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## Experimental Study of Pool Boiling at Low Heat Flux in Water Miscible Binary Mixtures

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### Abstract

Experimental studies are conducted to investigate pool boiling characteristics of water and its binary mixtures with ethanol and 2-propanol, at low heat fluxes. In-house fabricated experimental setup is used for the studies. Ethanol and 2-propanol are both water miscible and have a boiling point lower than that of pure water. The relation between the surface heat flux and degree of superheat for the above binary mixtures is obtained for low heat flux values in the range of 3 kW/m<sup>2</sup> to 30 kW/m<sup>2</sup>. Variation of change in concentration and degree of superheat with time is reported for water miscible binary mixtures. The experimental results obtained are compared against the results predicted by correlations in the literature.

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**Keywords:** Pool boiling; water miscible; low heat flux; binary mixtures;

### 1. Introduction

A number of well-established correlations in literature predict heat transfer coefficients during nucleate boiling of a pure liquid [1-4]. The boiling mechanism of binary mixture is different than the pure liquids due to combined heat and mass transfer process. The study of boiling in mixtures is important because they exhibit phase change over a range of temperatures at constant pressure. Fujita and Tsutsui [5] carried out experiments on a circular copper plate to find boiling heat transfer coefficients in binary mixtures. The mixtures used by them were methanol-water, ethanol-water, methanol-ethanol, ethanol-n-butanol and methanol-benzene, each saturated at atmospheric pressure. They compared their experimental results with correlations available in literature, for example those proposed by Thome [6]. Also a modification was suggested in Thome's correlation to include the effect of heat flux which helped in correlating their data to within  $\pm 20\%$ . Sarafranz and Peyghambarzadeh [7] performed experiments to study

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saturated pool boiling of three dilute binary mixtures at different heat fluxes and predicted heat transfer coefficient using thermodynamic models. A new correlation was developed by Sarafraz *et al.* [8] for estimating pool boiling heat transfer coefficient of monoethylene glycol (MEG), diethylene glycol (DEG) and water ternary mixtures at different concentrations and heat fluxes.

### Nomenclature

V	Output voltage of autotransformer (V)
I	Current flowing through the heater circuit measured by an ammeter (A)
A	Surface area of the plate (m <sup>2</sup> )
q	Surface heat flux (W/m <sup>2</sup> )
$\Delta T_{bp}$	Difference between dew and bubble point temperatures at a given mole fraction (°C)
$\Delta T_{id}$	Ideal wall superheat (°C)
h	Heat transfer coefficient (W/m <sup>2</sup> K)
$h_{id}$	Ideal heat transfer coefficient calculated from ideal wall superheat and heat flux (W/m <sup>2</sup> K)
X	Mole fraction of lower boiling alcohol in water alcohol mixture

Review of literature emphasizes the fact that nucleate pool boiling of binary mixtures is an important area of research and has got varied applications, ranging from electronic cooling to space. However, it is observed that the literature available on pool boiling of binary mixtures at low heat flux values and for low mole fractions is limited. Pool boiling consists of regimes like natural convection boiling, nucleate boiling and film boiling. These regimes correspond to different parts of the pool boiling curve. Extensive studies have been reported in literature for fully developed nucleate boiling and critical heat flux. But, experimental data available in literature consist of only a few points in low heat flux regime. There is a need for an elaborate experimental study in low heat flux regime at low mole fractions of alcohol, comprising of more data points. This is in order to compare the applicability of existing correlations in the considered regime of nucleate pool boiling. Current experimental study, consisting of pool boiling in water miscible binary mixtures at low heat flux, is one such attempt. Two distinct regimes are identified, one in which the correlation between experimental data and correlations available in literature agree and the other ( $X < 0.3$  and  $q < 20 \text{ kW/m}^2$ ) in which the correlations under predict the experimental data. In addition the current work is extended to predict the time variation of mole fraction of lower boiling component, at various heat fluxes.

