Assessment of Mixture Boiling Heat Transfer Correlations for Ammonia/Water Mixture

A. Sathyabhama[1] and Dr. T.P. Ashok Babu[2]

[1]NITK, Faculty MSRIT, Vidya Soudha, MSRIT post, MSR Nagar, B'lore-560054 Karnataka, India
[2]Department of Mech. Eng. NITK, Surathkal Post Srinivasnagar,
Mangalore 575 025 Karnataka, India

The aim of this work is to present a critical examination of both the available experimental data and the performance of the available mixture boiling heat transfer correlations for ammonia/water mixture. First, a selection and comparison of the experimental database found in the open literature at the mentioned working conditions is presented. Subsequently, after a short description of the most relevant heat transfer correlations, and in accordance with the selected data, a detailed analysis of the performance of each correlation is carried out. Results show a small divergence between the experimental data sets and conclude that the presently available correlations show considerable discrepancies in heat transfer coefficients within the selected conditions. © 2009 Wiley Periodicals, Inc. Heat Trans Asian Res, 38(7): 401–408, 2009; Published online 14 September 2009 in Wiley InterScience (www.interscience. wiley.com). DOI 10.1002/htj.20262

1. Introduction

Ammonia/water absorption refrigerating systems are receiving increasing attention as an environmentally safe replacement for the CFC-based compression cycles. This has created increasing research activities in pool boiling heat transfer of this mixture. However, detailed literature review shows that experimental data on boiling heat transfer coefficients of ammonia/water mixture are scarce. Mixture boiling heat transfer correlations with an acceptable level of accuracy have been reported and validated extensively. However, in the case of ammonia–water mixture, there is still an important lack of fundamental and empirical information.

Nomenclature

g: gravitational acceleration, ms^{-2}
h_{fg}:   latent heat of vaporization, $J \cdot kg^{-1}$
h: nucleate boiling heat transfer coefficient, $W \cdot m^{-2} K^{-1}$
P: pressure, kPa
q: heat flux, $W \cdot m^{-2} K^{-1}$
T: temperature, K

x: mole fraction in liquid phase
y: mole fraction in vapor phase

Greek Symbols

Δ*T*:   temperature difference, K
ρ: density, kgm^{-3}
σ: surface tension, Nm^{-1}

Subscripts

id: ideal
L: liquid
s: saturation
v: vapor

2. Ammonia–Water Available Experimental Data

Very few experimental studies on boiling heat transfer coefficient for ammonia/water mixture have been published in the open literature.

Inoue et al. [1] measured the pool boiling heat transfer coefficients of ammonia/water mixture and its pure components on a horizontal platinum wire (diameter of 0.3 mm, 37 mm length) at the pressure of 0.4 to 0.7 MPa with heat flux varying from 0.4 to 1.5 MW/m^2 and the mass fraction from 0 to 1. The wire was heated using a direct electric current. Arima et al. [2] obtained data using an experimental device where the heating surface was a horizontal flat circular surface of silver with a diameter of 10 mm. The flat surface was polished with No. 800 emery paper and had a mean surface roughness of 1 mm. With this surface, the authors obtained the boiling curve for the ammonia/water mixture and its pure components at a pressure level from 1 to 15 bar with heat flux varying from 0.1 to 2.0 MW/m^2. In summary, 157 experimental heat transfer coefficient data are selected from these two tests for the present work.

2.1 Comparative analysis between selected experimental data

Figure 1 shows the selected experimental heat transfer coefficient data plotted against heat flux. As can be seen, data of Inoue et al. [1] are slightly higher than the data of Arima et al. [2]. This
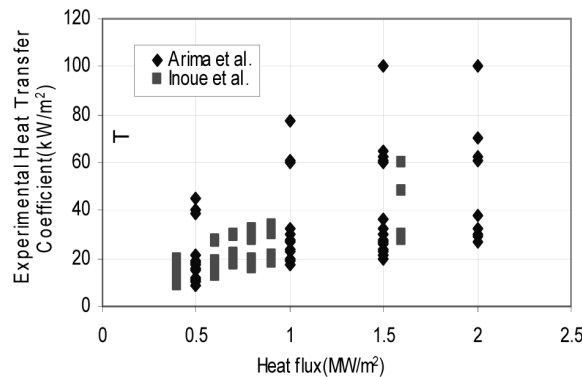

