16)

Analysis of thermodiffusion in the bubble absorption [18] shows that Soret and Dufour effects are negligible. Hence, heat and mass
transfer rates may not be coupled, resulting in pure diffusion and pure conduction, given as below:

\[ \frac{\partial x}{\partial t} + \frac{\partial}{\partial x} \left( \frac{R}{R} \right) \frac{\partial x}{\partial x} = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial x}{\partial r} \right) \]  \hspace{1cm} (17)

\[ p_i C_p \left( \frac{\partial T_i}{\partial t} + \frac{\partial}{\partial x} \left( \frac{R}{R} \right) \frac{\partial T_i}{\partial x} \right) = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial T_i}{\partial r} \right) \]  \hspace{1cm} (18)

The above equations are solved for modeling the bubble absorption. Eqs. (15) and (16) are solved to determine the bubble radius \( R \), rate of change in bubble radius \( \frac{\partial R}{\partial t} \), and second derivative of bubble radius \( \frac{\partial^2 R}{\partial t^2} \) at the interface and far from the interface or absorber boundary surface.

5. Initial and boundary conditions

To complete the model formulation, initial and boundary conditions must be specified. The initial conditions are adopted as follows:

At \( t = 0; \ r \geq R \):

\[ R(0) = R_0; \quad \frac{\partial R}{\partial t}(0) = \nu_{p,R}(0) = 0; \quad T_i(0, \ r) = T_\infty; \quad x(0, \ r) = x_\infty \]

\[ p_{g,i}(0) = p_{\infty} + 2\sigma T_\infty \frac{R}{K_T}; \quad p_{\beta}(0) = p_{\infty} + 2\sigma T_\infty \frac{R}{K_T}; \quad p_i(0, \ r) = p_\infty \]

The boundary conditions are specified at the interface and far from the interface or absorber boundary surface.

At interface, \( t > 0; \ r \geq R \):

\[ \delta x = (y - x)_{\delta} + D_{\text{eff}} \frac{\delta x}{\delta t}; \quad \delta T_i = \frac{1}{C_p} \left( j \cdot c + \frac{K T'}{p_i} \right) \]

At absorber boundary surface, \( t \geq 0 \):

\[ p_i = p_{\infty}; \quad x = x_\infty; \quad T_i = T_\infty \]

When the absorber is provided with a cooling system, coolant temperature can be chosen at the surface.

6. Numerical solution

In the mathematical model presented in Section 4, the non-linear ordinary differential equations (15) and (16) are solved by means of initial value problem solvers using explicit Runge–Kutta method with fourth-order accuracy. In this method, the bubble parameters are computed at a particular time step using the solution arrived at the immediately preceding time step as an input. The time steps \( 1 \times 10^{-3}, 1 \times 10^{-4} \) and \( 1 \times 10^{-5} \) s were used in the computation. For these time steps, the bubble radius varied by \( 0.5, 1 \times 10^{-3} \) and \( 1 \times 10^{-6} \) mm, respectively, in each step of computation. For the calculated bubble life span, the time step \( 1 \times 10^{-3} \) s gives less computing time and less accurate results, \( 1 \times 10^{-4} \) s takes optimum computing time and gives better accurate results and \( 1 \times 10^{-5} \) s takes more computing time and gives no improved results than that for \( 1 \times 10^{-4} \) s. So the time step \( 1 \times 10^{-5} \) s is chosen. The partial differential equations (17) and (18) are solved by using finite difference methods with fully implicit technique. The time derivative is approximated by forward differencing and the spatial derivatives are approximated by central differencing. First-order accuracy in time and second-order accuracy in space are achieved. Fully implicit techniques are unconditionally stable, without any constraints on choices of time step or grid spacing. An adaptive computational grid must be employed to handle the moving liquid–vapour interface. At each new time step the computational grid is adapted for each new bubble diameter. Once a new bubble radius is calculated at the new time step, the overall solution method steps in time by assigning node values based on the previous grid at the \( n + 1 \) time level. Staicović [1] noted that the liquid mass fraction and temperature fields diffuse over a radial distance of 1 mm. However, for accurate analysis, the computational domain was spaced over 2 mm. While studying the liquid mass fraction and temperature fields by adopting various values of spatial grid size \( \Delta r \) in the computational domain, it was noted that the liquid mass fraction and temperature diffused to reach the absorber surface conditions within 0.5 mm of the domain. When \( \Delta r \) was kept as \( 1 \times 10^{-3} \) and \( 1 \times 10^{-5} \) m, the surface conditions were reached within 5 and 50 radial nodes, respectively, and the results were not accurate for analyzing the liquid mass fraction and temperature fields. When \( \Delta r \) was kept as \( 1 \times 10^{-6} \) and \( 1 \times 10^{-7} \) m, the surface conditions were reached within 500 and 5000 radial nodes. \( \Delta r = 1 \times 10^{-6} \) m takes optimum computing time and gives better accurate results whereas \( \Delta r = 1 \times 10^{-7} \) m takes more computing time and gives no improved results than that for \( 1 \times 10^{-6} \) m. Hence, based on the calculated initial bubble diameter and boundary conditions at the bubble interface and absorber boundary surface, 2000 radial nodes were adopted with \( \Delta r = 1 \times 10^{-6} \) m.

