

Experimental investigation in pool boiling heat transfer of ammonia/water mixture and heat transfer correlations

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ABSTRACT

The nucleate pool boiling heat transfer coefficient of ammonia/water mixture was investigated on a cylindrical heated surface at low pressure of 4–8 bar and at low mass fraction of $0 < x_{\text{NH}_3} < 0.3$ and at different heat flux. The effect of mass fraction, heat flux and pressure on boiling heat transfer coefficient was studied. The results indicate that the heat transfer coefficient in the mixture decreases with increase in ammonia mass fraction, increases with increase in heat flux and pressure in the investigated range. The measured heat transfer coefficient was compared with existing correlations. The experimental data were predicted with an accuracy of $\pm 20\%$ by the correlation of Calus&Rice, correlation of Stephan–Koorner and Inoue–Monde correlation for ammonia/water mixture in the investigated range of low ammonia mass fraction. The empirical constant of the first two correlations is modified by fitting the correlation to the present experimental data. The modified Calus&Rice correlation predicts the present experimental data with an accuracy of $\pm 18\%$ and the modified Stephan–Koorner correlation with an accuracy of $\pm 16\%$.

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1. Introduction

Ocean thermal energy conversion (OTEC) and hot spring thermal energy conversion cycles using a small temperature difference are expected to be promising for the utilization of a renewal energy sources. When operating with these cycles, ammonia/water mixture, which is a nonazeotropic is considered to be one of the best working fluids (Arima et al., 2002). Ammonia/water mixture is also used in vapor absorption refrigeration systems which are environmentally sound and energy-efficient alternatives to CFC-based, ozone-depleting space-conditioning systems. One of the methods that has been considered for an improvement of power plant efficiency, is to use a binary mixture as the working fluid in a thermodynamic cycle. The Kalina cycle (Kalina, 1984), has been suggested as a replacement for the Rankine cycle, with nearly all development and evaluations focusing on the use of ammonia and water as the binary fluid.

Properties of the ammonia/water system have been established, and the system is well suited to the high temperatures and pressures associated with a power plant and refrigeration system. Little effort however, has gone into investigating the heat transfer characteristics of ammonia/water mixture which are indispens-

able in the design of the components of the above mentioned systems.

Heat transfer coefficient in nucleate boiling of mixture can be much lower than that of an equivalent ideal pure fluid with the same physical properties as the actual mixture or the interpolated coefficient between the composed components. This is due to (a) reduction in temperature driving force because of increase in the boiling point of the micro-layer (the liquid layer trapped under a growing bubble) which is due to the preferential evaporation of the light components during bubble growth, (b) the mass diffusion of the light components to the micro-layer (caused by the preferential evaporation) which is much slower than the heat transfer, (c) the fact that there is usually a significant and non-linear variation in the mixture physical properties with composition and (d) the effect of composition on nucleation itself.

Fig. 1 illustrates example of the concentration dependency of some properties important in boiling heat transfer for ammonia/water mixture. The properties are expressed in a normalized form by division with the values of the less volatile component. For the calculation of these properties of the mixture, the calculation methods described in Conde Engineering (2006) were adopted along with the necessary data for pure components from ASHRAE Fundamentals (2005). Mixture properties are calculated for equilibrium conditions, thus they reflect the double effect of composition and variation in the bubble point temperature with composition. It is evident from Fig. 1 that non-linear variations are significant for ammonia/water mixture.

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Nomenclature

| | | | |
|----------|--------------------------------------------------------------------------------|----------------------|----------------------------------------------------|
| A | area (m^2) | T | temperature (K) |
| C_p | specific heat capacity ($\text{J kg}^{-1} \text{K}^{-1}$) | <i>Greek symbols</i> | |
| D | diffusivity ($\text{m}^2 \text{s}^{-1}$) | ΔT | temperature difference (K) |
| F_{PF} | pressure function | α | thermal diffusivity ($\text{m}^2 \text{s}^{-1}$) |
| g | gravitational acceleration (m s^{-2}) | β | contact angle ($^\circ$) |
| h_{fg} | latent heat of vaporization (J kg^{-1}) | ν | kinematic viscosity ($\text{m}^2 \text{s}^{-1}$) |
| h | nucleate boiling heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$) | ρ | density (kg m^{-3}) |
| k | thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$) | σ | surface tension (N m^{-1}) |
| M | molecular weight (kg kmol^{-1}) | μ | viscosity (Pa s) |
| nf | exponent in Gorenflo correlation | <i>Subscripts</i> | |
| P | pressure (bar) | id | ideal |
| P_c | critical pressure (kPa) | L | liquid |
| Pr | Prandtl number, $\frac{\mu c_p}{k}$ | s | saturation |
| p_r | reduced pressure (dimensionless), $\frac{p}{p_c}$ | v | vapor |
| q | heat flux ($\text{W m}^{-2} \text{K}^{-1}$) | | |
| Q | heat input | | |

There have been relatively few studies on the boiling heat transfer of ammonia/water mixture. Inoue et al. (2002), 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 0.4–0.7 MPa with heat flux varying from 0.4 to 1.5 MW/m² and the mass fraction from 0 to 1. The wire was heated using a direct electric current. Arima et al. (2003), 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 μm . With this surface the authors obtained the boiling curve for 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/m². It was found by both the authors that the mixture in the range of the mass fraction, $C = 0.2$ – 0.9 gives smaller heat transfer coefficients than its individual components.

The objective of this experimental work is to clarify the characteristics of the pool nucleate boiling heat transfer of ammonia/

water binary mixture at low pressure of 4–8 bar and at low mass fraction of $0 < x_{\text{NH}_3} < 0.3$. Based on the measured data the mixture effects on boiling heat transfer coefficients are discussed. Pressure and temperature limitations of the experimental setup did not allow data to be taken at full concentration range. Inability of the condenser to condense the large volume of vapor produced to maintain the constant pressure set the upper limit to heat flux in this work. Aqueous ammonia solution 30 and 25 wt.% of ammonia of 99.99% purity supplied by Nice chemicals was used in this study. Distilled water was used to dilute the aqueous ammonia. Typical model equations are applied to correlate the measured heat transfer coefficients.