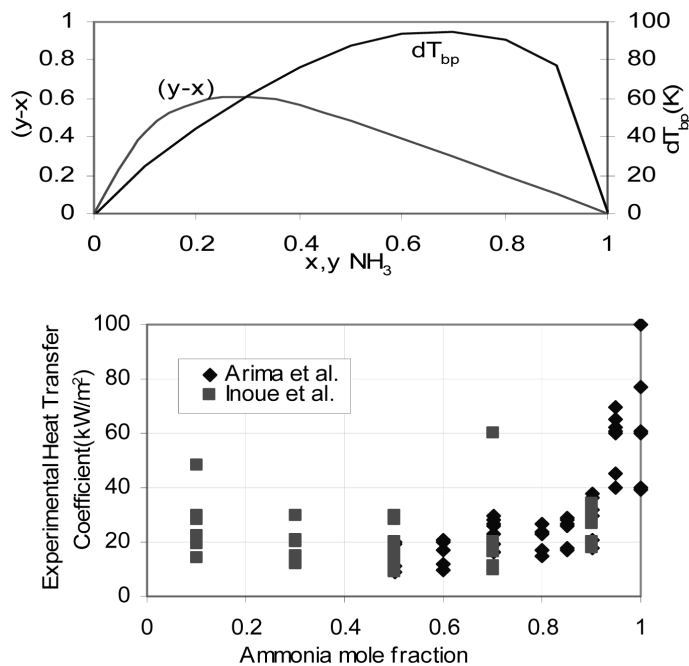Fig. 1. Selected test data plotted against heat flux.

Fig. 2. Effect of ammonia mole fraction on heat transfer coefficient.

difference in data may be due to the difference in the heating surface used in these tests, a thin platinum wire of 0.3 mm O.D in #1 and a circular surface of 10 mm O.D of silver in #2.

Figure 2 shows the effect of the mass fraction on the heat transfer coefficients, the temperature difference between boiling and dew points, ΔT_{bp}, and the molecular fraction difference between vapor and liquid, $(y_i - x_i)$. The coefficients in the mixtures become dramatically smaller than those in both single components, and in particular are steeply decreased in the vicinity of the single-component substances. The minimum values exist in wide range from $C = 0.3$ to 0.7 and would become independent of the fraction in this range. It is found that the trend in h against C is different from that in both ΔT_{bp} and $(y_i - x_i)$.

3. Available Correlations and Comparison with Experimental Data

3.1 Nucleate pool boiling of mixture

Mixture boiling plays an important role in many industrial processes. In general, chemical processes and separations involve binary or multi-component mixtures rather than pure components. Mixture boiling, however, involves several processes that do not occur in the boiling of pure components, which can be detrimental to a system. The rate of evaporation in a mixture is determined by the rate of mass diffusion as opposed to heat transfer. Because mass diffusion is slower than heat diffusion in the liquid, mass transfer of the more volatile component becomes the limiting process in bubble growth. As a result, heat transfer coefficients in a mixture can be significantly lower than those expected based on heat transfer coefficients of their pure components and the total surface area of a heat exchanger may need to be increased in order to transfer the same amount of heat.
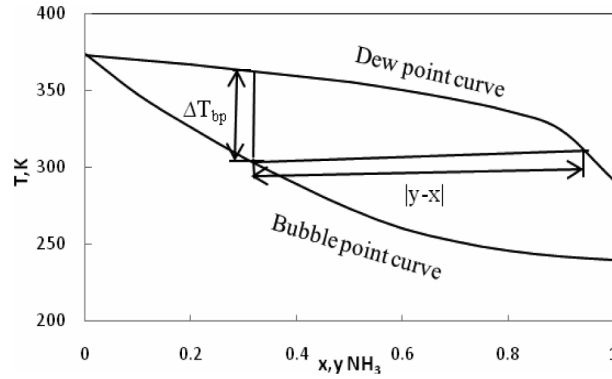
Fig. 3. Phase diagram of ammonia/water mixture at 1 bar.

Many nucleate boiling heat transfer correlations developed for mixtures use the composition difference between the vapor and liquid phases ($y_i - x_i$) and/or boiling range (ΔT_{bp}) as shown in Fig. 3 to account for the mixture effect. Generally, the mixture correlation can be expressed as follows:

$$\frac{h}{h_{id}} = \frac{1}{1 + K} \tag{1}$$

Here h_{id} is the ideal heat transfer coefficient defined using an ideal wall superheat ΔT_{id}, that is determined as a molar interpolation of the wall superheats for mixture components evaluated at the same heat flux as the mixture, that is

$$\Delta T_{id} = \frac{q}{h_{id}} = \frac{q}{\Sigma\left(\dfrac{x_i}{h_i}\right)} \tag{2}$$

or alternatively using mixture properties in empirical correlations applicable to pure liquids. The factor K, in general, is a function of thermophysical and transport properties of the mixtures, the vapor–liquid equilibrium relationship and the slope of the vapor pressure curve. It apparently takes into account slower bubble growth rates, smaller departure diameters, and non-linear variation of the mixture properties with composition. As for the factor K, several different kinds of K are proposed depending on different substances and combinations of mixtures. In this paper, only four of the well known correlations will be considered.

