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Boiling heat transfer coefficients inside a vertical smooth tube for water/ammonia and ammonia/lithium nitrate mixtures

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Abstract

This paper describes the experimental results obtained on the heat transfer in forced convective boiling for the water/ammonia and ammonia/lithium nitrate mixtures flowing upward in a vertical tube uniformly heated. The concentration range for both mixtures was 38–48 wt%. Correlations were proposed to correlate the experimental local heat transfer coefficients with a mean deviation of $\pm 16\%$ for the ammonia/lithium nitrate mixture and $\pm 25\%$ for the ammonia/water mixture. The results showed that the local heat transfer coefficients are strongly dependent on *Bo* for the ammonia/lithium nitrate mixture and more dependent on quality and $1/X_{tt}$ for the ammonia/water mixture at the analysed conditions. Comparing the heat transfer coefficient values for both mixtures, it was observed that the lowest values were obtained with the ammonia/lithium nitrate mixture. © 1998 Elsevier Science Ltd. All rights reserved.

Key words: Boiling heat transfer; Inside vertical tube; Water/ammonia mixtures; Ammonia/lithium nitrate mixtures

Nomenclature

A	heat transfer area (m^2)
Bo	boiling number, $q/G\lambda$
Cp	specific heat (kW m^{-2} °C^{-1})
D	diameter (m)
G	mass flux (kg m^{-2} s^{-1})
H	specific enthalpy (kJ kg^{-1})
h	heat transfer coefficient (kW m^{-2} °C^{-1})
k	thermal conductivity (kJ kg^{-1} °C^{-1})
M	mass flow rate (kg s^{-1})
P	pressure (bar)
Pr	Prandtl number, $\mu Cp/k$
Q	heat load (kW)
Re	Reynolds number, $uD\rho/\mu$
q	heat flux (kW m^{-2})
T	temperature (°C)
ΔT	temperature difference (°C)
u	velocity (m s^{-1})
X	inlet solution concentration (% wt.)
X_{tt}	Lockhart–Martinelli parameter, $(1-x/x)^{0.9}$ $(\rho_V/\rho_L)^{0.5}(\mu_L/\mu_V)^{0.1}$
x	quality (wt. fraction).

Greek symbols

λ	latent heat of vaporisation (kJ kg^{-1})
μ	dynamic viscosity (kg $m^{-1}s^{-1}$)
ρ	density (kg m^{-3}).

Subscripts

AV	average
F	fluid
i	inside
L	liquid
o	outside
TP	two phase
V	vapour
W	wall.

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1. Introduction

Boiling heat transfer is of great importance for a wide range of applications such as refrigeration and air conditioning systems, energy saving systems, chemical processing, power plants and many other kinds of industries. The chemical process and petroleum refining industries use kettle and thermosiphon reboilers for the separation of multicomponent mixtures. The refrigeration industry uses evaporators for the evaporation and superheating of pure and mixed refrigerants. Energy saving systems such as heat pumps and heat transformers use evaporators and/or generators to evaporate and separate the working fluids. To optimise the design of heat transfer equipment such as generators and evaporators used in refrigeration machines, absorption heat pumps and heat transformers, it is necessary to have a better knowledge of the heat transfer mechanism and the heat transfer coefficients. Boiling of binary mixtures differs substantially from that of pure fluids due to a number of factors such as (a) the effect of the composition on nucleation [1], (b) a significant change in physical properties of the mixtures with composition [2], and (c) the retardation of vapour/liquid exchange and evaporative mechanisms [3]. The heat transfer coefficient of mixtures is generally lower than that of the equivalent pure fluids at similar conditions. Studies have been conducted on the convective flow boiling of liquid mixtures of fluids. The experimental data are generally reported in tabular or graphical form. In spite of the potential advantages in using refrigerant mixtures to improve the performance of heat pump systems, the capacity of a particular system could be varied; by changing the circulating composition of the working fluid the evaporation and condensation temperatures of a nonazeotropic mixture will vary, allowing it to work in a more efficient Lorenz Heat Pump cycle [4], but there is still no reliable way to predict the forced convection boiling heat transfer coefficients of mixtures. In order to determine the heat transfer coefficients for mixtures boiling inside tubes, an experimental unit was designed, constructed and installed at the Centro de Investigación en Energía (CIE) of the Universidad Nacional Autónoma de México (UNAM), in Temixco, Morelos, México.

The heat transfer coefficients were obtained in saturated nucleate boiling for two refrigerant mixtures flowing upward in a uniformly heated vertical tube. The mixtures analysed were water/ammonia and ammonia/lithium nitrate. The ammonia concentration range for the water/ammonia mixture was 39–48 wt%, with a pressure range from 8.8 to 12.4 bar. The ammonia concentration range for the ammonia/lithium nitrate mixture was 40–48 wt%, with a pressure range from 8.7–14.8 bar.

The water/ammonia and ammonia/lithium nitrate mixtures were selected as a first step, in order to optimise the heat transfer surface required in the generators of absorption cooling systems and absorption heat pumps at the CIE of the UNAM.

2. Literature review

Bennett and Chen [5], conducted a series of experiments with an aqueous mixture of ethylene glycol and water in vertical channels. Their test section was composed of three electrically heated pieces with a length of 1.08 m and a 25.4 mm inner diameter. They measured the local heat transfer coefficients with different mixture compositions at liquid/vapour mixture qualities between 0–30%. Bennett and Chen introduced an extension of Chen's (1966) correlation to binary mixtures in forced convection flow boiling [6]. The authors compared their correlation against the experimental data obtained from water and ethylene glycol mixtures. The correlation predicted the heat transfer coefficients to within $\pm 15\%$.

Mishra et al. [7], conducted a series of experiments using a mixture of refrigerants R12 and R22 to evaluate the local heat transfer coefficient in forced convection boiling in a horizontal tube. The results revealed a lower heat transfer coefficient for binary mixtures relative to the linear interpolation between the heat transfer coefficients of the pure components.

Ramamohan et al. [8], published experimental data for subcooled flow boiling of binary mixtures. The mixtures studied were glycerol/water and water/isopropanol. They modified the correlation for the subcooled boiling of pure liquids proposed previously by Moles and Shaw [9], and used this to correlate their experimental data points. The equation predicted 95% of the experimental data points within $\pm 15\%$.

Ross et al. [10], carried out experiments on the flow boiling of a mixture of R152a (CH_3CHF_2) and R13B1 (CF_3Br) inside a horizontal tube. Their test section was composed of a 2 m long preheating section and a 2.29 m long main test section. The tube's inside diameter was 9 mm. The experimental results showed a substantial degradation of the heat transfer coefficient for the R152a/R13B1 mixture in the nucleate boiling dominated regime. The authors suggested the use of Bennett and Chen's correlation [5], with the suppression factor set to zero. They noted that in refrigerant binary mixtures, nucleate boiling is suppressed and evaporation becomes the main heat transfer mechanism.

Jung et al. [11], conducted flow boiling experiments with a binary mixture R22/R114 and R12/R152a in horizontal tubes. Their test section was made of a stainless steel tube 8 m long and 9.1 mm in internal diameter. The test section was heated by passing direct current through the tube. The authors measured more than 3000 local heat transfer coefficients for the pure refrigerants and their mixtures. They found that for given heat and mass fluxes, nucleate boiling for mixtures was suppressed at lower qualities of the liquid/vapour mixture than for pure fluids. The heat transfer coefficient of mixtures was lower than a weighted average of the pure component values.

Celata et al. [12] reported experimental data for heat transfer coefficients for forced convective boiling for pure refrigerants and binary mixtures flowing upward in a vertical tube. The refrigerants analysed were R12, R114 and their mixtures. The results showed that the reduction of the heat transfer coefficient as a function of mixture composition depended on both the saturation pressure and the mass flux. Also, the authors compared their results using Chen's correlation [6], Bennett and Chen's correlation [5], and Mishra et al.'s correlation [7]. They found that the best performance was obtained using Bennett and Chen's correlation.

Sami et al. [13], proposed a correlation to predict the average heat transfer coefficient and pressure drop of two new ternary refrigerant mixtures, flowing inside an enhanced surface tube. The two ternary mixtures proposed were R22/R152a/R114 and R22/R152a/R124. The authors reported that in general, the deviation between their experimental and predicted values was less than ±15%.

