



## Experimental Heat Transfer

A Journal of Thermal Energy Generation, Transport, Storage, and Conversion

ISSN: 0891-6152 (Print) 1521-0480 (Online) Journal homepage: <https://www.tandfonline.com/loi/ueht20>

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To cite this article: A. Sathyabhama & T. P. Ashok Babu (2012) Experimental Investigation of Pool Boiling Heat Transfer in Ammonia–Water–Lithium Nitrate Solution, Experimental Heat Transfer, 25:2, 127-138, DOI: [10.1080/08916152.2011.582568](https://doi.org/10.1080/08916152.2011.582568)

To link to this article: <https://doi.org/10.1080/08916152.2011.582568>



Published online: 21 Mar 2012.



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## EXPERIMENTAL INVESTIGATION OF POOL BOILING HEAT TRANSFER IN AMMONIA–WATER–LITHIUM NITRATE SOLUTION

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*The nucleate pool boiling heat transfer coefficient of an NH<sub>3</sub>-H<sub>2</sub>O-LiNO<sub>3</sub> mixture was investigated on a cylindrical heated surface at low pressure of 4 to 8 bar, low ammonia mass fraction of  $0 < x_{\text{NH}_3} < 0.3$ , and different heat fluxes. The lithium nitrate concentration of the solution was chosen in the range of 10–50% of mass ratio of lithium nitrate in pure water. The effects of concentrations, 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 the addition of lithium nitrate, and increases with an increase in heat flux and pressure in the investigated range.*

**Keywords** NH<sub>3</sub>-H<sub>2</sub>O, NH<sub>3</sub>-LiNO<sub>3</sub>, NH<sub>3</sub>-H<sub>2</sub>O-LiNO<sub>3</sub>, ternary mixture, nucleate pool boiling, heat transfer coefficient

### INTRODUCTION

Absorption refrigeration systems have attracted increasing research interest in recent years. Unlike mechanical vapor compression refrigerators, these systems cause no ozone depletion and reduce demand on electricity supply. Besides, heat-powered systems could be superior to electricity powered systems in that they harness inexpensive waste heat, solar, biomass, or geothermal energy sources for which the cost of supply is negligible in many cases. This makes heat-powered refrigeration a viable and economic option. The most common absorption systems are H<sub>2</sub>O-LiBr and NH<sub>3</sub>-H<sub>2</sub>O cycles. The advantage for refrigerant ammonia is that it can evaporate at lower temperatures (i.e., from  $-10^{\circ}\text{C}$  to  $0^{\circ}\text{C}$ ) compared to water (i.e., from  $4^{\circ}\text{C}$  to  $10^{\circ}\text{C}$ ). Therefore, for refrigeration, the NH<sub>3</sub>-H<sub>2</sub>O cycle is used. Research has been performed for NH<sub>3</sub>-H<sub>2</sub>O systems theoretically and experimentally. These studies show that the NH<sub>3</sub>-H<sub>2</sub>O system exhibits a relatively low coefficient of performance (COP). Also, water as an absorbent has limitations that stem from the appreciable vapor pressure of water. The ammonia vapor, which is desorbed from aqua-ammonia, always includes a small fraction of water vapor. The latter, if not removed by rectification, is detrimental, as water accumulates in the evaporator, increasing the evaporator pressure.

The performance of NH<sub>3</sub>-H<sub>2</sub>O absorption cycles can be improved by using various inorganic salts as additives to reduce the vapor pressure of water. For simple absorption

Received 17 January 2011; accepted 25 March 2011.

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### NOMENCLATURE

$A$	area ( $\text{m}^2$ )	<b>Greek Symbols</b>	
$A_o$	constant in Eq. (7)	$\alpha$	thermal diffusivity ( $\text{m}^2\text{s}^{-1}$ )
$d$	diameter (m)	$\Delta T$	temperature difference (K)
$D$	mass diffusivity ( $\text{m}^2\text{s}^{-1}$ )	$\rho$	density ( $\text{kgm}^{-3}$ )
$g$	gravitational acceleration ( $\text{ms}^{-2}$ )	$\sigma$	surface tension ( $\text{Nm}^{-1}$ )
$h$	nucleate boiling heat transfer coefficient ( $\text{W m}^{-2} \text{K}^{-1}$ )	$\omega$	uncertainty
$h_{fg}$	latent heat of vaporization ( $\text{J kg}^{-1}$ )	<b>Subscripts</b>	
$L$	length (m)	$id$	ideal
$P$	pressure (bar)	$L$	liquid
$q$	heat flux ( $\text{W m}^{-2} \text{K}^{-1}$ )	$s$	saturation
$Q$	heat input	$v$	vapor
$T$	temperature (K)	$w$	wall
$x, y$	mass fraction of liquid and vapor		