## 2. Experimental Description

An experimental setup is built to study nucleate pool boiling in water and water-miscible binary mixtures as schematically shown in Figs. 1(a) and 1(b). The setup consists of a test section, variable autotransformer, data acquisition system, plate heater, thermocouples, ammeter, voltage stabilizer and a computer. The test apparatus is a rectangular container with its walls made up of 0.2 mm thick galvanised iron sheet and the bottom surface made of 6 mm thick copper plate which acts as the test surface. Top of the rectangular container is covered by lid of galvanised iron sheet that has venting holes to maintain atmospheric pressure inside the container. Sides and top of the rectangular container are insulated with 4.5 mm thick rubber and 10 mm thick stretch polystyrene layer to prevent heat loss. Heat loss from the bottom side of heater plate is prevented by keeping the heater in a box having stretch polystyrene, rubber, glass wool and heat resisting paper as insulation material. Eleven T-type, calibrated thermocouples have been used in the experiment out of which four are used to measure plate temperature, six to measure liquid pool temperature and one thermocouple is kept floating to measure any other temperature as and when required. Four holes of diameter 4 mm and depth 30 mm are drilled in the copper plate along its width and a thermocouple is inserted in each hole to measure the plate temperature. The average reading shown by the four thermocouples is assumed to represent the mean plate temperature. All the thermocouples are connected to a data acquisition system. This allows multiple temperature readings to be recorded simultaneously which are stored in a computer.

The time between two successive scans is 40 s to allow sufficient time for thermocouples to respond to any sudden changes in temperature. The temperature is recorded by the software and the required data can be exported and plotted in an excel sheet to estimate time required for attenuation of the steady state. The power input to the heater can be controlled by a variable autotransformer through which output voltage can be set to a specific value. The input to the variable autotransformer is 230 V AC supply and maximum rated current is 10 A. An ammeter is connected in series with the heater to measure the electric current and the heat flux given to heater is calculated as