Wenzel et al. [14], published two papers on the heat transfer for mixtures of acetone/isopropanol/water flowing under subcooled boiling conditions. In the first paper, the authors reported the boiling heat transfer coefficients for the ternary mixture which were measured over a wide range of process parameters such as heat flux, flow velocity and concentration. The measurements covered the regimes of convective heat transfer, including the transition region and the fully developed subcooled boiling. The effect of the process parameters on the heat transfer coefficients in the various regimes was also discussed. In the second paper, the authors presented a model to predict the local heat transfer coefficients under subcooled flow boiling conditions for mixtures. The predictions of this model were compared with experimental data obtained in the first paper. The authors found a good agreement for their proposed correlation, independent of heat flux, subcooling, fluid composition and flow velocity.

Darabi et al. [15], provided a comprehensive review and discussion of the correlations and models available for the prediction of convective vaporisation in vertical and horizontal smooth and augmented tubes for both pure fluids and mixtures. The authors compared the mean deviation of the main heat transfer correlations. Darabi et al. also, compared the heat transfer coefficients obtained with different correlations using experimental data for R12 boiling inside a horizontal tube.

Rivera et al. [16] reported some average heat transfer coefficients and pressure drops against the heat flux for the water/ammonia and ammonia/lithium nitrate mixtures flowing upward in a uniformly heated vertical stainless steel tube. The average heat transfer coefficients were obtained by adding the local heat transfer coefficients along the test section. The inner wall temperatures were calculated from the average measured outside wall temperatures, by using the one-dimensional, radial, steady state heat conduction equation assuming the thermal conductivity and the heat flux constant for each section of the test tube. The results showed that higher coefficients of performance were obtained with both an increment on the heat flux and an increment in the solution concentration.

From the literature review it was clear that there are some correlations that predict the local heat transfer coefficients for refrigerant mixtures with a reasonable exactness, having some of these correlations mean deviations of less than ±15%.

In the present work, the model proposed by Mishra et al. [7], was chosen in order to correlate the experimental local heat transfer coefficients for the ammonia/water and ammonia/lithium nitrate mixtures. The Mishra et al. correlation has been validated by Celata et al. [12], who utilised it to correlate the local heat transfer coefficients of mixtures of refrigerants. Although this correlation presented a higher mean deviation compared with others, it has the advantage that it requires less number of thermodynamic and physical properties compared with others. This is an advantage when there is lack of information of physical properties for mixtures, as is the case for the ammonia/lithium nitrate mixture.

3. Experimental unit description

The main components of the experimental unit for determining heat transfer coefficients in two phase flow were a solution storage tank, two separation tanks, two condensate storage tanks, a condenser, two preheaters and the test section as shown in Fig. 1.

A water/ammonia (H_2O/NH_3) mixture stored in the solution tank was pumped to the first preheater where it was heated by means of hot water coming from the auxiliary heating tank. The preheated solution flowed through the second preheater where it was further heated by means of an electrical resistance heater, to attain the desired temperature at the exit of this component. The solution flowed through the test section where a known amount of heat was supplied to obtain ammonia vapour with a low concentration of water and a refrigerant weak liquid solution with a low ammonia concentration. The heat in the test section was uniformly supplied by an electrical resistance heater placed in a spiral winding along the tube. After this, the two phase flow mixture leaving the test section entered the main separation tank where the liquid was deposited at the bottom of the tank, and the vapour passed from the top of the tank to the condenser. In the condenser, the ammonia vapour was condensed by means of cooling water supplied from the

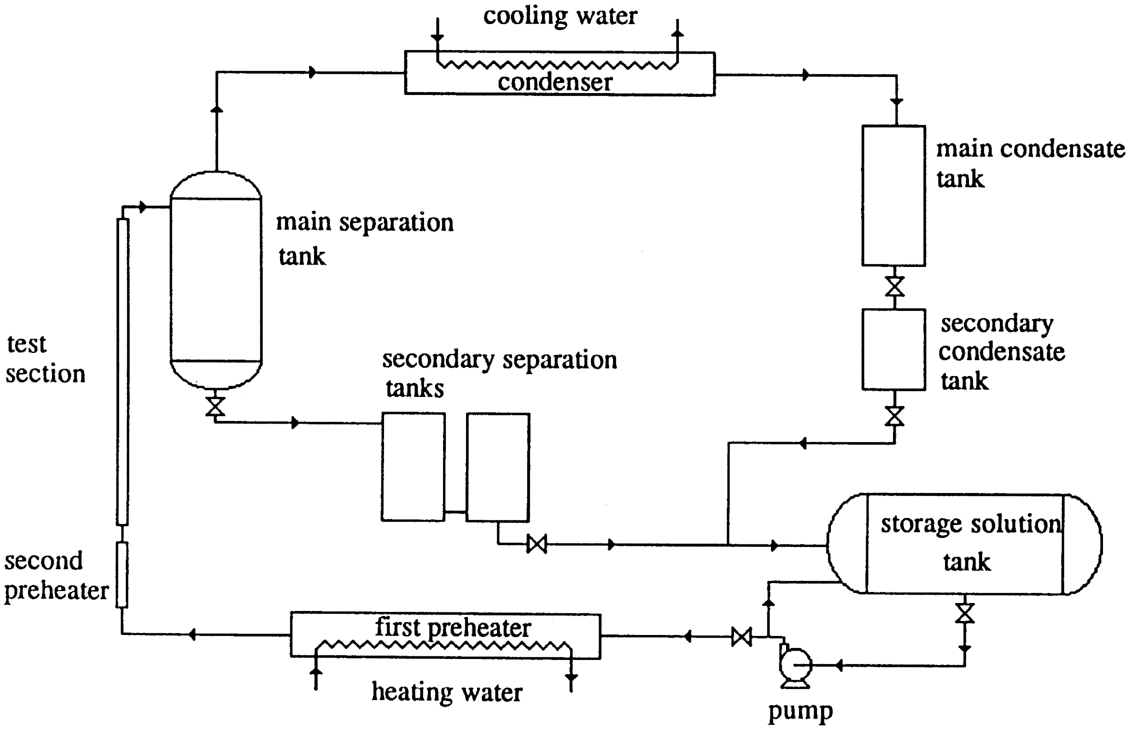

Fig. 1. Schematic diagram of the experimental unit to determine heat transfer coefficients in saturated nucleate boiling.

auxiliary cooling system. The liquid then entered the condensate tanks where it was stored until the end of the experimental test. After this, the valve at the exit of the separation tank was opened and the refrigerant weak solution returned to the solution storage tank. Subsequently, the valves at the exit of the condensate tanks were opened and the ammonia was absorbed by the refrigerant weak solution in the solution storage tank.

3.1. Test section

The test section consisted of a vertical stainless steel tube of external diameter 31.8 mm, wall thickness of 3.0 mm and 1.48 m long with twenty four thermowells welded to the tube as shown in Fig. 2.

Each temperature measurement station consisted of three thermowells, placed at an angle of 90° to each other. Two of them, opposite to each other, measuring the wall temperature and the other, measuring the bulk fluid temperature. Each thermocouple station was separated 165 mm to each other as can be seen in Fig. 2. Each thermowell was 3.2 mm in diameter and 35 mm long.

Heat was uniformly supplied to the test section by an electrical resistance heater of 1.31 Ω m^{-1} placed in a spiral winding along the tube. The resistance was made of nichrome and it was connected to a variable auto transformer (variac) with a maximum power of 3.2 kW with which it was possible to vary the heat supplied to the test section. In order to electrically insulate the test section from the electrical resistance heater, a thin mica insulator was placed between them. On the other side, to thermally insulate the test section from the environment, an asbestos cover was placed covering the electrical resistance heater and then two half tubes (50 mm thickness and 1.20 m long) of fibre glass were placed to cover the whole test section.

3.2. Instrumentation

In order to determine the heat transfer coefficients in forced convective boiling for the water/ammonia and ammonia/ lithium nitrate mixtures, the process parameters such as temperature, pressure, mass flow rate, concentration and electrical power were measured with the instrumentation described as follows.