cycles, this reduction in the water vapor pressure could potentially reduce the amount of rectification needed to separate ammonia from water. Reduction of ammonia rectification requirements would simplify the design and reduce the cost of the generator. For advanced absorption cycles, such as the generator absorber heat exchange (GAX) cycle, a ternary fluid ( $\text{NH}_3\text{-H}_2\text{O}$ -dissolved salt) would permit higher generator temperatures that would facilitate more generator and absorber heat exchange, thereby increasing the COP [1].

The first research that proposed the  $\text{NH}_3\text{-H}_2\text{O-LiNO}_3$  ternary system was Davis et al. [2]. Reiner and Zaltash [1] also proposed this system, but neither study presented enough data in order to characterize the system from the point of view of absorption cycles. Ehmke and Renz [3] presented the most important study of the properties of this system. They studied the effects of the water content on crystallization and viscosity. They also determined and correlated the density and the vapor pressure of the system with a water content of 25%. The vapor pressure of  $\text{NH}_3\text{-H}_2\text{O-LiNO}_3$  and  $\text{NH}_3\text{-LiNO}_3$  mixtures was measured by a static method from 293.15 K to 353.15 K in ammonia mass fractions ranging from 0.2 to 0.6 by Libotean et al. [4].

Properties and vapor liquid equilibria of the  $\text{NH}_3\text{-H}_2\text{O-LiNO}_3$  system have been established; no information, however, is available on the effect of dissolved salt on the mechanism of boiling, which is essential in the design of refrigeration system. The aim of the present article is to obtain the nucleate pool boiling heat transfer coefficient of the  $\text{NH}_3\text{-H}_2\text{O-LiNO}_3$  ternary system at different mass fractions of ammonia and lithium nitrate, at different pressures, and at different heat fluxes.

### EXPERIMENTAL SET-UP

The schematic diagram of the experimental set-up is shown in Figure 1. The unit consists of a boiling vessel, water pump, vacuum pump, condenser coil, and test section. The boiling vessel, with an 80-mm diameter and 200-mm length, is fitted with SS 316 flanges at the top and at the bottom, as shown in Figure 1. The vessel is fitted with two sight glasses to observe and record the boiling phenomena. The top flange has provisions for liquid charging, a condenser cooling water inlet and outlet, a vacuum pump, a pressure transducer, and thermocouples to measure liquid and vapor temperatures. Bottom flange