2. Experimental setup

The schematic diagram of experimental setup is shown in Fig. 2. The unit consists of boiling vessel, water pump, vacuum pump, condenser coil and test section. Boiling vessel, 80 mm diameter and 200 mm long made up of SS 316 is fitted with SS 316 flanges

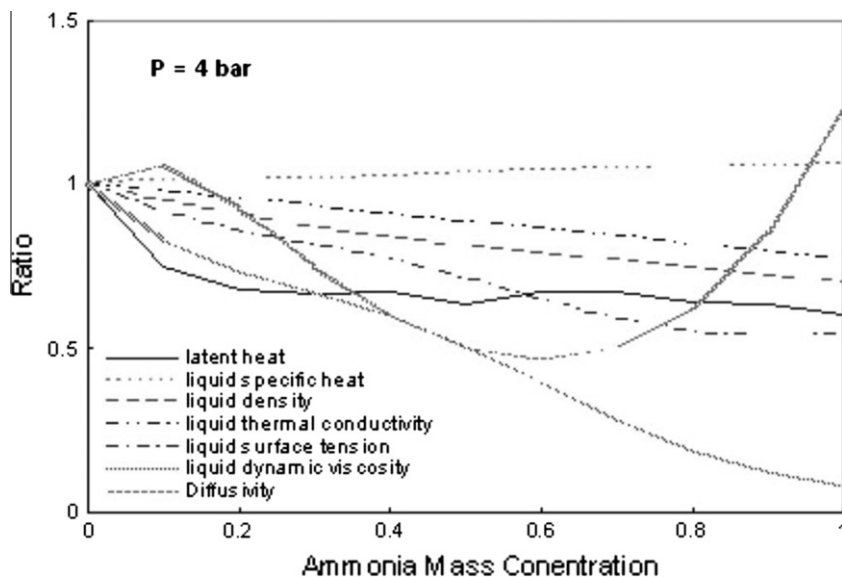


Fig. 1. Physical property variations with mixture composition.

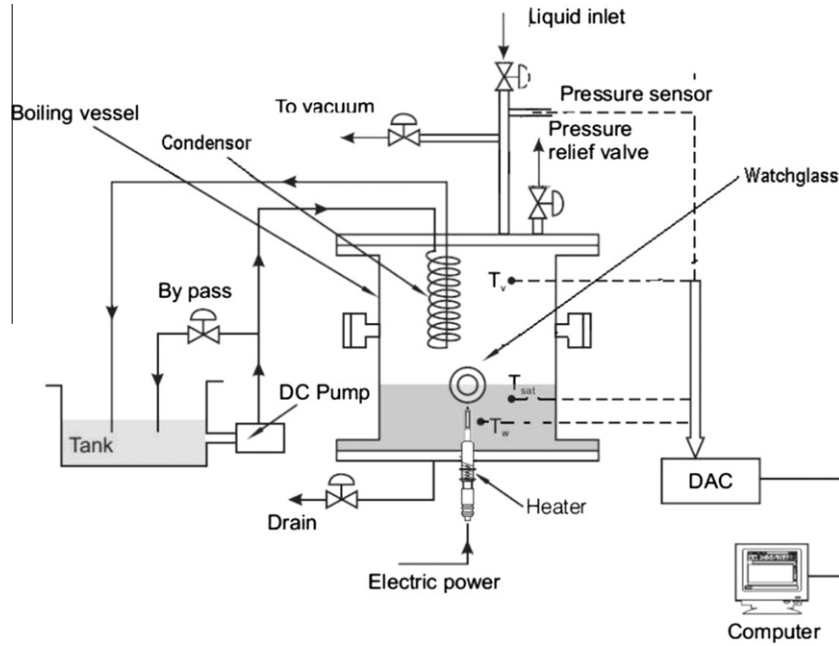


Fig. 2. Schematic diagram of experimental setup.

at the top and at the bottom as shown in Fig. 2. The vessel is fitted with two sight glasses to observe the boiling phenomena. The top flange has provisions for liquid charging, condenser cooling water inlet and outlet, vacuum pump, pressure transducer and thermocouples to measure liquid and vapor temperatures. Bottom flange has provisions for test section and drain. The test section is a rod heater mounted vertically within the boiling vessel. Boiling takes place at the outer surface of a cylindrical stainless steel rod with a diameter of 6 mm and a heating length of 20 mm. The test section is heated by an electrical heating element of 1 kW capacity. The heating element is connected to a wattmeter through a dimmerstat to read the power supplied to it. The details of the test heater are given in Fig. 3.

All temperatures of the system are measured using chrome alumel K type thermocouples. Two thermocouples are set in the liquid pool and vapor respectively. These liquid and vapor temperatures confirm the system being maintained at the saturation state during the experiments. Two thermocouples are embedded along the circumference of the heater close to the heating surface. The surface temperature is calculated by correcting the minor temperature drop due to the small distance between the heating surface and the thermocouple location using Fourier heat conduction equation.

The internal pressure of boiling vessel is measured by a pressure transducer. The power input to the test heater is measured using a wattmeter. The boiling vessel is well insulated. Electrical signals from the thermocouples, pressure transducer and wattmeter are processed by a data acquisition system.

3. Experimental procedure

3.1. Boiling

In order to start the boiling tests, the boiling vessel should be filled with the ammonia/water mixture. Before filling the chamber with the mixture, it was evacuated using a vacuum pump. The pressure of the boiling vessel was read on the logger display. Once the evacuation process was completed, the boiling vessel was filled with ammonia/water mixture. The amount of mixture was chosen so as to maintain a fixed level in all experiments. The test pressure was set in the logger. When the system was ready, the tests were started by giving a heat input to the test heater. The magnitude of the heat input was known from the wattmeter. All experimental runs were carried out with decreasing heat flux to avoid the

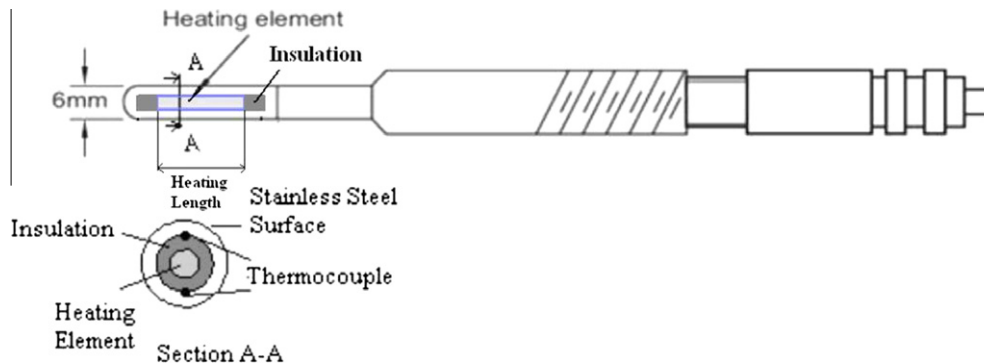


Fig. 3. Details of test heater.

hysteresis effect. Some runs were repeated twice and even thrice to ensure the reproducibility of the experiments.

Prior to the start of each boiling experiment, the heating surface was polished with 4/0 emery paper and the surface roughness as characterized by the center line average R_a was measured using a surface profilometer (Mitutoyo SurfTest). It was found to be $0.33 \mu\text{m}$. The R_a value has been extensively used in boiling literature to characterize the surface micro-roughness.