The temperature was measured by means of twenty seven type T thermocouples (copper/constantan) insulated with fiber glass. In order to facilitate the heat transfer, the thermowells were filled with vacuum oil. Each one of the thermocouples was calibrated separately by means of a constant temperature source. The thermocouples were calibrated in a range between 40 and 140°C. Using the least squares method, polynomial equations were obtained for the thermocouples and sub-

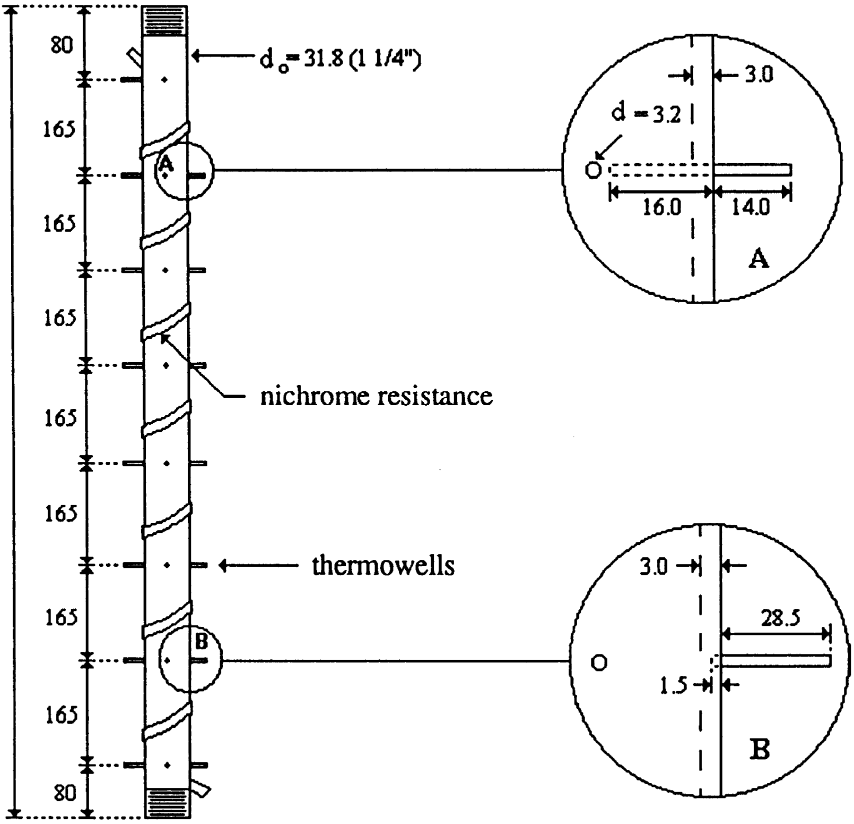

Fig. 2. Test section schematic diagram. Dimensions in mm.

sequently incorporated to a computer program previously written. The correlation coefficient for the equations was higher than 0.996.

Two Bourdon gauges were utilised in the equipment in order to have qualitative pressure readings during the experimental process. One of those was connected to the solution tank and the other to the main separation tank.

In addition to the gauges, two pressure transducers (Omega, model PX 105) were utilised to measure the pressure difference between the inlet and the outlet of the test section. The transducers were of the solid state type with a maximum error of 0.1% and a working range between 1–13.6 bar. The power required for the pressure transducers was supplied by a power source (Lambda, model LQ-413). The output signal of the transducers was sent to the data logging system which was connected to the work station.

In order to determine the mass flow rates of the water/ammonia or ammonia/lithium nitrate at different solution concentrations, a differential pressure transducer (Fisher and Porter Co. U.S.A., model 50 DP101) was placed in the unit. The differential pressure transducer was previously calibrated by means of a device constructed at CIE for different concentration and mass flow rates for both the water/ammonia and the ammonia/lithium nitrate mixtures. Polynomial equations were also introduced to the computer program. The correlation coefficient for these equations was higher than 0.99.

The solution concentrations for the water/ammonia and ammonia/lithium nitrate mixtures were determined by recording the weight of each component fed to the solution storage tank on an accurate weighing platform.

The electrical power supplied by the electrical resistance placed in a spiral winding along the test section and the second preheater were measured by a voltmeter (Keithley, model 169-DMM) and an ammeter (Amprobe, model ACD-10).

The experimental data were gathered by a data logging system Hewlett Packard model 3421A with a maximum capacity of 30 channels. Twenty-seven channels were used to measure directly the temperatures in the test section and in the main components. Two more were used to measure the pressure drop through the test section and the last one was used to measure the mass flow rate of the mixtures studied. The data logging system was programmed to read the channels every thirty seconds.

A work station (Hewlett Packard model 382) was connected to the data logging system. A computer program was developed based on HP VTEST software developed by the Hewlett Packard Co. USA.

3.3. Accuracy of instruments

Temperatures were recorded to an accuracy of 0.1°C. Readings of current intensity and voltages to determine the power supplied by the heaters were measured to accuracies of 0.01 amperes and 0.01 V respectively. Voltage readings for the pressure transducers were obtained to three decimal figures. Voltage readings for the differential pressure transducer were obtained to four decimal figures. Atmospheric pressure was measured with a barometer to an accuracy of 1 mmHg. The flowmeters were readable up to 5% of full scale. The experimental uncertainty of the heat transfer coefficients have been evaluated within ±15%.

4. Data collection

The experimental tests were made taking account of the thermodynamic properties for both mixtures and the security margins established by the experimental unit design characteristics.

All measurements were taken by the data logger and the work station after the system had reached steady state for the given conditions. It was considered that the steady state conditions were reached when the parameter readings remained almost constant for a period of at least forty min. Steady state was observed on the computer screen by plots of temperatures and pressure against time. The data logger system scanned and stored all inputs each thirty s.

The selected mixtures compositions, the heat and mass fluxes, the temperatures and the pressures were typical of those which might be employed in absorption cooling systems and absorption heat pumps.

For each one of the test runs, an energy balance was performed for the test section. One hundred and twenty test runs were conducted for both mixtures. However, only those in which the difference between the heat supplied and the heat absorbed by the solution were less than 10% were considered. In all, sixty-nine test runs were analysed for the ammonia/water mixture and thirty-two for the ammonia/lithium nitrate mixture.

The energy gained by the working mixtures across the entire test section was calculated by the enthalpy difference (between the inlet and outlet) and the solution mass flow rate. The enthalpies and vapour qualities were determined from the thermodynamic property data equations for both mixtures using the temperatures and pressures at the inlet and outlet of the test section.

Thermodynamic and physical properties of ammonia/lithium nitrate mixtures were obtained from Aggarwal and Agarwal [17] and Infante Ferreira [18], and for the ammonia/water mixtures from the Institute of Gas Technology [19] and Linde Industries [20].

For the data analysis the following assumptions were made:

(i) The bulk fluid temperature is the same for a given cross section of the test section.
(ii) The heat flux is uniform over all the test section length.
(iii) The pressure drop is linear over all the test section length.

Using the above assumptions, at each thermocouple section, the temperatures, pressures, enthalpies, qualities and compositions for both mixtures were known.

In order to determine the local heat transfer coefficients from the gathered data, the following equation was employed:

$$q = \frac{Q}{A} = h(T_{\mathrm{Wi}} - T_{\mathrm{F}}). \tag{1}$$

The inner wall temperatures, T_{Wi}, were calculated from the average measured outside wall temperatures T_{Wo}, by one dimensional, radial, steady state heat conduction, assuming that the inside and outside temperatures, and the thermal conductivity across the tube wall, were constant.

Due to the high heat losses by conduction at the top of the test section, the average heat transfer coefficients were calculated based only on the local heat transfer coefficients of the first six thermocouples stations.

$$h_{AV} = \frac{h_1 + h_2 + h_3 + h_4 + h_5 + h_6}{6} \tag{2}$$

5. Heat transfer correlations

Mishra et al. [7] correlated their experimental data with the following equation:

$$h_{TP} = Ch_L \left(\frac{1}{X_{tt}}\right)^m Bo^n \tag{3}$$

where h_{L} can be estimated by the Dittus–Boelter equation:

$$h_L = 0.023 \frac{k_L}{D} Re_L^{0.8} Pr_L^{0.4} \tag{4}$$

X_{tt} is the Lockhart and Martinelli parameter defined as:

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9} \left(\frac{\rho_G}{\rho_L}\right)^{0.5} \left(\frac{\mu_L}{\mu_G}\right)^{0.1} \tag{5}$$

and Bo is the boiling number, which can be interpreted as the mass flux of vapour generated at the tube surface to the total mass flux parallel to the pipe surface.

$$Bo = \frac{q}{G\lambda} \tag{6}$$

The values of the constant C and the exponents for two different mixture compositions were published in the paper. This correlation was able to predict the experimental data for the mixtures of refrigerants R12 and R22 with a mean deviation of ±30%.