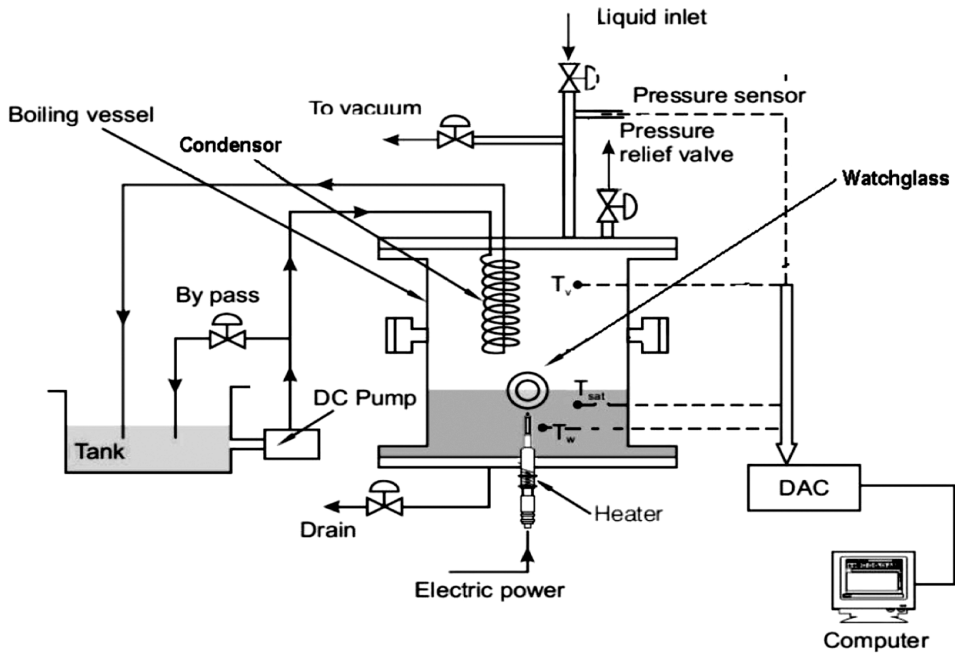


Figure 1. Experimental set-up.

has provisions for the 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 alloy 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 with 1 kW of 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 Figure 2.

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

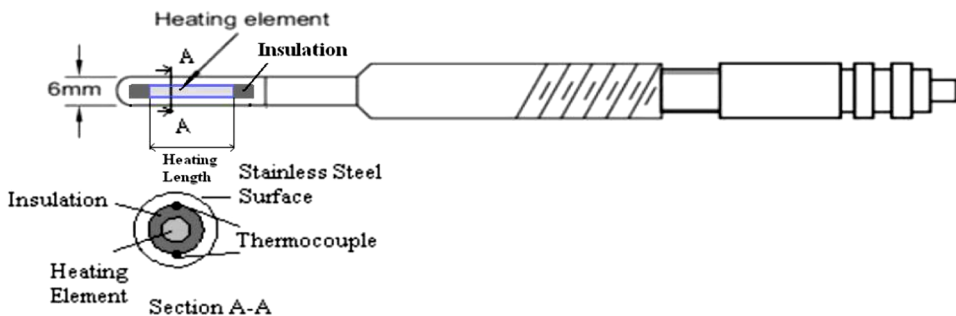


Figure 2. Details of test heater. (color figure available online)

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 the Fourier heat conduction equation. The internal pressure of the 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.

## EXPERIMENTAL PROCEDURE

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

Determination of the nucleate pool boiling heat transfer coefficient in the  $\text{NH}_3\text{-H}_2\text{O}$  and  $\text{NH}_3\text{-H}_2\text{O-LiNO}_3$  systems, at low concentrations of ammonia in the liquid phase, and at low pressure is made in the present work. Pressure and temperature limitations of the experimental set-up and difficulty in preparing  $\text{NH}_3\text{-H}_2\text{O}$  mixture of different concentration did not allow data to be taken at full concentration range. An aqueous ammonia solution of approximately 30 wt% and 25 wt% of ammonia of 99.99% purity supplied by Nice Chemicals (Cochin, India) was used in this study. Distilled water was used to dilute the aqueous ammonia. Subsequently, a measured quantity of the  $\text{LiNO}_3\text{-H}_2\text{O}$  solution of known concentration was added, and the ternary mixture was heated to saturation temperature by giving heat input to the rod heater. After equilibrium was reached, the saturation temperature and heater surface temperature were noted for different heat fluxes, and the set pressure was changed. The measurements were performed in the pressure range  $p = 4$  to 8 bar. The  $\text{LiNO}_3$  concentration of the solution was chosen in the range of 10–50% of mass ratio of  $\text{LiNO}_3$  in pure water.

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.

## 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 is  $q = \frac{Q}{A}$ , where  $A$  is the surface area of the test section;  $A = \pi dL$ , where  $d$  is the diameter of the heater rod, and  $L$

is the heating length of the heater rod. The 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 as indicated by the thermocouple brazed on the test section surface.

### 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  $\pm 0.5$  full scale. The power input to the heater is measured by an accurate digital power meter of accuracy  $\pm 1$  W. The uncertainty in temperature measurement is  $\pm 1.25^\circ\text{C}$ . Uncertainty in length and diameter measurement is  $\pm 0.1$  mm. The resulting uncertainty in the area of the heated surface is 1.74%. The Kline and McClintock [5] technique was used to estimate the uncertainty for the derived quantities.