3.2. Regulation and data collection

The set pressure is maintained constant throughout an experiment by the combination of the cooling water pump, pressure transducer and a proportional integral derivative (PID) pressure controller. The PID senses the pressure level in the boiling chamber through pressure transducer and compares it with the set value fed to it by the researcher. To go from a higher pressure level to a lower pressure level, the PID sends a signal to cooling water pump to open the suction line and pump water through the condenser coils. The digital temperature indicator reads the spontaneous temperatures. In total it reads four temperatures, of the two thermocouples in the test section, and of the one in the liquid and the one in the vapor. The digital wattmeter displays the power input to the heater. The Data Acquisition Unit logged data from all thermocouples as well as recorded the boiling vessel pressure, and heater supply power. Data was then transferred through the general programming interface bus data link to a computer. A custom MATLAB program was developed to save the results and chart the data as it was acquired.

4. Calculations

Heat input Q is a known quantity as there can be no losses since the test heater is completely immersed in the liquid. Then heat flux, $q = \frac{Q}{A}$, where A is the surface area of the test section. Heat transfer coefficient between the surface and the liquid is calculated by applying Newton's law of cooling

$$h = \frac{q}{T_w - T_s} \quad (1)$$

where T_s is the saturation temperature of the liquid at the corresponding pressure, and T_w is the surface temperature of the test section.

5. Experimental uncertainty

All chrome alumel K type thermocouples used in this study have an accuracy of $\pm 0.5\%$ full scale. The pressure transducer has an accuracy of ± 0.5 full scale. The power input to the heater is measured by an accurate digital power meter of accuracy ± 1 W. The uncertainty in temperature measurement is ± 1.25 °C. Uncertainty in length and diameter measurement is ± 0.1 mm. The resulting uncertainty in the area of the heated surface is 1.74%. The Kline and McClintock (1953) technique was used to estimate the uncertainty for the derived quantities. The resulting maximum uncertainty in the heat flux was 1.94%. The maximum uncertainty in the wall superheat values was 10.71%. The maximum uncertainty in the heat transfer coefficient was 10.86%.

6. Experimental results

6.1. Pure fluids

To corroborate the validity of the achieved experimental data in the present experiments, measured boiling heat transfer for pure

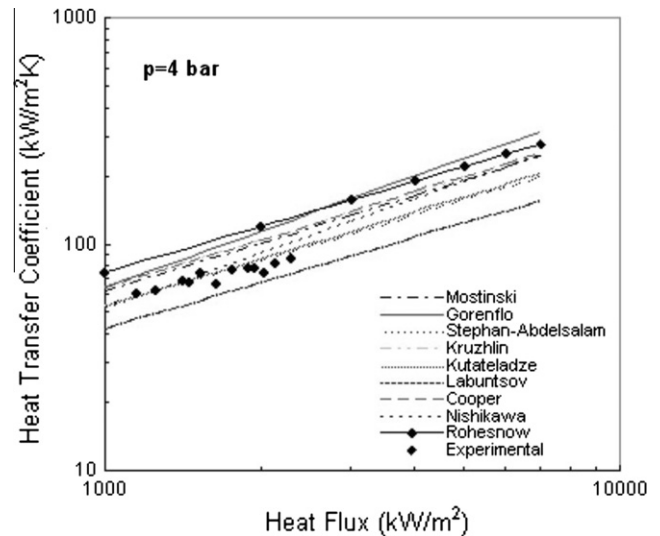


Fig. 4. Measured and predicted boiling heat transfer coefficient for pure water.

water are compared with eight well known correlations including Gorenflo (1997), Stephan and Abdelsalam (1980), Labuntsov (1972), Nishikawa et al. (1982), Kutateladze (1990), Kruzhlín (1947), Mostinski (1963) Rohsenow (1952) and Cooper (1984). Fig. 4 presents evaluations for pure water. The original correlations are summarized in Table 1. For water all the correlations predict similar results. Stephan–Abdelsalam, Kutateladze and Nishikawa correlations predict the present experimental data with reasonable accuracy in the investigated range of heat flux.

6.2. Binary mixture

The boiling curve and variation of heat transfer coefficient with heat flux at pressures of 4, 6 and 8 bar is shown in Fig. 5. It is observed that the wall superheat increases with increase in ammonia mass fraction and for a given heat flux, the heat transfer coefficient decreases with increase in ammonia concentration. Variation of heat transfer coefficient with pressure at different heat flux and concentration is depicted in Fig. 6. Heat transfer coefficient increases with increase in pressure.

6.3. Comparison of present experimental data with binary correlations in the literature

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. 7 to account for the mixture effect. Generally, the mixture correlation can be expressed as follows:

$$\frac{h}{h_{id}} = \frac{1}{1 + K} \quad (11)$$

where K is a factor representing the heat transfer reduction due to mixture effects. The factor K , in general, is a function of thermo-physical 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. 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

Table 1
Existing nucleate boiling correlations for pure fluid.

| Author | Correlation |
|-------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Kruzhlin (1947) | $\frac{hd}{k} = 0.082 \left(\frac{h_{fg} q}{g T_s k \rho_L - \rho_v} \right)^{0.7} \left(\frac{T_s c_{pL} \sigma_L \rho_L}{h_{fg}^2 \rho_v^2 d} \right)^{0.33} Pr^{-0.45} \quad (2)$ <p>where d is the pool boiling characteristic dimension</p> $d = \left[\frac{\sigma}{g(\rho_L - \rho_v)} \right]^{1/2}$ |
| Kutateladze (1990) | $h = \left[3.37 \times 10^{-9} \frac{k}{d} \left(\frac{h_{fg}}{c_{pl} q} \right)^{-2} \left(\frac{P/\rho_v}{\sigma/g} \right)^2 \right]^{1/3} \quad (3)$ |
| Labuntsov (1972) | $h = 0.075 \left[1 + 10 \left(\frac{\rho_v}{\rho_L - \rho_v} \right)^{0.67} \right] \left(\frac{k^2}{v \sigma (T_s + 273.15)} \right)^{0.33} q^{0.7} \quad (4)$ |
| Mostinski (1963) | $h = 0.00417 q^{0.7} P_c^{0.69} F_{PF} \quad (5)$ <p>F_{PF} is a non-dimensional pressure correction factor</p> $F_{PF} = 1.8 p_r^{0.17} + 4 p_r^{1.2} + 10 p_r^{10}$ |
| Nishikawa et al. (1982) | $h = \frac{31.4 P_c^{0.2} (8 R_p)^{0.2(1-p_r)}}{M^{0.17} c_p^{0.9}} \frac{(p_r)^{0.23}}{[1 - 0.99(p_r)]^{0.9}} q^{0.8} \quad (6)$ <p>$R_p = 0.125 \mu\text{m}$</p> |
| Stephan and Abdelsalam (1980) | $\frac{hd}{k} = 207 \left(\frac{q d_b}{k T_s} \right)^{0.745} \left(\frac{\rho_v}{\rho_L} \right)^{0.581} (Pr)^{0.533} \quad (7)$ <p>where d_b is the bubble departure term and given by Fritz type of equation</p> $d = 0.0146 \beta \left[\frac{2\sigma}{g(\rho_L - \rho_v)} \right]^{1/2}$ |
| Cooper (1984) | $h = 55 (p_r)^{0.12 - 0.4343 \ln R_p} (-0.4343 \ln p_r)^{-0.55} M^{-0.5} q^{0.67} \quad (8)$ |
| Gorenflo (1997) | $h = h_o F_{PF} \left(\frac{q}{q_o} \right)^{nf} \left(\frac{R_p}{R_{p0}} \right)^{0.133} \quad (9)$ <p>Pressure correction factor F_{PF} is</p> $F_{PF} = 1.2 p_r^{0.27} + \left(2.5 + \frac{1}{1 - p_r} \right) p_r$ $nf = 0.9 - 0.3 p_r^{0.3}$ |
| Rohsenow (1952) | $\frac{c_p \Delta T}{h_{fg}} = C_{sf} \left[\frac{q}{\mu h_{fg}} \sqrt{\frac{\sigma}{g(\rho_L - \rho_v)}} \right]^n \left(\frac{C_p \mu}{k} \right)^{m+1} \quad (10)$ <p>$n = 0.33$ and $m = 0.7$, for water $m = 0$. C_{sf} is a constant depending on different nucleation properties of a particular liquid-surface combination</p> |