In the present work, the above equations were used to correlate the experimental local heat transfer coefficients for the ammonia/water and ammonia/lithium nitrate mixtures. Specific values for the constant C and the exponents m and n in eqn (3) were determined for each mixture.

The equations obtained that correlate the experimental local heat transfer coefficients for the ammonia/lithium nitrate and ammonia/water mixtures were respectively:

$$h_{TP} = 25(1/X_{\mathrm{tt}})^{0.1}(Bo)^{0.2} \tag{7}$$

and

$$h_{\mathrm{TP}} = 65(1/X_{\mathrm{tt}})^{0.5}(Bo)^{0.15} \tag{8}$$

which correlated the experimental data with a mean deviation of ±16 and ±25% respectively.

6. Experimental results

Figure 3 shows the comparison of predicted against experimental local heat transfer coefficients for the ammonia/lithium nitrate mixture. In this figure it can be seen that only few data (10%) have a deviation higher than ±30%. The mean deviation for all the predicted local heat transfer coefficients employing eqn (7) was ±16%. The experimental local heat transfer coefficients were in a range 1.3–4.0 (kW m^{-2} $^{\circ}\mathrm{C}^{-1}$).

Figure 4 shows representative data for the ammonia/lithium nitrate mixture of the ratio of the local heat transfer coefficient in two phase flow to the local heat transfer coefficient for the liquid phase against the reciprocal of the Martinelli parameter. It can be seen that the ratio of the local heat transfer coefficients depend significantly on both the boiling number and the reciprocal of the Martinelli parameter. The results show that both the forced convective and nucleate boiling mechanisms are significant. This phenomenon has been observed and analysed by Jung et al. [11] and Ross et al. [10] for mixtures of refrigerants at low qualities (partial low regime). Shah [21] showed that the heat transfer coefficients in the partial boiling regime are a strong function of Bo. The higher Bo, the larger heat transfer coefficients. In eqn (7) it can be seen that the exponents of Bo and $1/X_{\mathrm{tt}}$ are not too different and in fact, the exponent of Bo is little higher than the exponent of $1/X_{\mathrm{tt}}$ which confirms the aforementioned. The ratio of the local heat transfer coefficients fall in a range of 5.2–8.2 (kW m^{-2} $^{\circ}\mathrm{C}^{-1}$).

Figure 5 shows the ratio of the local heat transfer coefficient in two phase flow to the local heat transfer coefficient for the liquid phase against the reciprocal of the Martinelli parameter for all the data obtained for the ammonia/lithium nitrate mixture and for the six stations of thermocouples placed in the text section. It can be seen that the curves for each thermocouple station get close to each other with the increment of $1/X_{\mathrm{tt}}$ indicating that the nucleate boiling is getting suppressed. Also if the tendency continues, all the data will fall into a single line showing only the dependence of the heat transfer coefficients on quality or $1/X_{\mathrm{tt}}$. This can be observed more clearly for the ammonia/water mixture in Fig. 8.

Figure 6 is a plot of the average heat transfer coefficient against heat flux for the ammonia/lithium nitrate mixture for different ammonia concentration values. It can be seen that the average heat transfer coefficients increase with the solution concentration. However, for higher values of the heat flux, the heat transfer coefficients tend to be the same for the higher solution concentrations.

Figure 7 shows the comparison of predicted against experimental local heat transfer coefficients for the ammonia/water mixture. A higher dispersion of the predicted heat transfer coefficients than those obtained for the ammonia/lithium nitrate mixture can be seen. In this case 28% of the data have a deviation higher than ±30% and the mean deviation for all the predicted heat transfer coefficients employing eqn (8) was ±26%. The experimental local heat transfer coefficients were in a range 1.7–6.2 (kW m^{-2} $^{\circ}\mathrm{C}^{-1}$).

Figure 8 shows the ratio of the local heat transfer coefficient in two phase flow to the local heat transfer coefficient for the liquid phase against the reciprocal of the Martinelli parameter for all the data obtained for the ammonia/water mixture. In this figure it can be seen how for lower values of $1/X_{\mathrm{tt}}$ there is some dispersion, however, for higher values of $1/X_{\mathrm{tt}}$, all the data fall approximately into a single line, meaning that the nucleate boiling has been suppressed and the heat transfer coefficients depend only on the quality or the $1/X_{\mathrm{tt}}$. The ratio of the local heat transfer coefficients fall in a range of 15–60 (kW m^{-2} $^{\circ}\mathrm{C}^{-1}$).

Figures 9 and 10 are plots of the average heat transfer coefficients against heat flux for the ammonia/water mixture for different solution concentration values. In Fig. 9 it can be observed that the average heat transfer coefficients increase with both heat flux and solution concentration. Also it can be seen that the difference between the average heat transfer values for different solution concentrations decreases with an increment in the heat flux which means again, that the nucleate boiling condition is being suppressed. Figure 10 reports the same