The percentage uncertainty in heat transfer coefficient is

$$\omega_h = \left[ \left( \frac{\omega_Q}{Q} \right)^2 + \left( \frac{\omega_d}{d} \right)^2 + \left( \frac{\omega_L}{L} \right)^2 + \left( \frac{\omega_{T_w}}{T_w - T_s} \right)^2 + \left( \frac{\omega_{T_s}}{T_w - T_s} \right)^2 \right]^{\frac{1}{2}}. \quad (2)$$

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%.

### EXPERIMENTAL RESULTS

#### Ammonia–Water Binary Mixture

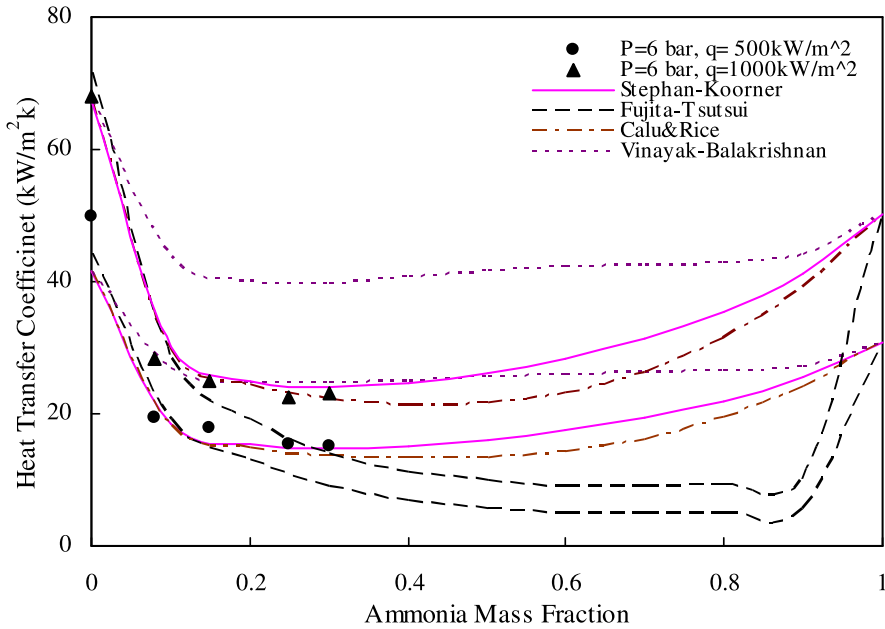
The mass fraction of ammonia is defined as follows:

$$x_{\text{NH}_3} = \frac{m_{\text{NH}_3}}{m_{\text{NH}_3} + m_{\text{H}_2\text{O}}}. \quad (3)$$

Figure 3 shows the measured heat transfer coefficients against the mixture concentration with heat flux as parameter for the NH<sub>3</sub>-H<sub>2</sub>O binary mixture. As seen in Figure 3, the heat transfer coefficient of binary mixtures reduces with an increase in ammonia mass concentration with a more pronounced reduction at higher heat flux. The measured data were compared with correlations of Fujita and Tsutsui [6], Stephan and Koorner [7], Calus and Rice [8], and Vinayak and Balakrishnan [9], which are reduced to a common form as

$$\frac{h}{h_{id}} = \frac{1}{1 + K}, \quad (4)$$

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



**Figure 3.** Heat transfer coefficient of binary mixture  $\text{NH}_3\text{-H}_2\text{O}$ . (color figure available online)

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  $\Delta T_{id}$ , which is determined as a molar interpolation of the wall superheats for mixture components evaluated at the same heat flux as the mixture; that is,

$$\Delta T_{id} = \frac{q}{h_{id}} = \frac{q}{\sum \left( \frac{x_i}{h_i} \right)} \quad (5)$$

or alternatively using mixture properties in empirical correlations applicable to pure liquids. Among the four referred correlations, the Stephan–Kooerner [7] correlation well predicts the data for the present binary mixture at a high heat flux of  $1,000 \text{ kW/m}^2$  and at a low heat flux of  $500 \text{ kW/m}^2$ , as exemplified in Figure 3. The correlations are given below:

Fujita–Tsutsui [6]:

$$\frac{h}{h_{id}} = \left\{ 1 + \frac{\Delta T_{bp}}{\Delta T_{id}} \left[ 1 - \exp \left( \frac{-60q}{\rho_v h_{fg}} \left\{ \frac{\rho_v^2}{\sigma g (\rho_L - \rho_v)} \right\}^{\frac{1}{4}} \right) \right] \right\}^{-1}, \quad (6)$$

Stephan–Kooerner [7]:

$$\frac{h}{h_{id}} = [1 + A_o(0.88 + 0.12P)(y_1 - x_1)]^{-1}, \quad (7)$$

Calus–Rice [8]:

$$\frac{h}{h_{id}} = \left[ \left\{ 1 + (y_1 - x_1) \left( \frac{\alpha_L}{D} \right)^{0.5} \right\}^{0.7} \right]^{-1}, \quad (8)$$

Vinaya–Balakrishnan [9]:

$$\frac{h}{h_{id}} = \left[ 1 + (y_1 - x_1) \left( \frac{D}{\alpha_L} \right)^{0.5} \right]. \quad (9)$$

The Fujita–Tsutsui correlation was 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 a function of heat flux. They determined this function in reference to their heat transfer data of seven different kinds of binary mixtures, including aqueous, organic, non azeotropic, and azeotropic mixtures. The influence of heat flux was made dimensionless in order to extend their correlation to a wider use. In Eq. (7),  $A_o$  is an empirical constant. Stephan and Koorner [7] determined the value of  $A_o$  to range from 0.42 to 3.56 for 17 mixtures by fitting Eq. (7) to the measured data. Their average value of 1.53 is recommended for mixtures where the data are not available. One of the few correlations (Eq. (8)) to attempt to quantitatively relate the reduction in the heat transfer coefficient to the reduction in bubble growth rate is that of Calus and Rice [8]. Vinayak and Balakrishnan [9] developed the correlation (Eq. (9)) by incorporating the binary diffusivity of the mixture.

### Ammonia–Water–Lithium Nitrate Ternary Mixture

The concentration of lithium nitrate salt is expressed as weight percentage on an ammonia-free solution basis, as defined below:

$$x_{\text{LiNO}_3} = \frac{m_{\text{LiNO}_3}}{m_{\text{LiNO}_3} + m_{\text{H}_2\text{O}}}. \quad (10)$$

For ternary mixtures of 9 concentrations, 280 data points are measured in this work. Since it is difficult to represent all these data in graphical form, the boiling curves are presented in Table 1 in the form of the following equation expressing the heat transfer coefficient  $h$  as a function of heat flux  $q$ :

$$h = Cq^n, \quad (11)$$

where constant  $C$  and exponent  $n$  were determined by fitting Eq. (11) to the data points in the fully developed nucleate boiling region. The values of the exponent  $n$  in Table 1 match well with the generally obtained values of 0.6–0.8. The average error deviation from Eq. (11) is 0.65%. Note in the table that the suffixes NH<sub>3</sub> and H<sub>2</sub>O refer to the more volatile component ammonia and the moderate volatile component water in the present ternary mixture, respectively. LiNO<sub>3</sub> refers to non volatile salt lithium nitrate. Mixture composition is expressed in terms of mass fraction, such as  $x_{\text{NH}_3}$ ,  $x_{\text{H}_2\text{O}}$ , and  $x_{\text{LiNO}_3}$  in the liquid phase.