$$\Delta T_{id} = \frac{q}{h_{id}} = \frac{q}{\sum \left(\frac{x_i}{h_i} \right)} \quad (12)$$

or alternatively using mixture properties in empirical correlations applicable to pure liquids. The summary of the correlations is given in Table 2.

ΔT_{bp} in Eq. (13) is the temperature difference between the dew point and bubble point curves as shown in Fig. 6. Thus its value is determined from phase equilibrium data. A_o in Eq. (14) is an empirical constant. Stephan and Korner (1969) determined the value of A_o , to range from 0.42 to 3.56, for seventeen mixtures by fitting Eq. (14) to the measured data. Their average value of 1.53 is recommended for mixtures whose data are not available. K_o in Eq. (15) is a constant determined from the combination of the mixtures and limited in $0.5 < K_o < 2.0$. Ideal heat transfer coefficient in the mixtures, h_{id} is defined as $h_{id} = x_1 h_1 + x_2 h_2$. In Eq. (17), T_s , is the saturation temperature of pure components at the same pressure as the mixture and B_o , the scaling factor, is equated to unity on the assumption that all the heat transfer from the heated surface in nucleate boiling passes into the bubble in the form of latent heat. Schlunder (1983) assigned a fixed value of 0.0002 m/s for β_L , the liquid side mass transfer coefficient. Thome and Shakir (1987)

combine the boiling range and the mass diffusion effects from Schlunder's model. New value of β_L was determined as 0.0003 m/s. Fujita and Tsutsui (1994, 1997) correlations are based on a model that the drop of effective temperature difference is a main reason for heat transfer reduction in mixtures.

Inoue et al. tested the correlations of Stephan–Koorner, Jungnickel, Schlunder and Inoue et al. against their experimental data. They concluded that these correlations fail to predict their experimental data and they attributed this failure to the fact that the tested correlations are closely related to $(y_i - x_i)$ and/or ΔT_{bp} but the experimental data are not related to both $(y_i - x_i)$ and ΔT_{bp} and also to the fact that $(y_i - x_i)$ and ΔT_{bp} of ammonia/water mixture are much larger than those of the mixtures that have been studied in developing these correlations. Arima et al. compared the values predicted from the correlation of Stephan–Koorner and Inoue–Monde with their experimental data. They also reported that the characteristics of mass fraction and heat transfer coefficient relate to neither $(y_i - x_i)$ nor ΔT_{bp} . They proposed a correlation based on Stephan–Koorner and Inoue–Monde correlation but did not find improvement with the new correlation. Taboas et al. (2007) used the correlations of Schlunder, Fujita–Tsutsui '97 and Thome–Shakir to predict the heat transfer coefficient data for

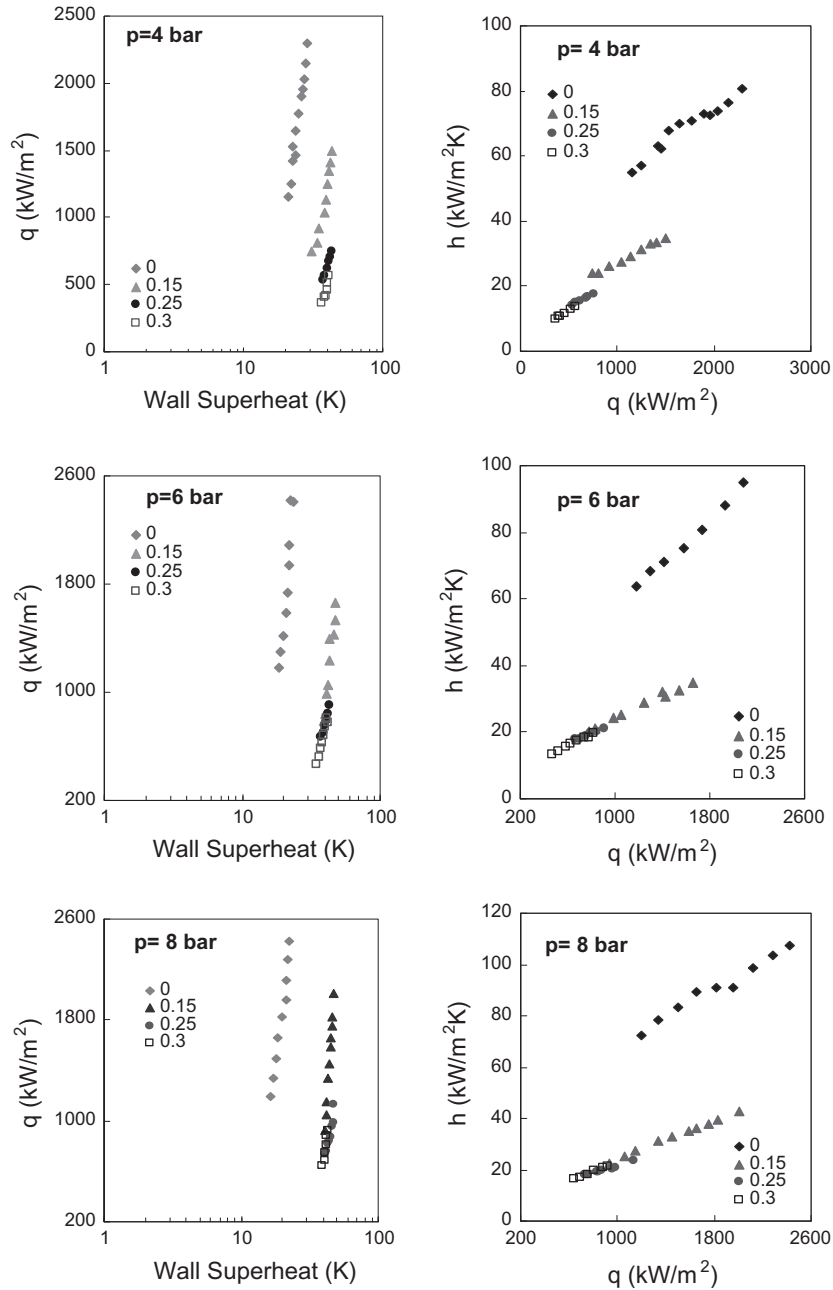


Fig. 5. Boiling curve and variation of heat transfer coefficient with heat flux at pressures 4, 6 and 8 bar.