In 1969, Stephan and Körner [3] suggested the following equation for K:

$$K = [1 + A_o(0.88 + 0.12P)(y_1 - x_1)] \tag{3}$$

where P is in bar and A_o is a constant dependent on the particular binary system studied. Stephan and Körner found $0.42 \leq A_o \leq 3.56$ for 17 kinds of binary mixtures. They recommended the mean value of $A_o = 1.53$ for mixtures that are not listed in their table. Stephan and Körner's correlation is known

to work for 1 to 10 atmospheric pressures. The major drawback of Stephan and Körner's correlation, however, is that it requires different constant for each pair of binary mixture.

In 1983, Schlünder [4] developed a new boiling model that includes the effect of heat flux using a film theory diffusion model on the mass diffusion shell formed around a growing vapor bubble and suggested the following equation for K.

$$K = \left\{ 1 + \frac{h_{id}}{q} \left[(T_{s2} - T_{s1})(y_1 - x_1) \left(1 - \exp \frac{-B_o q}{\rho_L h_{fg} \beta_L} \right) \right] \right\} \quad (4)$$

where T_{s1} and T_{s2} are the saturation temperatures of the more volatile and less volatile components and B_o is a scaling factor relating the fraction of total heat flux converted to latent heat and is equated to unity. He assigned a fixed value of 0.0002 m/s for β_L, the liquid side mass transfer coefficient.

The Fujita–Tsutsui [5] correlation is based on a model that the drop of effective temperature difference is a main reason for heat transfer reduction in mixtures. They assumed that the bubble point temperature near the heating surface is not constant but variable as a function of heat flux. They determined this function in reference to their experimental data of seven different kinds of binary mixture including acqueous, organic, non-azeotropic, and azeotropic mixtures. The influence of heat flux was made dimensionless in their equation in order to extend their correlation to a wider use.

$$K = \left\{ 1 + \frac{\Delta T_{bp}}{\Delta T_{id}} \left[1 - \exp \left(\frac{-60q}{\rho_v h_{fg}} \left\{ \frac{\rho_v^2}{\sigma g (\rho_L - \rho_v)} \right\}^{1/4} \right) \right] \right\} \quad (5)$$

The K factor of the Inoue–Monde [6] correlation is given by

$$K = \left\{ 1 + \frac{\Delta T_{bp}}{\Delta T_{id}} \left[1 - 0.75 \exp \left(- \frac{0.75q}{10^5} \right) \right] \right\} \quad (6)$$

3.2 Comparison of the correlations against the experimental data

In this section, a comparison of the selected correlations is given. Four correlations are tested and compared against the experimental data. Correlations of Fujita–Tsutsui and Inoue–Monde include boiling range ΔT_{bp} as a parameter. The Stephan–Körner and Schlünder correlations include concentration difference between the vapor and liquid phases $(y_i - x_i)$ as a parameter. The thermophysical and transport properties required to compare the correlations were calculated by selecting appropriate correlations from Conde Engineering [7].

Table 1 presents the average deviation of each selected correlation against each selected data set. The best global deviation, 13.29%, was obtained with the correlation of Stephan–Körner. The Fujita–Tsutdui correlation also gives good prediction with average deviation of 14.45%. Less accurate predictions were obtained with the correlations of Inoue–Monde and Schlünder.

Figure 4 shows predictions obtained with the correlation of Stephan and Körner. This correlation shows a good agreement with the experimental data of Inuoe et al. Figure 5 shows

Table 1. Comparison of Experimental Data with the Correlations

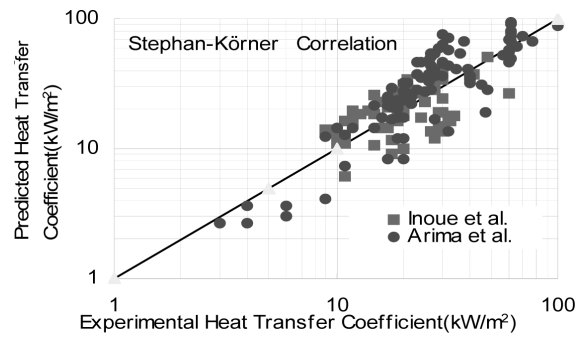|	Stephan and Körner		Schlünder		Fujita-Tsutsui		Inoue–Monde	
	Avg. dev.	Mean dev.	Avg. dev.	Mean dev.	Avg. dev.	Mean dev.	Avg. dev.	Mean dev.
Inoue et al.	1.901	27.16	69.87	70.14	-22.1	24.4	-59.54	59.54
Arima et al.	20.21	38.48	97.97	103.77	-9.31	24.52	-51.43	53.31
All data	13.29	35.36	87.68	91.36	-14.45	24.78	-54.91	56.07