The necessary properties for R134a–DMF solution namely liquid density, surface tension, diffusion coefficient, thermal conductivity, specific heat, etc., have been calculated as functions of liquid temperature, at each time step, using experimental correlations from [17] with 3–5% error. The liquid enthalpy has been calculated from the equations of Nezu et al. [19]. The density and enthalpy of R134a gas have been calculated from the equations of Yokozeki [14].

7. Results and discussion

To validate the model, ammonia–water is used as the working fluid and the model results have been compared with the literature experimental results. Results have been obtained by means of a computer code written in MATLAB.

Kang et al. [9] used the following thermal conditions in the hydrodynamic fluid (ethylene glycol 35% aqueous solution) cooled absorber for their GAX system using ammonia–water.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid temperature (K)</td>
<td>347.6</td>
<td>321.9</td>
</tr>
<tr>
<td>Vapour temperature (K)</td>
<td>285.3</td>
<td></td>
</tr>
<tr>
<td>Coolant temperature (K)</td>
<td>319.5</td>
<td>329.0</td>
</tr>
<tr>
<td>Liquid mass flow rate (kmol h(^{-1}))</td>
<td>3.91</td>
<td>5.25</td>
</tr>
<tr>
<td>Vapour mass flow rate (kmol h(^{-1}))</td>
<td>2.42</td>
<td>1.09</td>
</tr>
<tr>
<td>Coolant mass flow rate (kg h(^{-1}))</td>
<td>1360.8</td>
<td>1360.8</td>
</tr>
<tr>
<td>Liquid concentration (g g(^{-1}))</td>
<td>0.2795</td>
<td>0.4558</td>
</tr>
<tr>
<td>Vapour concentration (g g(^{-1}))</td>
<td>0.9873</td>
<td></td>
</tr>
<tr>
<td>System pressure (kPa)</td>
<td>557.2</td>
<td>557.2</td>
</tr>
</tbody>
</table>

The model was simulated for the above inlet conditions. The absorption rate predicted by the model is \( 6.1 \times 10^{-3} \) kg s\(^{-1}\), whereas the calculated absorption rate from the GAX system is \( 6.29 \times 10^{-3} \) kg s\(^{-1}\), with 3% difference. The coupled heat rate predicted by the model is 7.85 kW whereas the calculated heat rate from the GAX system is 9.1 kW, with the difference of 13.7%.

The bubble radius at the end of its life span, predicted from the model is 7.26 mm. Bubble radius calculated from the experimental correlation developed by Kang et al. [11] is 7.48 mm, overestimated by 3%. The bubble radius calculated from the correlations proposed by Bhavaraju et al. [15] is 10.16 mm, overestimated by 28%. Kang et al. reported that Bhavaraju’s correlations overestimated their experimental observed bubble radius for ammonia-water mixture by about 20%.
Then the model is simulated for R134a/DMF. The following range of input data is used for the model analysis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption pressure</td>
<td>163–412 kPa</td>
</tr>
<tr>
<td>Gas mass flow rate</td>
<td>0.91–2.11 g s⁻¹</td>
</tr>
<tr>
<td>Gas inlet temperature</td>
<td>–10–10 °C</td>
</tr>
<tr>
<td>Gas mole fraction</td>
<td>0.99</td>
</tr>
<tr>
<td>Liquid inlet temperature</td>
<td>17–60 °C</td>
</tr>
<tr>
<td>Initial liquid mass fraction</td>
<td>0.2–0.4 kg kg⁻¹</td>
</tr>
</tbody>
</table>

At low and continuous gas mass flow rates \((10^{-4}–10^{-5} \text{ g s}^{-1})\), the bubble dynamics takes place in two stages: periodic bubble growth to a maximum volume and collapse to a zero volume without detaching itself from the nozzle. At high and continuous gas mass flow rates, the bubble collapse does not occur. Instead a high frequency of bubble growth from a minimum volume to a maximum volume without detachment from the nozzle occurs \([1,2]\). Fig. 2 shows the numerical solution for the bubble dynamics during absorption. The bubble radius continuously increases till the bubble interface reaches equilibrium conditions and then, replaced by next new bubble. Bubble interference is not considered since bubble is not detached from the nozzle.