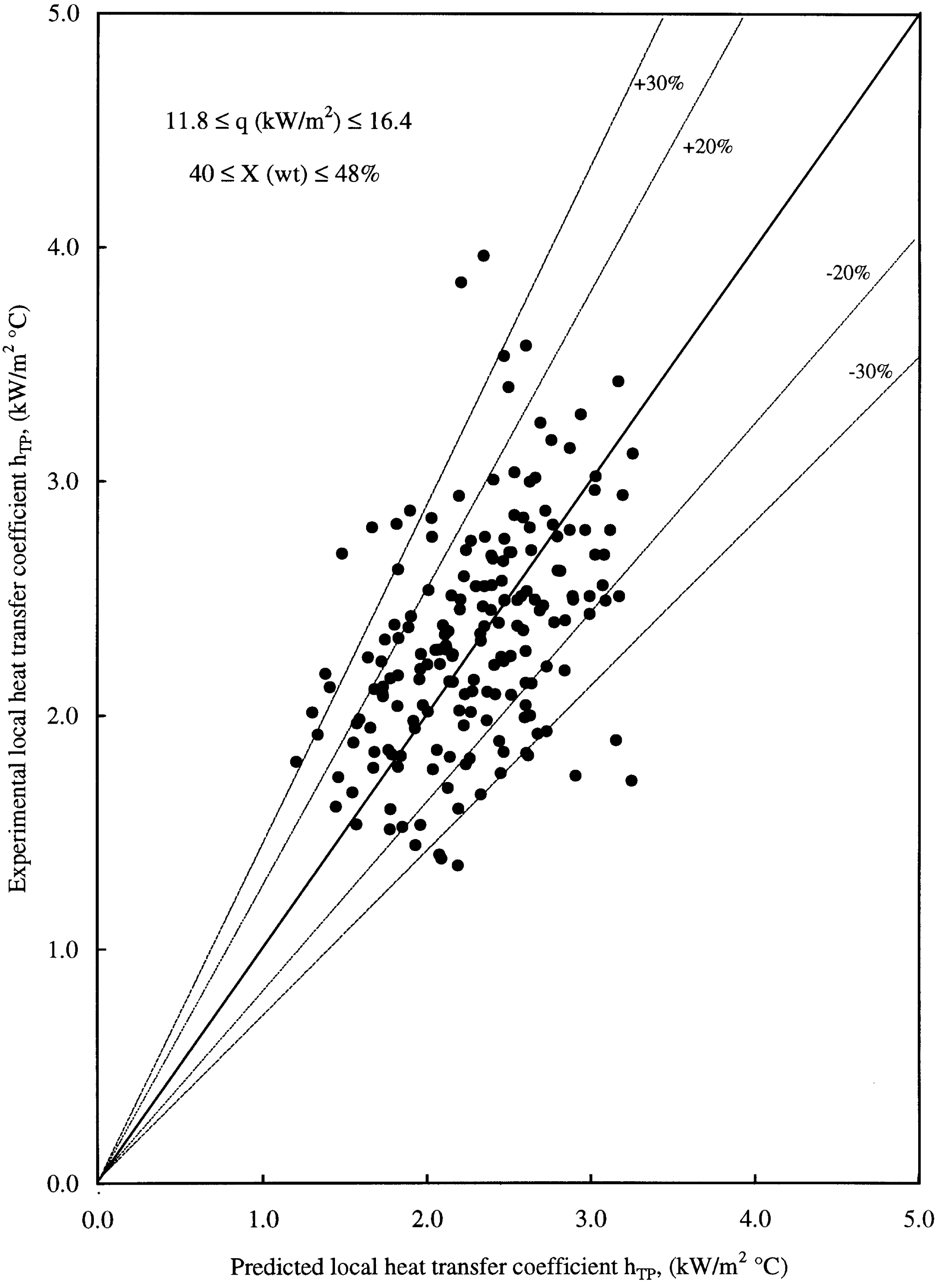

Fig. 3. Comparison of predicted against experimental local heat transfer coefficient for the ammonia/lithium nitrate mixture.

parameters but for three different solution concentrations. It can be seen that for high values of the heat flux the average heat transfer coefficients fall approximately in a single line the same way that it was observed and explained for the local heat transfer coefficients.

Figure 11 is a plot of the average heat transfer

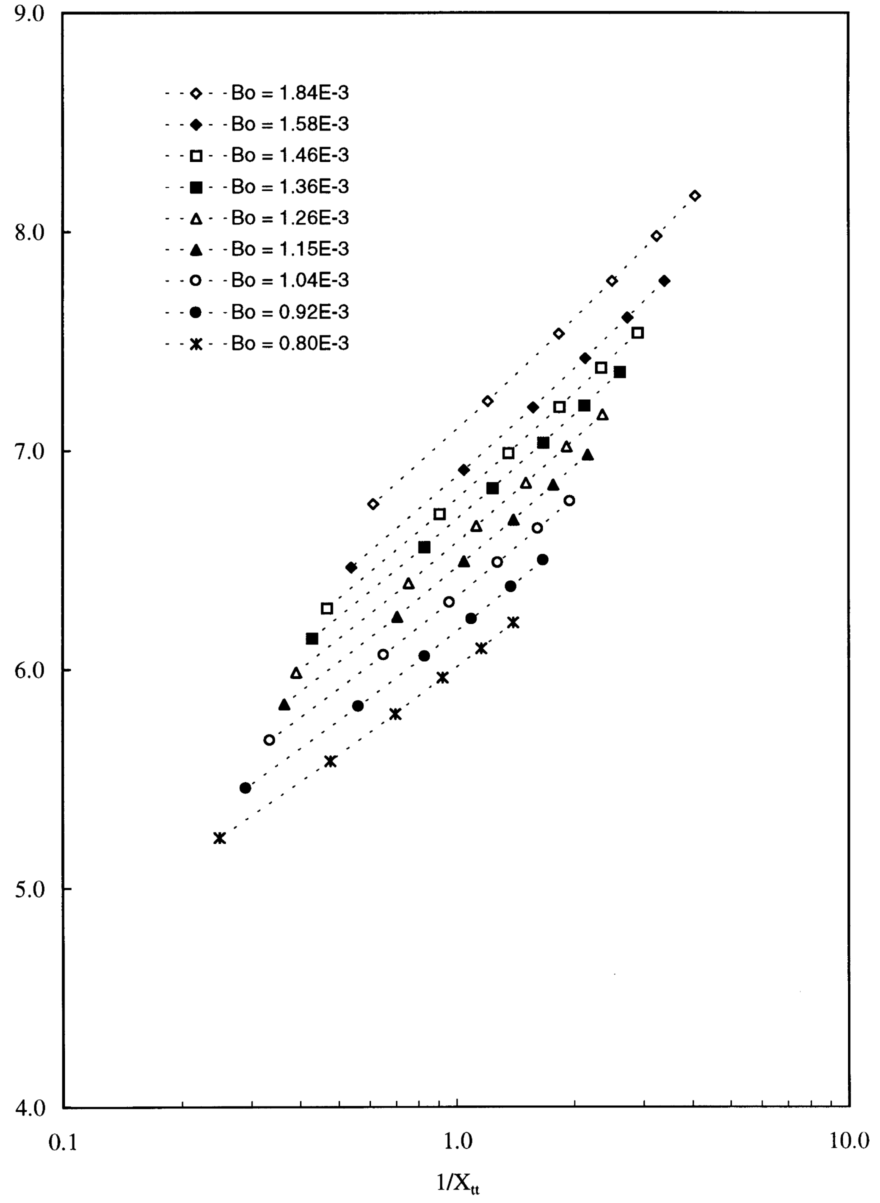

Fig. 4. Local heat transfer coefficents ratio against Lockart–Martinelli parameter at different boiling numbers for the ammonia/lithium nitrate mixture.

coefficients against heat flux for the ammonia/water and ammonia/lithium nitrate mixtures for similar ammonia concentration ranges. It can be observed that the average heat transfer coefficients for the ammonia/water mixture were between two and three times higher than those obtained with the ammonia/lithium nitrate mixture. Also it can be seen that the coefficients for the ammonia/water mixture tend to grow exponentially while the coefficients for the ammonia/lithium nitrate mixture tend to grow linearly.

7. Conclusions

Experimental results were presented of heat transfer coefficients of water/ammonia and ammonia/lithium

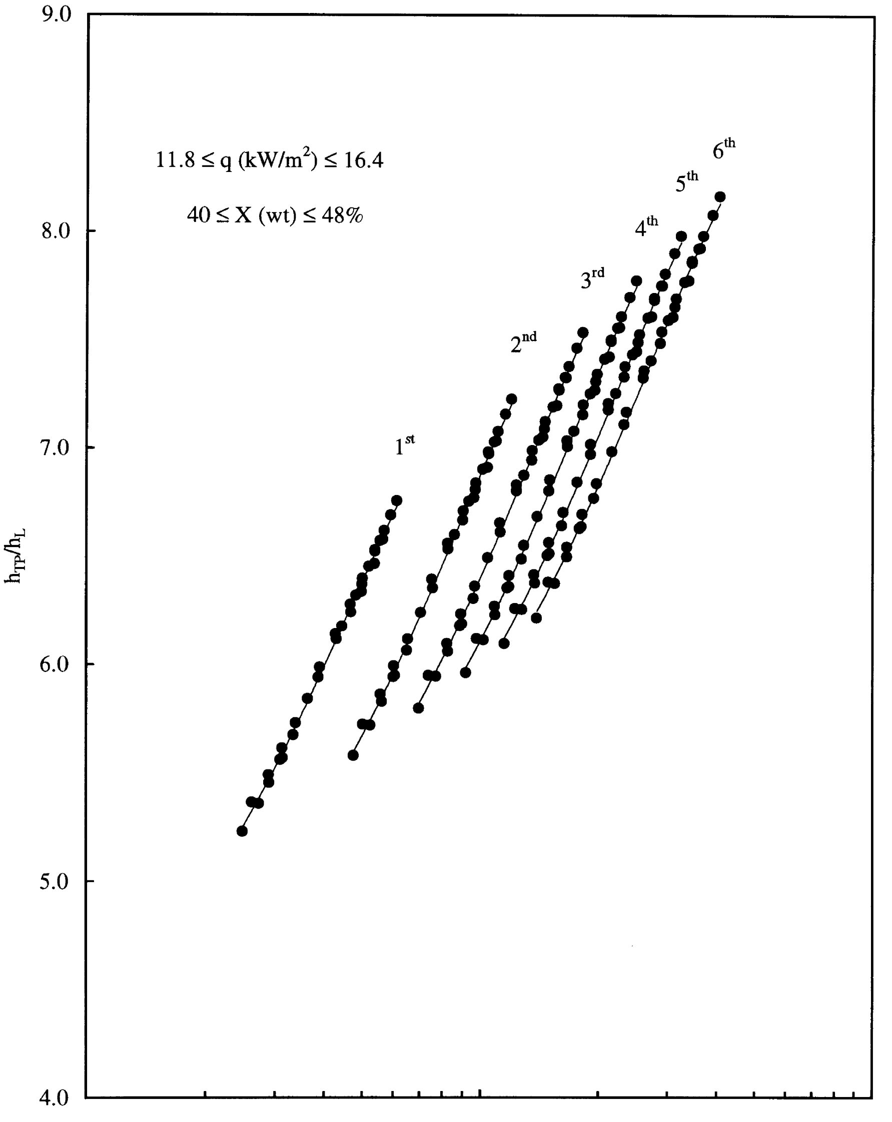

Fig. 5. Local heat transfer coefficients ratio against Lockart–Martinelli parameter for different thermocouples stations for the ammonia/lithium nitrate mixture.