$$q = \frac{VI}{A} \quad (1)$$

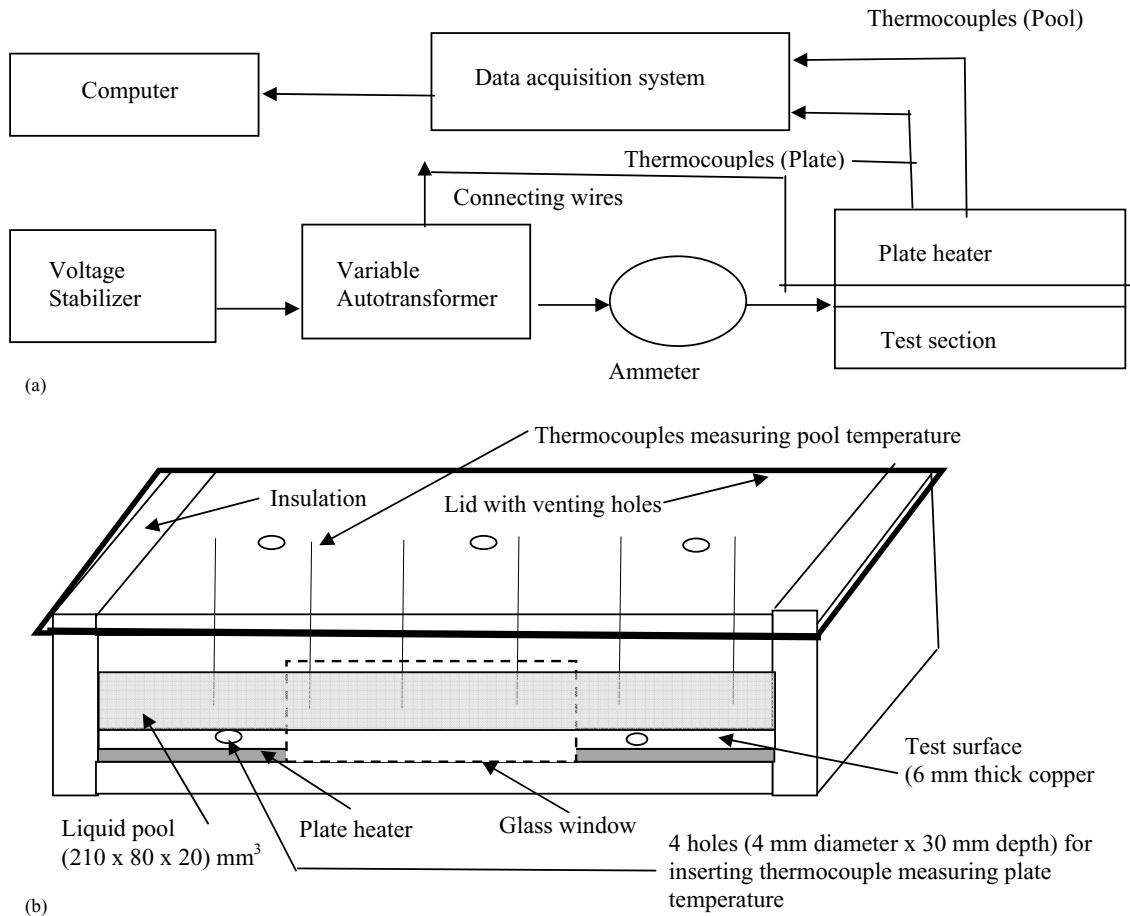


Fig. 1. (a) Schematic diagram of the experimental setup (b) details of test section

In Eqs. (1)  $V$  is output voltage of autotransformer which is applied across heater ( $V$ ),  $I$  is current measured by an ammeter flowing through heater circuit ( $A$ ) and  $A$  is the surface area of plate ( $m^2$ ) through which heat is taken from plate heater and given to the liquid pool.

It is assumed that the heat flux absorbed by the liquid is same as that supplied to the heater by electric source. To avoid power fluctuations, a Krykard make voltage stabilizer of 5 kVA is used that maintains the input voltage to the autotransformer in the range  $230 \pm 2V$ . Mean uncertainty in measurement of power was  $\pm 2.9\%$  and in heat transfer

coefficient calculation was  $\pm 12.2\%$ . The temperature of the plate is measured by the thermocouples which are positioned not exactly at the test surface but at a distance of 3mm from the test surface. It needs to be ensured that the temperature gradient between the position of thermocouples and the test surface is less compared to the degree of superheat calculated at a given value of heat flux. One-dimensional modeling has been used to calculate the temperature gradient within the plate. The maximum error in temperature measurement in the range of heat flux considered is about 3%.

The liquids used for study of nucleate boiling are deionised water, water-ethanol and water-2-propanol mixture of varying mole fractions. The main criteria used for selecting these liquids are miscibility in water and the boiling temperature being lower than that of pure water. Following the procedure suggested by Fujita and Tsutsui [5], initially the liquid is boiled in the test section at the highest heat flux after which the heat flux is lowered in steps. This procedure provides reproducible boiling curves and avoids boiling hysteresis.

### 3. Results and discussion

Figure 2 compares the variation of heat flux with degree of superheat for ethanol-water and 2-propanol-water binary mixtures, each having mole fraction of alcohol as  $X = 0.07$ , against that for pure water. Since the bubble point and dew point curves for these mixtures differ appreciably in the low mole fraction region, there is a difference in trend observed for boiling of ethanol-water and 2-propanol-water. For the same value of heat flux, the lowest degree of superheat is obtained for pure water. This indicates the heat transfer deterioration for binary mixtures as compared to the pure liquid which is commonly observed in literature (Fujita and Tsutsui [5]). This effect gets even more pronounced at higher heat flux values. Figure 3 shows the variation of mole fraction of ethanol in ethanol-water mixture as function of time for different values of heat flux. The values of mole fraction of ethanol are calculated after every scan which has duration of 40 seconds. For a given heat flux, the close to linear decrease in concentration of ethanol with time demonstrates that the rate of evaporation of ethanol is almost constant. Moreover, with increase in the value of heat flux, the rate of evaporation of ethanol in the binary mixture increases. Similarly, Fig. 4 shows the time variation of mole fraction of 2-propanol in 2-propanol-water mixture for different values of heat flux. It is observed that in the binary mixtures of these alcohols with water, the rate of evaporation is higher for the lower boiling alcohol (2-propanol) which is even otherwise expected. By adopting this procedure, the mole fraction of the alcohol in the mixture ( $X$ ) can be calculated at a particular time and for a given value of heat flux.