Fig. 4. Comparison of Stephan–Körner correlation with experimental data.
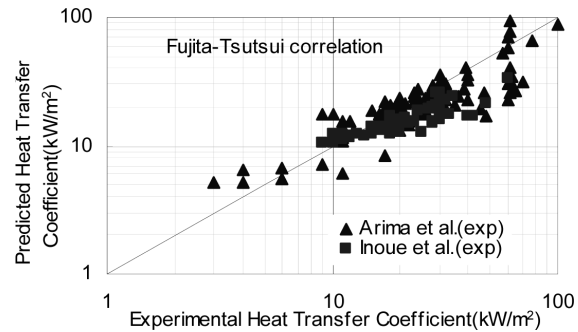

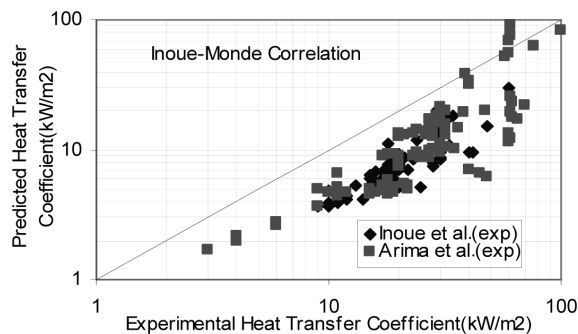Fig. 5. Comparison of Fujita–Tsutsui correlation with experimental data.

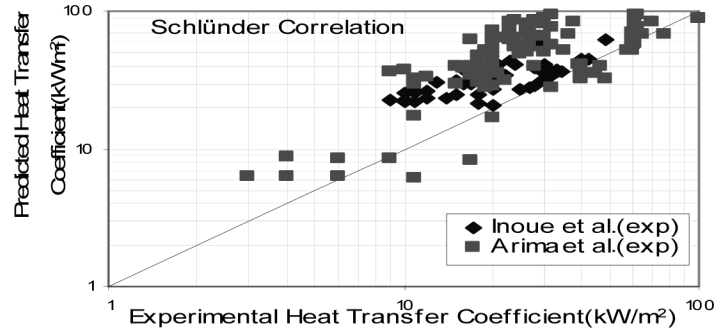Fig. 6. Comparison of Inoue–Monde correlation with experimental data.

Fig. 7. Comparison of Schlünder correlation with experimental data.

predictions obtained with the correlation of Fujita–Tsutsui. This correlation shows a good agreement with the experimental data of Arima et al. Figure 6 shows that the Inoue–Monde correlation underpredicts the data of both Inoue et al. and Arima et al. As seen from Fig. 7, The Schlünder correlation overpredicts the experimental data.

$$Avg. \ dev. = \frac{1}{n} \sum_{1}^{n} \left[\frac{(h_{cal} - h_{exp}) \times 100}{h_{exp}} \right] \tag{7}$$

$$Mean \ dev. = \frac{1}{n} \sum_{1}^{n} ABS \left[\frac{(h_{cal} - h_{exp}) \times 100}{h_{exp}} \right] \tag{8}$$

4. Conclusions

The aim of this work was to examine the experimental data and the available correlations for ammonia–water mixture nucleate pool boiling heat transfer. It was noticed that not much experimental data were available in the open literature. In spite of this limitation, some useful data could be found to pursue the objective of this paper, from the works of Arima et al. and Inoue et al. The small discrepancies between selected experimental data sets may be due to different test conditions, the shape of the heating elements—a thin wire of 0.3 mm O.D. in #1 and a horizontal flat plate of 10 mm O.D. in #2—and their material—platinum in #1 and silver in #2.

The performance of various mixture boiling correlations was studied. The selected data were compared against some of the well-known mixture boiling correlations that were mainly developed for other refrigerant mixtures. From this comparison, it is observed that none of the available correlations show a complete agreement when predicting data. The correlations of Inoue–Monde and Schlünder exhibit a considerable disagreement with the data. Better results were found with the correlations of Stephan–Körner and Fujita–Tsutsui. This failure may be attributed to the fact that Eqs. (3) to (6) are closely correlated with ΔT_{bp} and $(y_i - x_i)$, though the data are not related to both ΔT_{bp} and $(y_i - x_i)$, as shown in Fig. 2, and to the fact that ΔT_{bp} and $(y_i - x_i)$ of ammonia/water mixtures are much larger than those of mixtures that have been studied.

Based on the present study, it is suggested that further experimental works should be carried out in order to enlarge the present ammonia–water nucleate pool boiling heat transfer database. The experiments should be focused on the shape and material of the heating surface very similar to the tubes made of mild steel that are used in practice. The data will be essential in clarifying current data set discrepancies and in developing/modifying heat transfer coefficient correlations, which should preferably contain both ΔT_{bp} and $(y_i - x_i)$ as parameters.

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