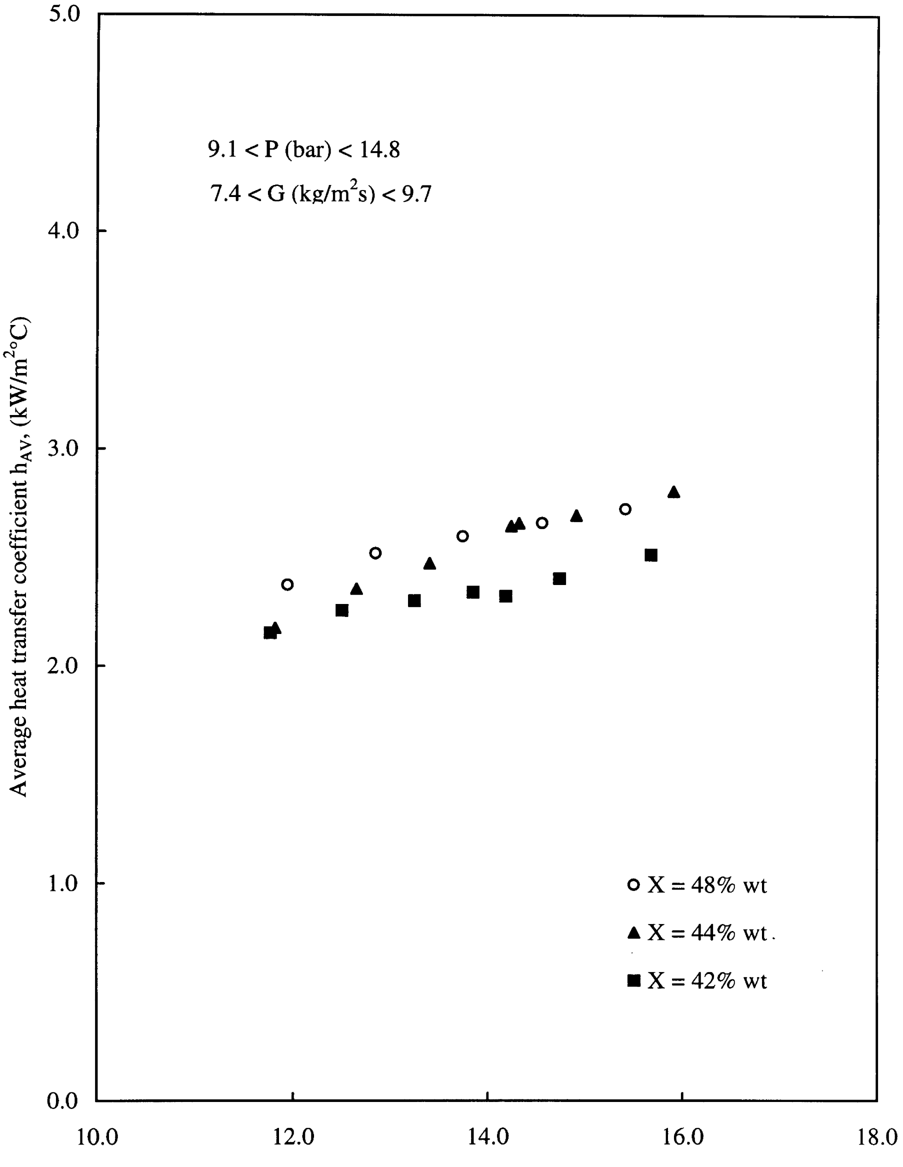

Fig. 6. Average heat transfer coefficients against heat flux for the ammonia/lithium nitrate mixture at solution concentration values of 44, 46 and 48%.

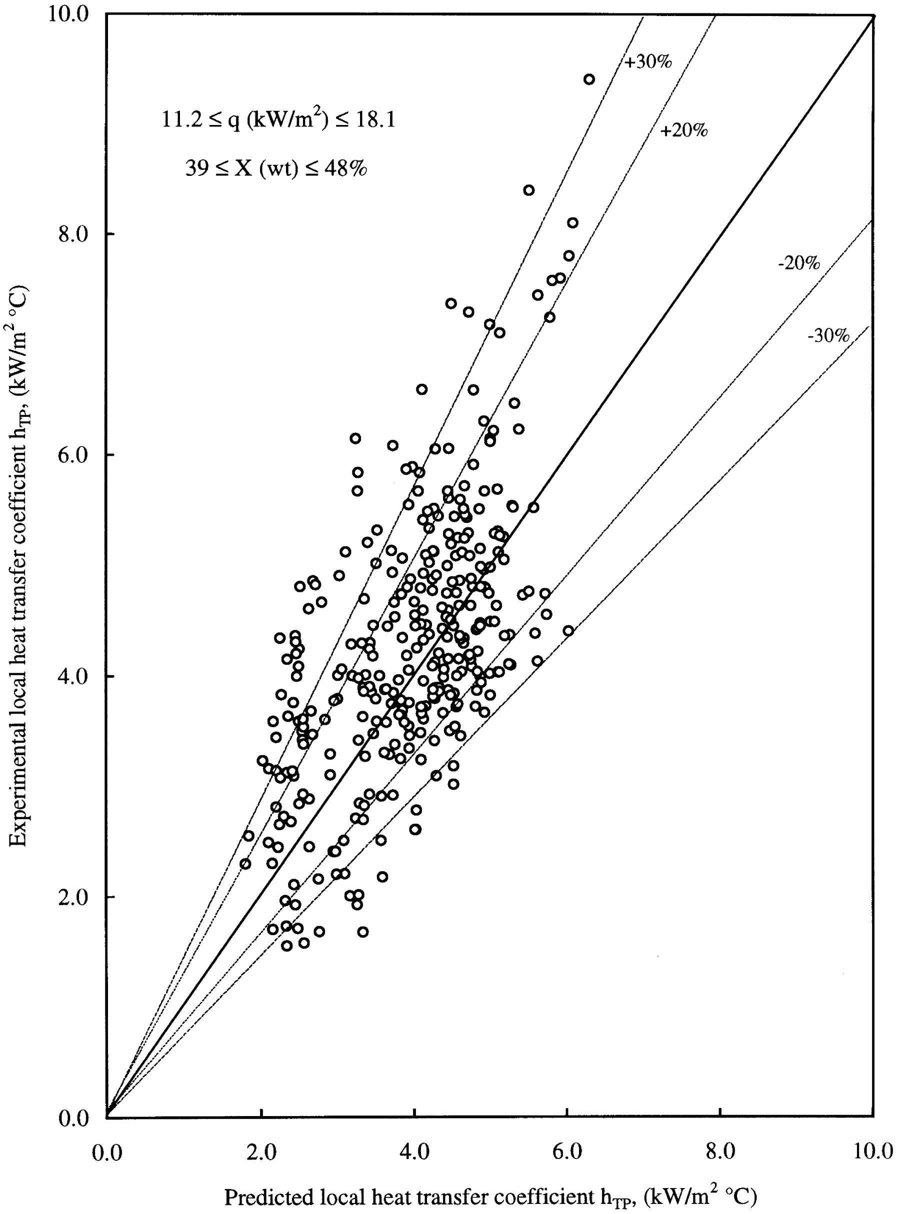

Fig. 7. Comparison of predicted against experimental local heat transfer coefficient for the ammonia/water mixture.