The actual mass transfer rate is calculated as
\[
\dot{j_r} = \rho_1 \frac{\partial V}{\partial t}
\]

The coupled heat transfer rate is calculated as
\[
\dot{Q} = \dot{j_r} \rho_1 \frac{\partial V}{\partial t}
\]

In Fig. 3, actual mass transfer rate, coupled heat transfer rate and bubble feed rate \((m_b)\) continuously increase. The rate of increase slows down when bubble interface approaches equilibrium conditions. In Fig. 4, bubble gas pressure and header gas pressure continuously increase, since bubble feed rate is higher than the actual absorption rate. When heat and mass transfer rates slow down, both pressures start decreasing. The cumulative absorbed mass and heat transfer rates against bubble growth time are plotted in Fig. 5. Fig. 6 shows the solution concentration and temperature at bubble interface against bubble growth time. The reduced mass transfer rate and reduced thermodynamic force plotted in Fig. 7 continuously increase till bubble interface reaches equilibrium conditions. Fig. 7 also shows that actual heat and mass transfer coefficients at bubble interface continuously decrease.

![Fig. 2. Bubble dynamics of vapour during absorption process.](image)

![Fig. 3. Variation of heat and mass transfer rates during absorption process.](image)
Figs. 8 and 9 show the comparison of absorption and heat transfer rates calculated using temperature dependent thermo-physical properties with those calculated using constant thermo-physical properties for various gas flow rates. The absorption
The rate calculated using temperature dependent thermo-physical properties is more than that calculated using constant thermo-physical properties by 4–7% and the heat transfer rate calculated using temperature dependent thermo-physical properties is less than that calculated using constant thermo-physical properties by 3–5%.

Fig. 7. Variation of actual mass and heat transfer coefficients, reduced mass transfer rate and reduced thermodynamic force at interface during absorption process.

Fig. 8. Comparison of absorption rate with temperature dependent and constant thermo-physical properties for various gas flow rates.

Fig. 9. Comparison of heat transfer rate with temperature dependent and constant thermo-physical properties for various gas flow rates.
In Fig. 10, maximum bubble radius and absorption rate increase as gas mass flow rate increases. In Fig. 11, heat transfer rate also increases as gas mass flow rate increases due to higher absorption rates. Absorption efficiency increases at higher gas mass flow rates due to increase in liquid mass fraction at absorber outlet at higher absorption rates. Fig. 12 depicts variation of average mass and heat transfer coefficients with gas mass flow rate. The average mass transfer coefficient increases with gas mass flow rates due to the increase in absorption rate at higher gas mass flow rates. The average heat transfer coefficient also increases with higher gas flow rates due to increase in coupled heat transfer rate at higher absorption rates.

In Fig. 13, bubble life decreases at higher solution inlet temperatures since the bubble interface reaches the equilibrium temperature faster. The maximum bubble radius also decreases at higher solution inlet temperatures due to reduction in bubble life. In Fig. 14, absorption rate decreases as solution inlet temperature increases due to reduction in bubble life. The heat transfer rate also decreases with higher solution inlet temperatures due to lower absorption rates. Fig. 15 depicts variation of average mass and heat transfer coefficients with solution inlet temperature. The average mass transfer coefficient increases with higher solution inlet temperatures. At high solution inlet temperatures, reduction in average bubble volume and concentration potential at bubble interface is more than reduction in absorption rate. The equilibrium conditions are reduced and are nearer to the initial conditions at high solution inlet temperatures, indicating higher average absorption. This results in higher values of average mass transfer coefficients. The average heat transfer coefficient also increases with higher solution inlet temperatures. At high solution inlet temperatures, reduction in average bubble volume and temperature potential at bubble interface is more than reduction in heat transfer rate. Since the equilibrium conditions are nearer to the initial conditions at high solution inlet temperatures, higher values of average heat transfer coefficients are indicated. In Fig. 16, absorption efficiency increases as solution inlet temperature increases due to reduction in equilibrium mass fraction at bubble interface, whereas interface concentration at maximum bubble radius decreases as solution inlet temperature increases due to reduction in bubble life.