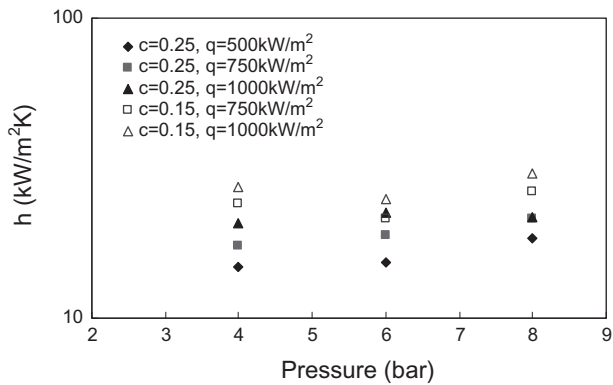


Fig. 6. Variation of heat transfer coefficient with pressure.

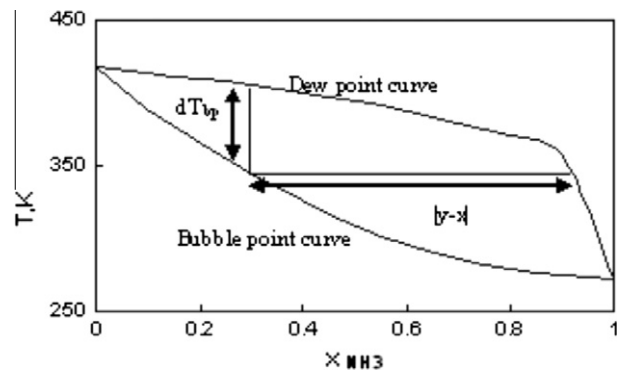


Fig. 7. Phase diagram of ammonia/water mixture at 4 bar.

Table 2
Existing nucleate boiling correlations for mixture.

| Author | Correlation | |
|-------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| Palen and Small (1964) | $\frac{h}{h_{id}} = \exp[-0.027\Delta T_{bp}]$ | (13) |
| Stephan and Korner (1969) | $\frac{h}{h_{id}} = [1 + A_o(0.88 + 0.12P)(y_1 - x_1)]^{-1}$ | (14) |
| Jungnickel et al. (1980) | $\frac{h}{h_{id}} = [1 + K_o(y_1 - x_1)(\rho_v/\rho_L)q^{(0.48+0.1x_1)}]^{-1}$ | (15) |
| Thome (1983) | $\frac{h}{h_{id}} = \frac{1}{1 + \frac{\Delta T_{bp}}{\Delta T_{id}}}$ | (16) |
| Schlunder (1983) | $\frac{h}{h_{id}} = \left\{ 1 + \frac{h_{id}}{q} \left[(T_{s2} - T_{s1})(y_1 - x_1) \left(1 - \exp \frac{-B_o q}{\rho_L h_{fg} \beta_L} \right) \right] \right\}^{-1}$ | (17) |
| Thome and Shakir (1987) | $\frac{h}{h_{id}} = \left\{ 1 + \frac{h_{id}}{q} \Delta T_{bp} \left[\left(1 - \exp \frac{-B_o q}{\rho_L h_{fg} \beta_L} \right) \right] \right\}^{-1}$ | (18) |
| Fujita and Tsutsui (1994, 1997) | $\frac{h}{h_{id}} = \left\{ 1 + \frac{\Delta T_{bp}}{\Delta T_{id}} \left[1 - 0.8 \exp \left(-\frac{q}{10^5} \right) \right] \right\}^{-1}$ | (19) |
| | $\frac{h}{h_{id}} = \left\{ 1 + \frac{\Delta T_{bp}}{\Delta T_{id}} \left[1 - \exp \left(\frac{-60q}{\rho_v h_{fg}} \left\{ \frac{\rho_v^2}{\sigma g (\rho_L - \rho_v)} \right\}^{1/4} \right) \right] \right\}^{-1}$ | (20) |
| Inoue et al. (1998) | $\frac{h}{h_{id}} = \left\{ 1 + \frac{k\Delta T_{bp}}{\Delta T_{id}} \right\}^{-1}$ | (21) |
| | $k = \left[1 - 0.75 \exp \left(-\frac{0.75q}{10^5} \right) \right]$ | |
| Calus and Rice (1972) | $\frac{h}{h_{id}} = \left[\left\{ 1 + (y_1 - x_1) \left(\frac{\alpha_L}{D} \right)^{0.5} \right\}^{0.7} \right]^{-1}$ | (22) |
| Vinayak Rao and Balakrishnan (2004) | $\frac{h}{h_{id}} = \left[1 + (y_1 - x_1) \left(\frac{D}{\alpha_L} \right)^{0.5} \right]$ | (23) |
| Inoue and Monde (2009) | $\frac{h}{h_{id}} = \left\{ 1 + \frac{K_i k \Delta T_{bp} + \left[K_{Sh} (T_{s2} - T_{s1})(y_1 - x_1) \left(1 - \exp \frac{-B_o q}{\rho_L h_{fg} \beta_L} \right) \right]}{\Delta T_{id}} \right\}^{-1}$ | (24) |
| | $K_i = 0.15, K_{St} = 0.65$ | |
| | $\frac{h}{h_{id}} = \left[1 + K_i \frac{k\Delta T_{bp}}{\Delta T_{id}} + K_{St} A_o (0.88 + 0.12P)(y_1 - x_1) \right]^{-1}$ | (25) |
| | $K_i = 0.15, K_{Sh} = 0.25$ | |

Table 3
Accuracy of correlations.