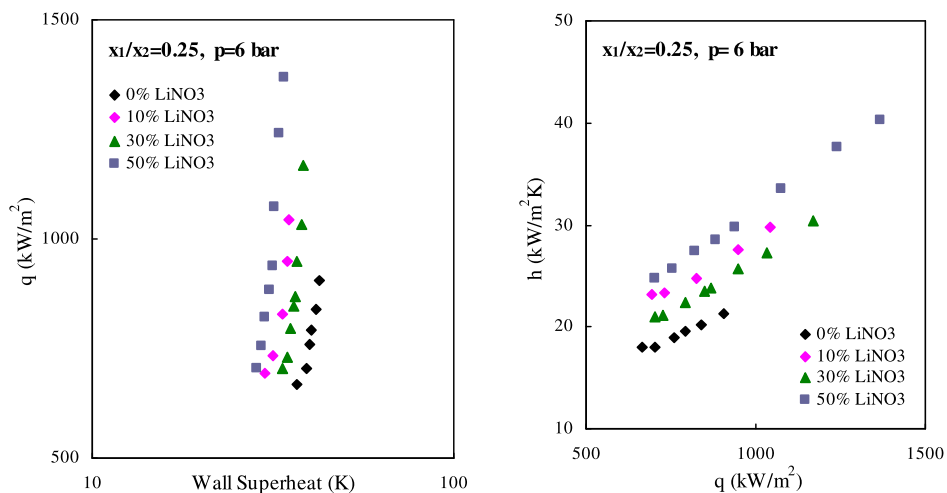


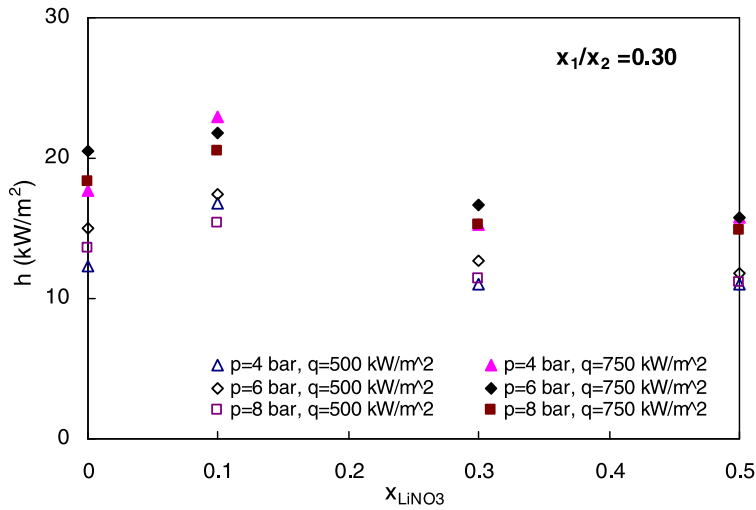
**Table 1.** Coefficient  $C$  and exponent  $n$  in Eq. (11) to reproduce the measured heat transfer coefficients for ternary mixture  $\text{NH}_3\text{-H}_2\text{O-LiNO}_3$ 

$x_{\text{NH}_3}$	$x_{\text{H}_2\text{O}}$	$x_{\text{LiNO}_3}$	Heat flux ( $\text{kW}/\text{m}^2$ )	Number of data points	$C$	$n$	Error (%)
0.15	0.75	0.10	836–2,303	37	0.29	0.6949	3.42
0.15	0.55	0.30	806–2,215	33	0.229	0.7178	4.81
0.15	0.35	0.50	635–2,321	49	0.138	0.8137	2.21
0.25	0.65	0.10	610–1,463	17	0.0748	0.878	6.12
0.25	0.45	0.30	617–1,803	32	0.1301	0.7796	7.41
0.25	0.25	0.50	578–2,296	42	0.1506	0.7756	2.95
0.30	0.60	0.10	421–1,040	22	0.3741	0.6124	25.20
0.30	0.40	0.30	474–1,281	17	0.1929	0.775	0.57
0.30	0.20	0.50	507–1,477	29	0.0722	0.8021	3.59

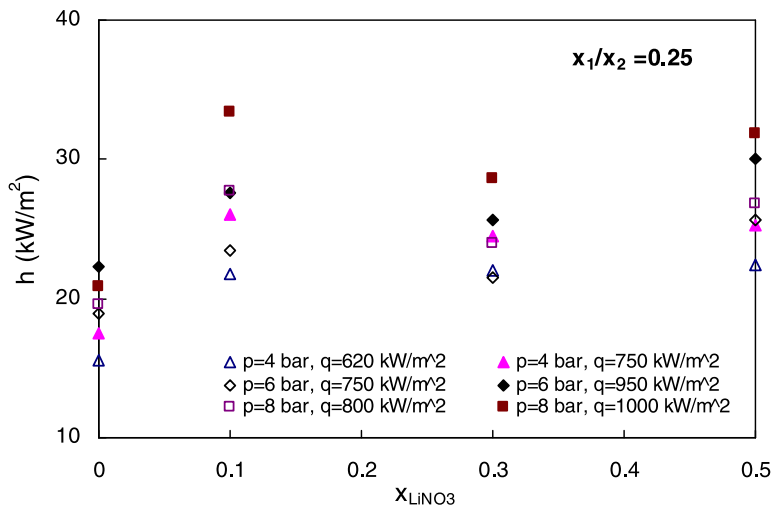
The heat transfer coefficient of the three-component mixture varies as a function of the mixture composition and heat flux. So the heat transfer coefficient of the ternary mixture needs three-dimensional representation. Here, two-dimensional representation is used with the concentration of ammonia kept constant. Figure 4 represents the boiling curve and variation of the heat transfer coefficient with the heat flux for an ammonia mass fraction of 0.25 at 6 bar pressure.