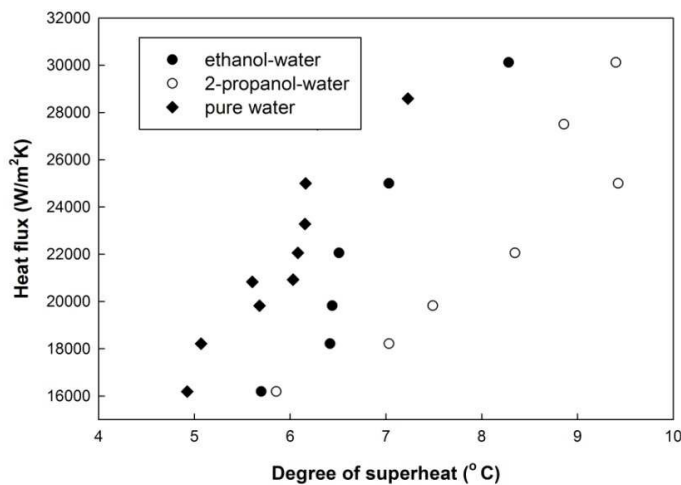


Fig. 2. Variation of degree of superheat with heat flux for ethanol-water mixture ( $X = 0.07$ ), 2-propanol-water mixture ( $X = 0.07$ ) and pure water