| Experimental condition | Correlation | Mean error (%) | RMS error (%) |
|----------------------------------------------------------------------------------------------------------------------------------|----------------------|----------------|---------------|
| $p = 4\text{--}8 \text{ bar,}$ $q = 360\text{--}2000 \text{ kW/m}^2$ $x_{NH_3} = 0\text{--}0.3$ No. of data points = 98 | Stephan and Korner | 5.48 | 9.56 |
| | Schlunder | -147.75 | 151.25 |
| | Fujita-Tsutsui '97 | -24.29 | 36.66 |
| | Calus and Rice | 0.51 | 12.97 |
| | Vinayak-Balakrishnan | 39.4 | 39.91 |
| | Inoue-Monde 2009 (1) | 4.4 | 11.3 |
| | Inoue-Monde 2009 (2) | 20.7 | 21.7 |

ammonia/water mixture and compared with those measured by Inoue et al. and Arima et al. They reported that Schlunder's correlation better fits the experimental data at high ammonia concentrations while at low ammonia concentrations the results predicted by the Thome-Shakir correlation are closer to experimental data. Therefore a new correlation that combines both correlations was proposed by the authors that reproduced the measured data within a $\pm 40\%$ accuracy range. Inoue and Monde (2009) further improved the existing correlations for ammonia/

water mixtures, considering that the heat transfer coefficients of the mixtures are governed by both ΔT_{bp} and $(y_i - x_i)$. They proposed two correlations (Eqs. (24) and (25)). Eq. (24) is made up of a combination of Eqs. (14), (21) and (25) is made up of a combination of Eqs. (17) and (21). The adjustable parameters K_i , K_{St} , and K_{Sh} are the values that make the mean deviation between the correlations and their experimental data as small as possible. They claim that their equations can predict 97% of all of the data within an accuracy of $\pm 20\%$ over the entire ammonia mass fraction range.

In this study seven typical correlations represented by Eqs. (14), (17), (20), (22)–(25) in Table 2 are selected. Correlations represented by Eqs. (14) and (17) include concentration difference between the vapor and liquid phases $(y_i - x_i)$ as parameter, correlations represented by Eq. (20) includes boiling range ΔT_{bp} as parameter and Eqs. (22) and (23) include concentration difference between the vapor and liquid phases $(y_i - x_i)$ as parameter and mass diffusivity. Eqs. (24) and (25) developed by Inoue-Monde for ammonia/water mixture include both ΔT_{bp} and $(y_i - x_i)$ as parameter. For the calculation of the properties of the ammonia/water mixture, the calculation methods described in Conde Engineering (2006) were adopted along with

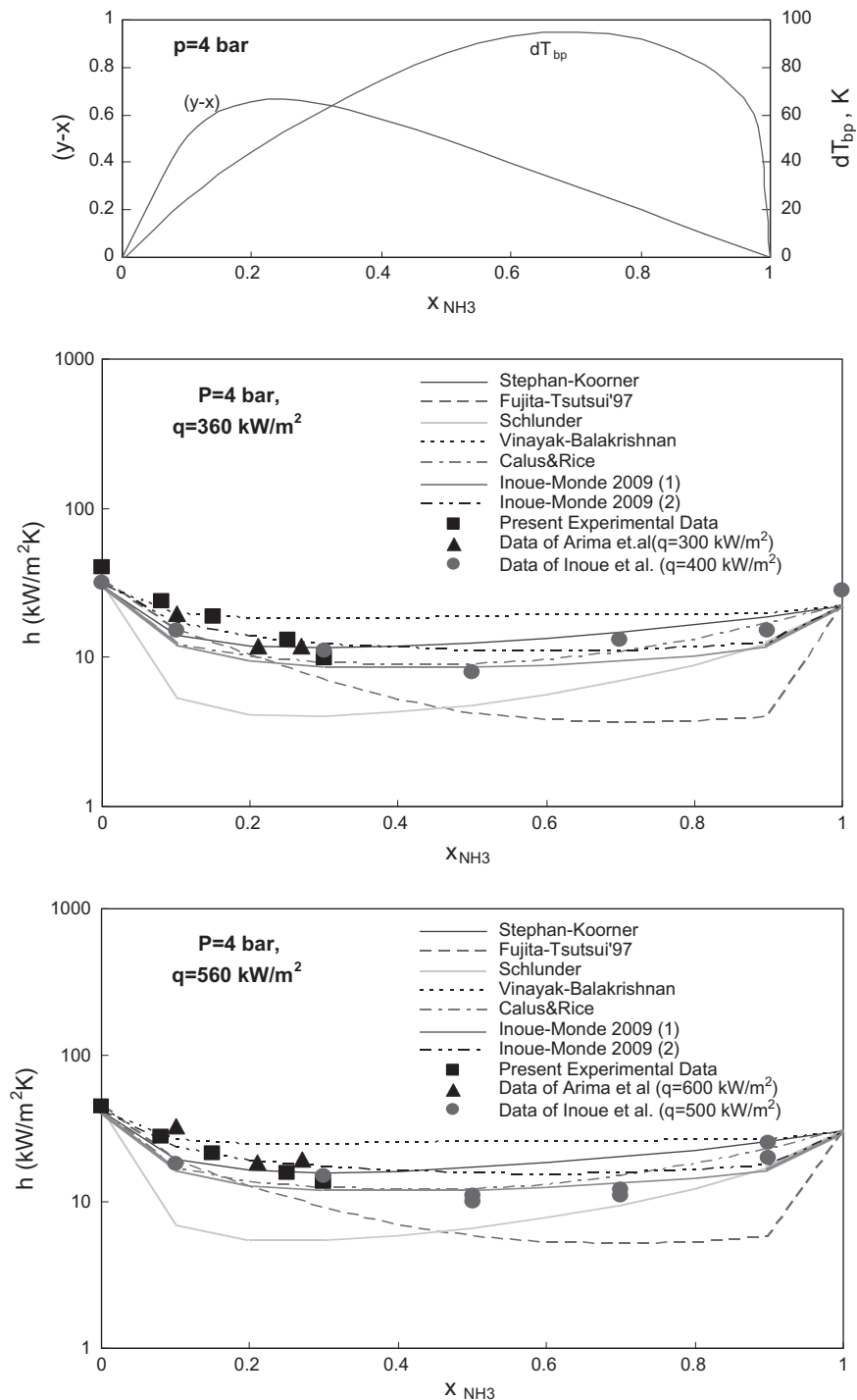


Fig. 8a. Comparison between experimental heat transfer coefficient and those predicted by correlations showing the effect of mass fraction along with relation for ΔT_{bp} and $(y-x)$ at 4 bar pressure.

the necessary data for pure components from [ASHRAE Fundamentals \(2005\)](#). Prediction accuracy of correlations is presented in [Table 3](#).