Figures 5a–5c present the effect of  $\text{LiNO}_3$  on the heat transfer coefficient for ammonia mass fractions of 0.3, 0.25, and 0.15, respectively. The heat transfer coefficient increases significantly up to an  $\text{LiNO}_3$  concentration of 0.10 at all heat fluxes and pressures. The heat transfer coefficient increases slightly with the increase in the concentration of  $\text{LiNO}_3$ . The effect of the  $\text{LiNO}_3$  salt on the heat transfer coefficient becomes smaller with increases in the ammonia fraction, as can be seen from Figure 5a. The reason for the enhancement of the heat transfer coefficient is quite complex.

**Figure 4.** Boiling curve and variation of heat transfer coefficient with heat flux. (color figure available online)



(a)



(b)

**Figure 5.** Effect of LiNO<sub>3</sub> concentration on heat transfer coefficient. (color figure available online)(continued)

Additives are known to affect the boiling process. One particular type of additive that has been shown to affect nucleate boiling is surfactant. Inoue et al. [10] studied the effect of cationic surfactant on boiling heat transfer enhancement of an ethanol/water mixture. They reported an increase in the boiling heat transfer coefficient in low heat flux range in low ethanol fraction range by the surfactant. They attributed this increase to the decrease in surface tension of the mixture by the addition of surfactant.

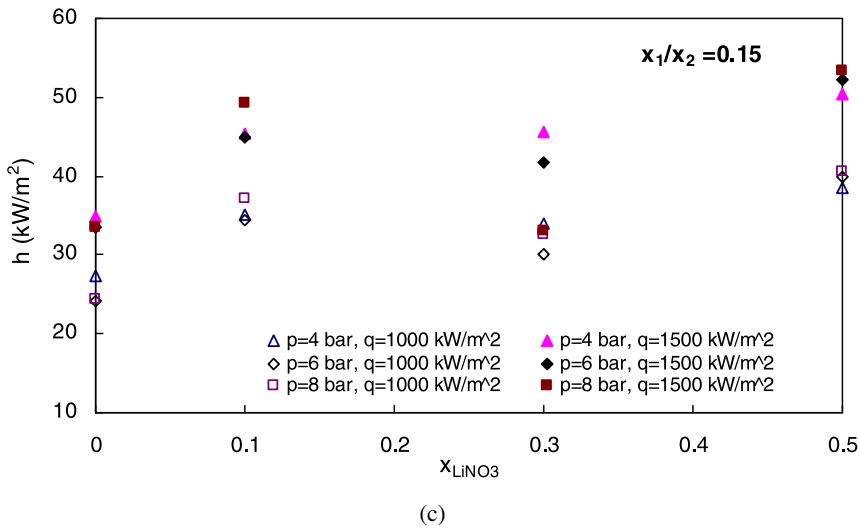


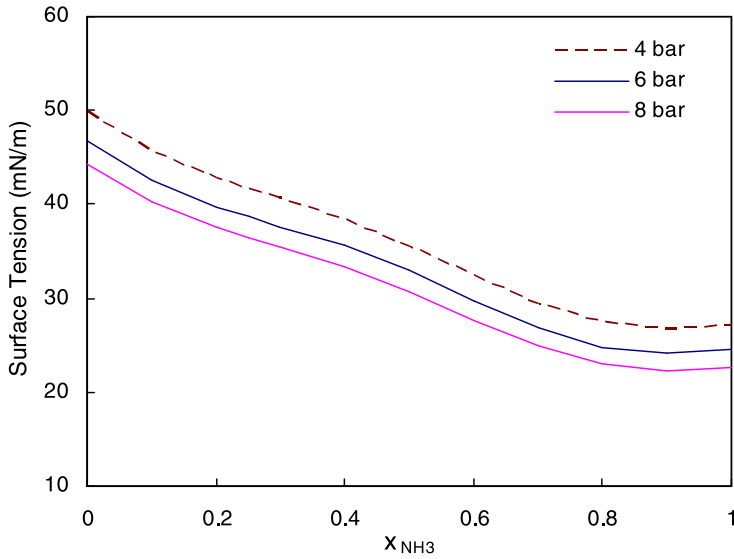
Figure 5. (Continued).