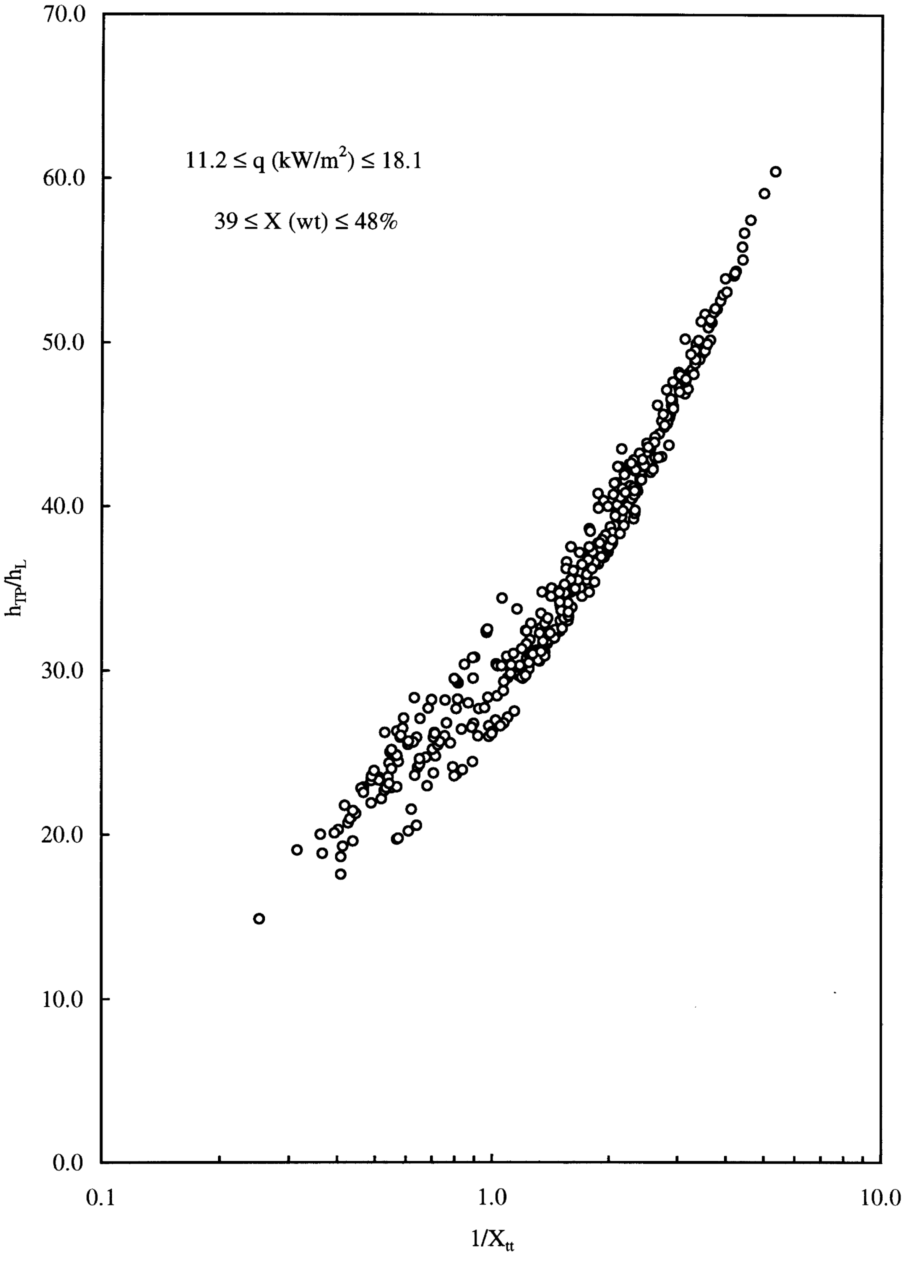

Fig. 8. Local heat transfer coefficients ratio against Lockart–Martinelli parameter for the ammonia/water mixture.

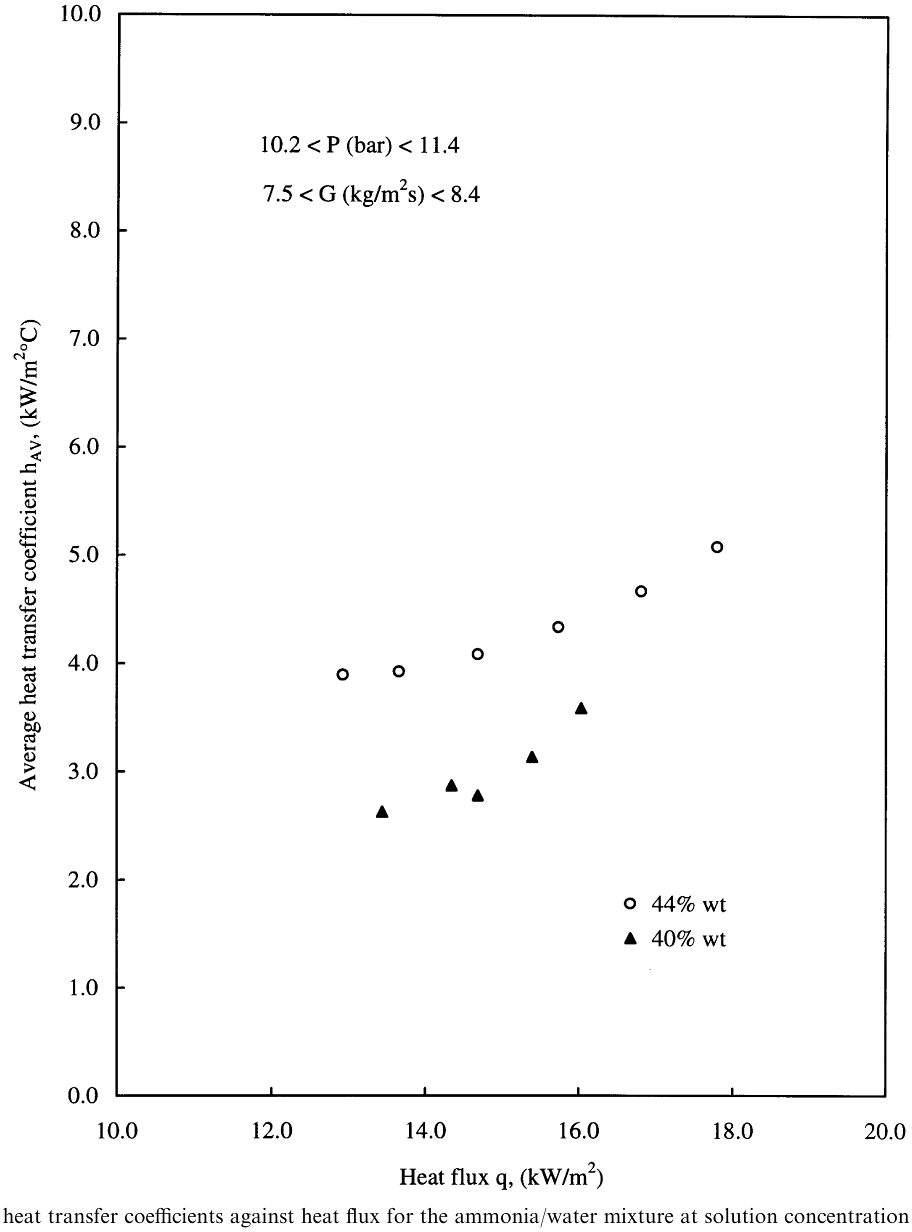

Fig. 9. Average heat transfer coefficients against heat flux for the ammonia/water mixture at solution concentration values of 40 and 44%.