As seen from [Figs. 8a–c](#), the heat transfer coefficient decreases with an increase in ammonia mass concentration and matches well with the findings of Arima et al. and Inoue et al. The data of Arima et al. are slightly higher than the data of Inoue et al. and the present experimental data falls in between. The reason for this small difference could be the shape and material of the heating elements

– a thin wire of 0.3 mm diameter of platinum in Inoue et al. and a horizontal flat plate of 10 mm diameter of silver in Arima et al. and a vertical cylindrical rod of 6 mm diameter of stainless steel in the present work. Comparison of the correlations with the present data is also shown in [Figs. 8a–c](#). At 4 bar pressure, it is very difficult to discuss the applicability of the correlations to the present experimental data. Schlunder correlation underpredicts the experimental data and Vinayak–Balakrishnan correlation overpredicts the present experimental data at all pressures and heat flux and in the

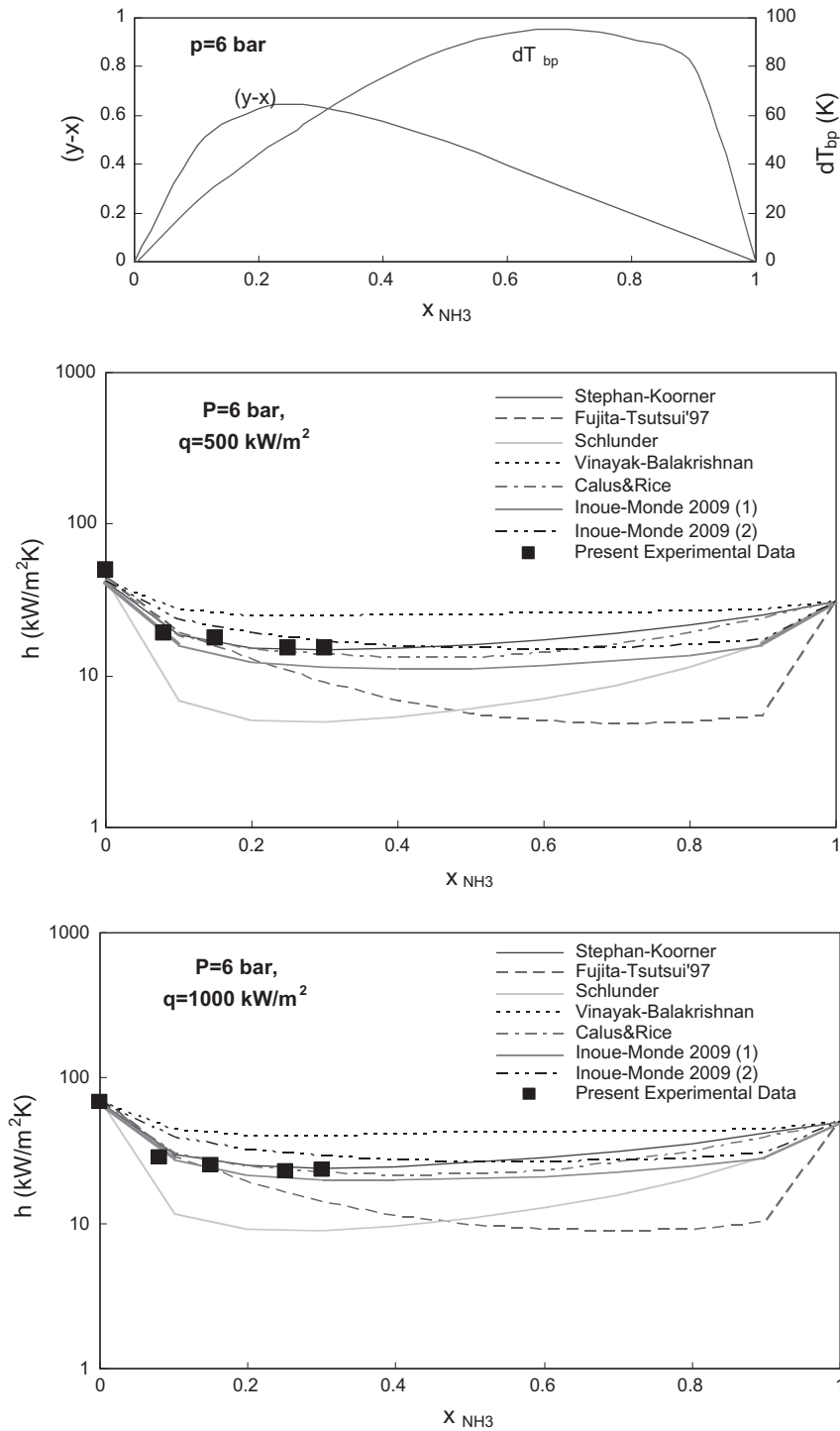


Fig. 8b. Comparison between experimental heat transfer coefficient and those predicted by correlations showing the effect of mass fraction along with relation for ΔT_{bp} and $(y - x)$ at 6 bar pressure.

investigated range of mass fraction. Fujita-Tsutsui correlation gives better prediction at low mass fraction at all pressures and heat flux. At 6 bar and 8 bar pressures, Stephan-Koorner correlation predicts the data well at low heat flux and at high heat flux Calus&Rice predicts the data closer to the experimental data. It may be noted that both Stephan-Koorner and Calus&Rice correlations include concentration difference between the vapor and liquid phases $(y_i - x_i)$ as parameter. This suggests that boiling heat trans-

fer coefficient of ammonia/water mixture is a function of $(y - x)$ of the more volatile component ammonia. Experimental data are fairly predicted by Calus&Rice correlation with a mean error of 0.51% and by Stephan-Koorner correlation with a mean error of 5.48% in the investigated range of pressure, heat flux and concentration. One of the two correlations (Eq. (24)) proposed by Inoue-Monde for ammonia/water mixture also predicts the present experimental with good accuracy with a mean error of 4.4%. Pre-