Cui et al. [11] conducted experiments on the effect of dissolving one of three salts ( $\text{NaCl}$ ,  $\text{Na}_2\text{SO}_4$ , or  $\text{MgSO}_4$ ) in water sprays used for cooling of a hot surface. The results were compared with those obtained using pure water sprays. Dissolved  $\text{NaCl}$  or  $\text{Na}_2\text{SO}_4$  increased nucleate boiling heat transfer but had little effect on transition boiling during spray cooling.  $\text{MgSO}_4$  increased both nucleate and transition boiling heat flux. Enhanced nucleate boiling was attributed to foaming in the liquid film generated by the dissolved salts.

$\text{LiNO}_3$  salt is expected to reduce the surface tension of the  $\text{NH}_3\text{-H}_2\text{O}$  mixture, thus increasing the boiling heat transfer coefficient. The effect of  $\text{LiNO}_3$  on surface tension is supposed to become weaker as the ammonia fraction increases, since the surface tension decreases with an increase in the mass fraction of ammonia, as shown in Figure 6. Systematic experimental measurements of dynamic surface tension and contact angle are required to explain the complex dependence of concentration of  $\text{LiNO}_3$  salt additive on boiling heat transfer observed in this work.

Many researchers observed significant improvement in critical heat flux/boiling heat transfer coefficient with innovative heat transfer fluids suspended by nanometer-sized solid particles called “nanofluids.” The precise reasons for this behavior is unknown but could be explained by particles depositing onto the surface and increasing the nucleation site density. Higher concentrations resulted in the deposition of a thin film on the heater surface, and a decrease in nucleate boiling heat transfer was observed. At what point the degradation mechanisms outweigh any enhancement remains unclear. The increase in the boiling heat transfer coefficient observed in this work could be due to the deposition of high molecular weight  $\text{LiNO}_3$  salt additive on the heater surface providing particles that act as nucleation sites within the superheated boundary layer.

A second possible explanation for the observed behavior could be provided by the nucleation theory as speculated by Lowery and Westwater [12]. With the addition of small particles or large molecules, additional interfacial tensions become important,



**Figure 6.** Effect of ammonia mass fraction on surface tension. (color figure available online)

namely the particle-liquid-vapor system. This could create a synthetic nucleus, promoting vapor generation on the hot solid and/or in surrounding superheated liquid.

## CONCLUSION

Heat transfer coefficients in a nucleate pool boiling of pure water, ammonia–water binary, and ammonia–water–lithium nitrate ternary are measured. The effect of lithium nitrate salt on the heat transfer of the ammonia–water binary mixture is studied from the measured data. The following conclusions can be drawn.

- Heat transfer reduction in binary ammonia–water mixture is dependent on the mixture concentration and heat flux. The heat transfer coefficient is successfully predictable using the Stephan–Koorner correlation in the investigated range of low ammonia concentration, which includes the boiling range and heat flux as influencing factors to account for the mixture effects.
- The addition of non volatile lithium nitrate salt increases the boiling heat transfer coefficient of the ammonia–water mixture. This effect is more evident at a decreasing ammonia concentration.
- The increase in heat transfer coefficient could be attributed to
  - i) the high molecular weight of  $\text{LiNO}_3$  salt additive providing particles that act as nucleation sites within the superheated boundary layer or
  - ii) the surface tension depression with the addition of  $\text{LiNO}_3$  producing foaming in the boiling liquid.
- The heat transfer exceedingly enhanced up to an  $\text{LiNO}_3$  concentration of 10%; the effect reduced with a higher concentration of  $\text{LiNO}_3$ .

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