Fig. 17 presents variation of maximum bubble radius with solution pressure at different initial concentrations of refrigerant in solution. At lower pressures (1–2.5 bar), maximum bubble radius increases and reaches a maximum value. As pressure increases, maximum bubble radius starts decreasing and reaches a constant value. The maximum bubble radius decreases as initial
The concentration of refrigerant in solution increases. Fig. 18 shows variation of bubble life with solution pressure at different initial concentrations of refrigerant in solution. The bubble life increases as solution pressure increases and decreases as initial concentration of refrigerant in solution increases. The reason is that equilibrium temperature at bubble interface increases at high
solution pressures and decreases at high initial concentrations of refrigerant in solution. Fig. 19 depicts variation of absorption rates with solution pressure at different initial concentrations of refrigerant in solution. As solution pressure increases, absorption rate increases. The rate of increase is more at lower pressures and less at higher pressures due to proportional rate of change in bub-
ble life (Fig. 18). The absorption rate decreases at high initial concentrations of refrigerant in solution due to decrease in bubble life. Fig. 20 portrays variation of heat transfer rates with solution pressure at different initial concentrations of refrigerant in solution. As solution pressure increases, heat transfer rate increases. The rate of increase is more at lower pressures and negligible at higher pressures due to proportional rate of change in absorption rate (Fig. 19). The heat transfer rate decreases at high initial concentrations of refrigerant in solution due to decrease in absorption rate. The bubble interface concentration and temperature at maximum bubble volume increase as solution pressure increases (Fig. 21) due to increase in bubble life at high pressures. Fig. 22 describes variation of average mass transfer coefficient with solution pressure at different initial concentrations of refrigerant in solution. Though absorption rate is high, average mass transfer coefficient decreases as solution pressure increases due to increase in concentration potential at maximum bubble volume, which results from increase in bubble interface concentra-

![Fig. 18. Effect of solution pressure on maximum bubble life at different solution initial concentrations.](image1)

![Fig. 19. Effect of solution pressure on absorption rate at different solution initial concentrations.](image2)

![Fig. 20. Effect of solution pressure on heat transfer rate at different solution initial concentrations.](image3)
tion (Fig. 21). Also, the equilibrium conditions are reduced and are nearer to the initial conditions at lower solution pressures, indicating higher values of average mass transfer coefficients. The average mass transfer coefficient increases as initial concentration of refrigerant in solution increases due to decrease in concentration potential at maximum bubble volume. Fig. 23 describes variation of average mass transfer coefficient with solution pressure at different initial concentrations of refrigerant in solution. Though heat transfer rate is high, average heat transfer coefficient decreases as solution pressure increases due to decrease in temperature potential at maximum bubble volume, which results from increase in bubble interface temperature (Fig. 21). Since the equilibrium conditions are nearer to the initial conditions at lower solution pressures, higher values of average heat transfer coefficients are indicated. The average heat transfer coefficient increases as initial concentration of refrigerant in solution increases due to decrease in temperature potential at maximum bubble volume. Fig. 24 illustrates variation of absorption efficiency with solution pressure at different initial concentrations of refrigerant in solution. The efficiency decreases as solution pressure increases.
due to increase in equilibrium concentration at bubble interface at high pressures. At low pressures, efficiency increases as initial concentration of refrigerant in solution increases, due to increase in liquid mass fraction at absorber outlet. At high pressures, efficiency variation is negligible for different initial concentrations of refrigerant in solution.

8. Conclusions

A phenomenological theory of heat and mass transfer is applied to model the absorption of the refrigerant R134a bubble in di-methyl formamide (DMF) solution. The necessary properties for R134a–DMF solution have been calculated as functions of liquid temperature using experimental correlations. The bubble dynamics during bubble growth and collapse are studied from the model. Liquid concentration, temperature, heat and mass transfer rates, local heat and mass transfer coefficients are estimated at the bubble interface. The absorption rate, coupled heat transfer rate, average heat and mass transfer coefficients over the entire bubble life span are also calculated.

For validation of the model, results available in the literature are compared. The model uses ammonia–water as the working fluid. The maximum bubble radius determined from this study is compared with available experimental correlations. The heat and mass transfer rates obtained from this model are compared with the literature results. The results are in good agreement with the predictions of the model.

The following are results of numerical study of R134a–DMF bubble absorption process:

- Heat and mass transfer rates, average heat and mass transfer coefficients and absorption efficiency increase as gas mass flow rate increases.
- Heat and mass transfer rates decrease and average heat, mass transfer coefficients and absorption efficiency increase as solution inlet temperature increases.
- Gas inlet temperature has little influence on the above parameters
- Heat and mass transfer rates increase as solution pressure increases and decrease as solution initial concentration increases.
- Average heat and mass transfer coefficients decrease as solution pressure increases and increase as solution initial concentration increases.
- Absorption efficiency decreases as solution pressure increases. At low solution pressures, efficiency increases as solution initial concentration increases. At high pressures, efficiency does not vary as initial concentration increases.

References