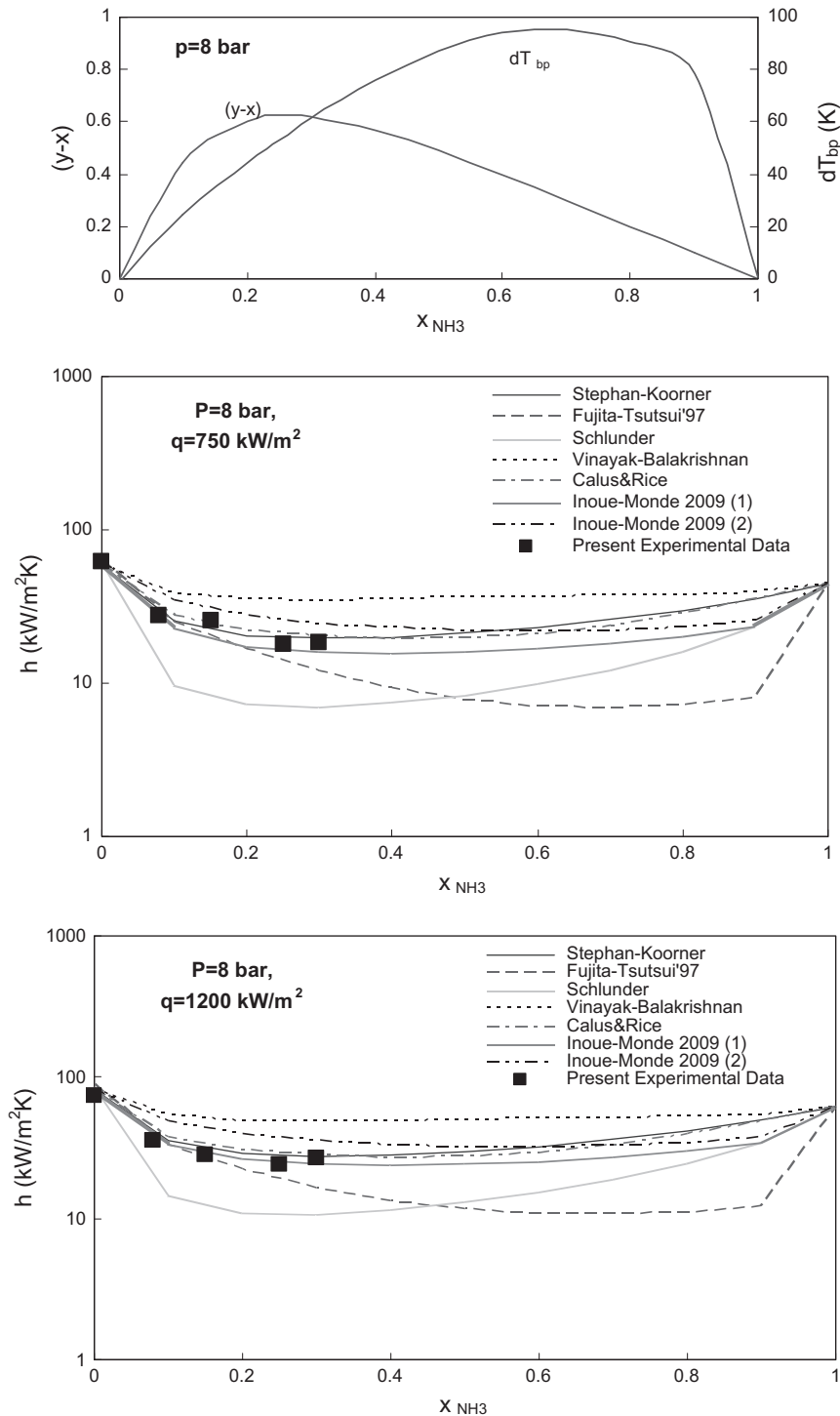


Fig. 8c. Comparison between experimental heat transfer coefficient and those predicted by correlations showing the effect of mass fraction along with relation for ΔT_{bp} and $(y - x)$ at 8 bar pressure.

diction error of these three correlations is shown in Fig. 9. Most of the data are predicted with $\pm 20\%$ by the three correlations in the investigated range of low ammonia mass fraction. It is also worthwhile to note that Calus&Rice correlation predicts the data of Inoue et al. over all ranges of concentration with reasonable accuracy as their improved correlation (Fig. 8a). The empirical constant of the Calus&Rice and Stephan-Koorner correlations is now modified by using the least mean square method, which minimizes the error between the predicted values and the present experimental data.

The exponential constant of Eq. (22) that best fits the experimental data is 0.67 and the constant A_0 of Stephan-Koorner correlation is 1.6631. The modified Calus&Rice correlation also compared satisfactorily with the ammonia/water boiling data of Arima et al. and Inoue et al. available in the literature. The comparison is shown in Fig. 10. The correlation predicts the literature data to within $\pm 40\%$. It can be concluded that both $(y_i - x_i)$ and mass diffusivity of ammonia play a major role in the heat transfer reduction in ammonia/water mixture. This is also evident from Fig. 1 which

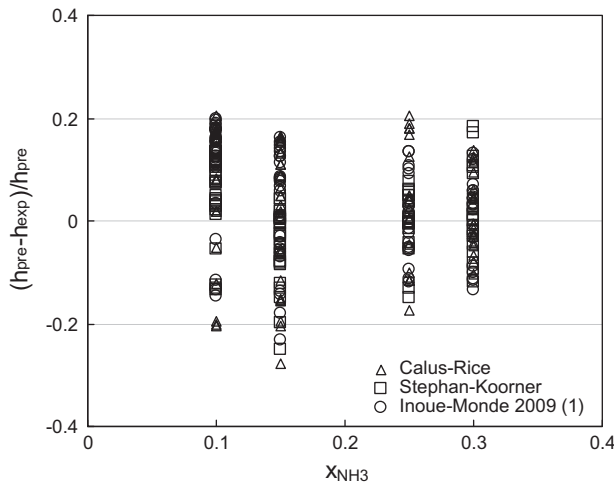


Fig. 9. Prediction error of Inoue-Monde, Stephan-Koorner and Calus&Rice correlations.

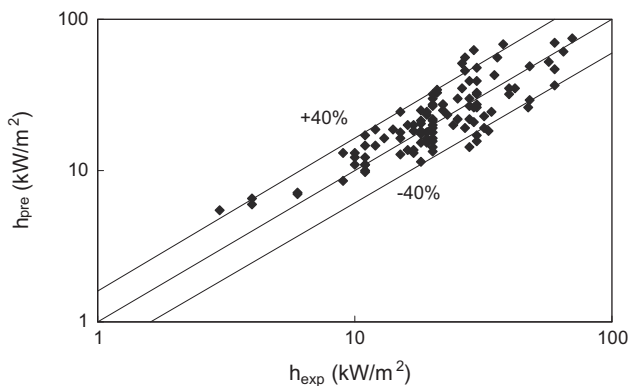


Fig. 10. Comparison between the predicted heat transfer data with modified Calus&Rice correlation and the literature data.

shows that non-linear variation of diffusivity coefficient is most significant for ammonia/water mixture.

7. Conclusion

Heat transfer coefficients of pool boiling were measured for saturated binary mixture ammonia/water at low pressure of 4–8 bar and at low mass fraction of $0 < x_{\text{NH}_3} < 0.3$ and at different heat flux. Significant influences of concentration and heat flux on the heat transfer reduction were found. The performance of the existing correlations for predicting the boiling heat transfer coefficient for binary ammonia/water mixture has been discussed. Conclusions can be drawn as follows:

1. The experimental results show that heat transfer reduction in binary mixture is dependent on the mixture concentration and heat flux. When the heat flux increases the reduction of heat transfer coefficient becomes larger by almost 1.5 times.
2. Heat transfer coefficient is successfully predictable using Calus&Rice and Stephan-Koorner correlation and the improved equation suggested by Inoue-Monde for ammonia/water mixture in the investigated range of low concentration in this work. All the correlations include the concentration difference

between the vapor and liquid phases ($y_i - x_i$) as influencing factors to account for the mixture effects. Calus&Rice correlation that includes mass diffusivity of ammonia as an additional influencing factor predicts the literature data also with good accuracy over all ranges of ammonia mass fraction.

3. The modified Calus&Rice correlation predicts the present experimental data with an accuracy of $\pm 18\%$ and the modified Stephan-Koorner correlation with an accuracy of $\pm 16\%$.

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