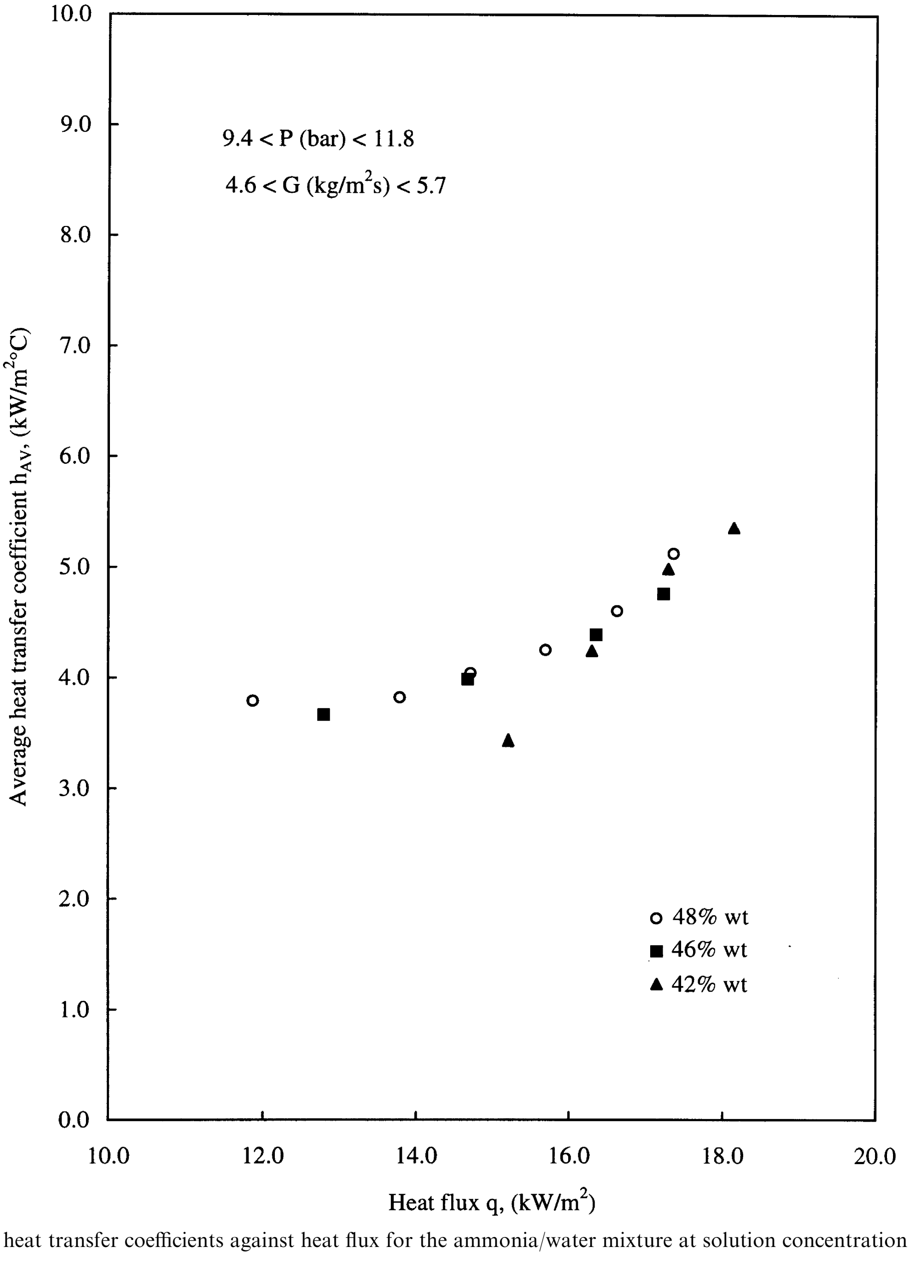

Fig. 10. Average heat transfer coefficients against heat flux for the ammonia/water mixture at solution concentration values of 42, 46 and 48%.

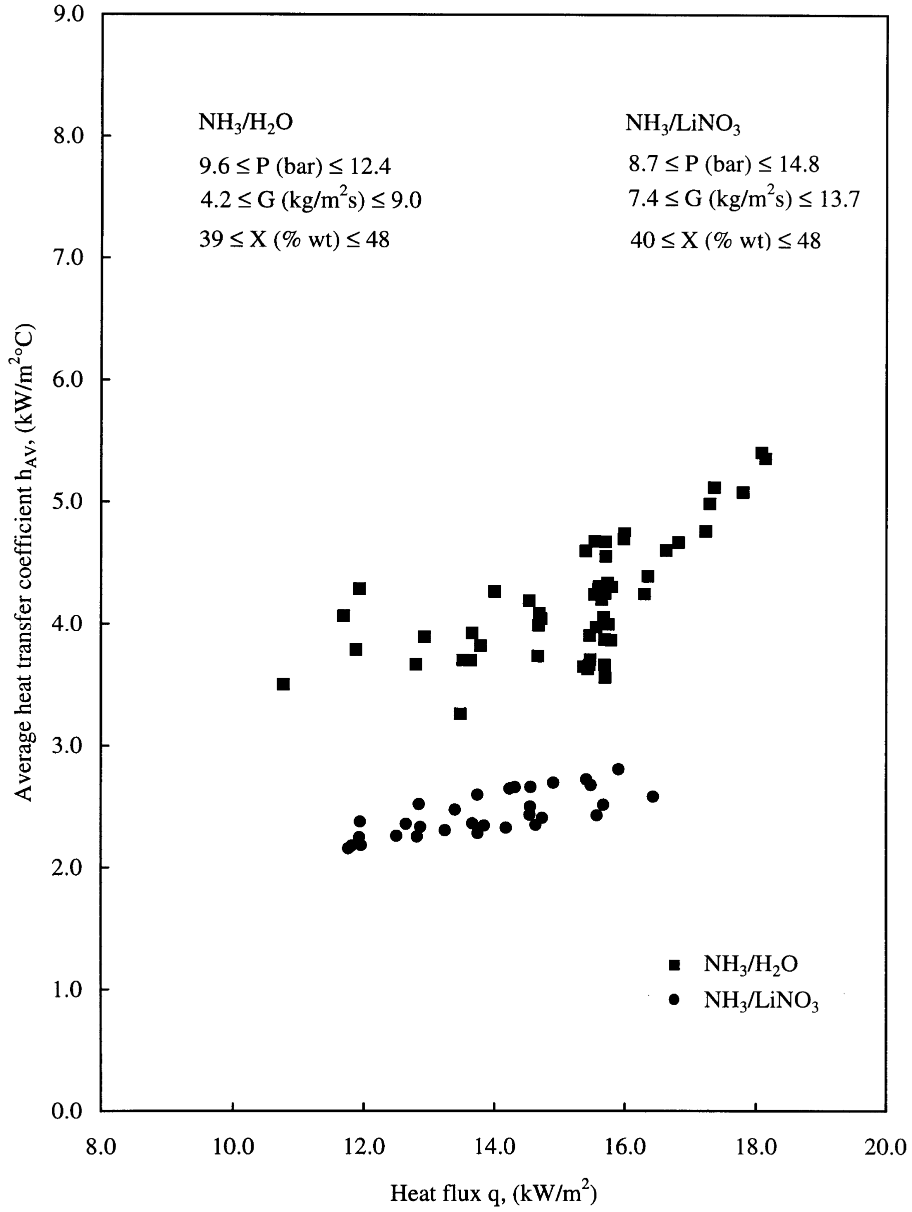

Fig. 11. Average heat transfer coefficients against heat flux for the ammonia/water and ammonia/lithium nitrate mixtures.

nitrate mixtures in forced convective boiling flowing upward in a vertical tube uniformly heated. The concentration range for the water/ammonia was from 38 to 48 wt.%, with a pressure range from 9.4 to 12.4 bar. The concentration range for the ammonia/lithium nitrate was from 38 to 48 wt. %, with a pressure range from 8.7 to 14.8 bar.

Correlations were proposed based on Mishra et al. model [7], to correlate the experimental local heat transfer coefficients with a mean deviation of $\pm 16\%$ for the ammonia/lithium nitrate mixture and $\pm 25\%$ for the ammonia/water mixture. The results showed that the local heat transfer coefficients are strongly dependent on *Bo* for the ammonia/lithium nitrate mixture and more dependent on quality and $1/X_{tt}$ for the ammonia/water mixture at the analysed conditions, as can be observed in

Figs 4, 5 and 8, and also in the exponents on *Bo* and $1/X_{tt}$ in equations (7) and (8).

Comparing both mixtures, it was observed that the average heat transfer coefficients for the water/ammonia mixture were between two and three times higher than those obtained with the ammonia/lithium nitrate mixture.

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