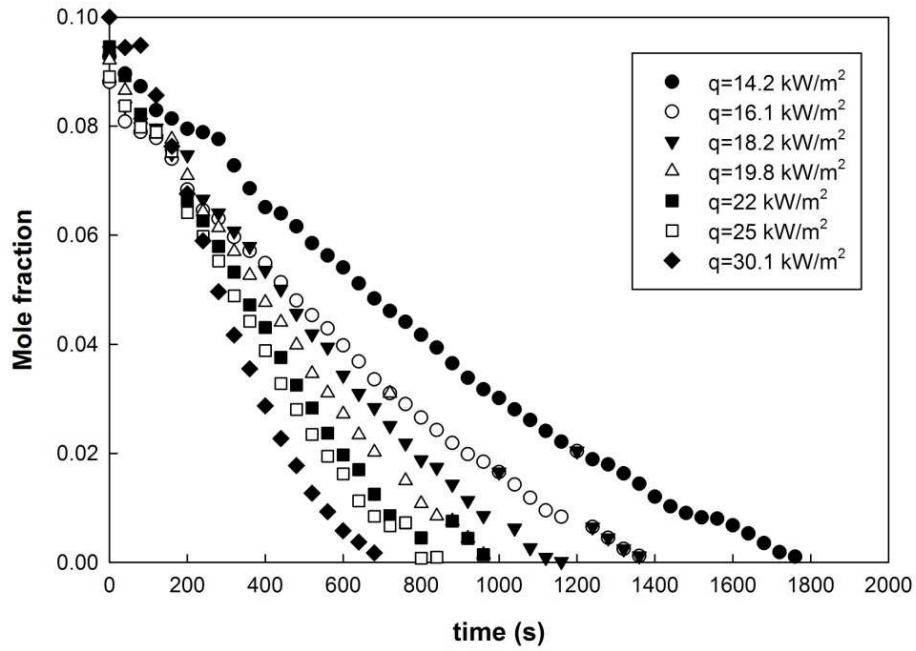


Fig. 3. Time variation of mole fraction of ethanol in ethanol-water mixture

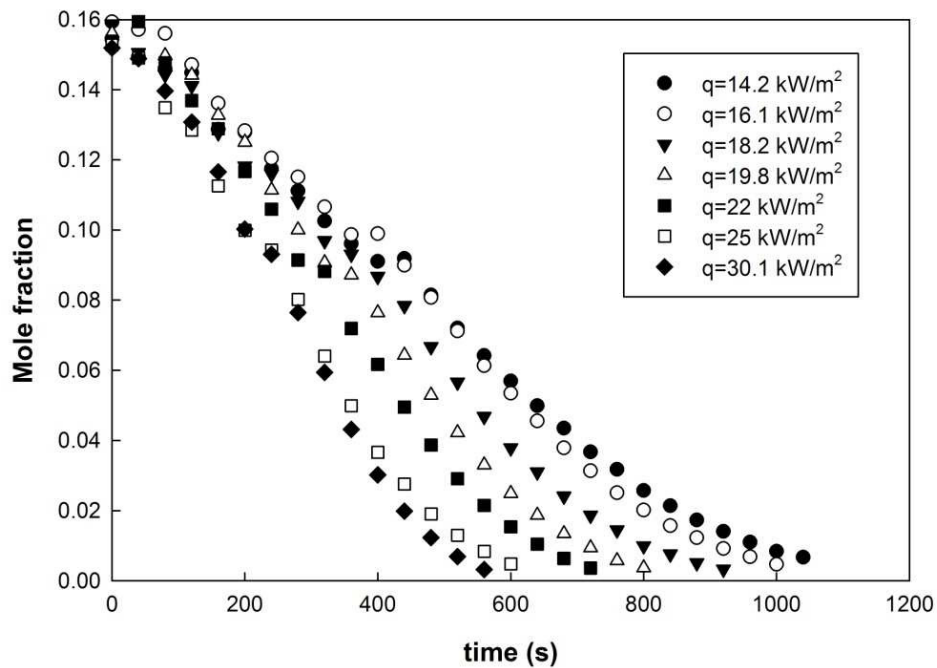


Fig. 4. Time variation of mole fraction 2-propanol in 2-propanol-water mixture

The heat transfer coefficient for binary mixtures from present experimental results is compared with that predicted by the following correlation given by Fujita and Tsutsui [5], as per Eqs. 2.

$$\frac{h_{id}}{h} = \left[ 1 + \left[ 1 - 0.8 \exp\left(\frac{-q}{10^5}\right) \right] \left( \frac{\Delta T_{bp}}{\Delta T_{id}} \right) \right] \quad (2)$$

Where,

$\Delta T_{bp}$  is the difference between dew and bubble point temperatures at a given mole fraction ( $^{\circ}\text{C}$ )

$\Delta T_{id}$  is the ideal wall superheat ( $^{\circ}\text{C}$ )

$h$  is heat transfer coefficient ( $\text{W}/\text{m}^2\text{K}$ )

$h_{id}$  is the ideal heat transfer coefficient calculated from ideal wall superheat and heat flux ( $\text{W}/\text{m}^2\text{K}$ )

$q$  is the heat flux ( $\text{W}/\text{m}^2$ )

The correlation holds good for the binary mixtures of ethanol-water as well as of 2-propanol-water in the range,  $X > 0.3$  for all values of heat flux, and  $0 < X < 0.3$  for heat flux values greater than  $20 \text{ kW}/\text{m}^2$ . In both the binary mixtures considered in present study, for  $0 < X < 0.3$  and heat flux less than  $20 \text{ kW}/\text{m}^2$ , the experimental data does not show good agreement with the correlations of Fujita and Tsutsui [5]. They conducted experiments for heat flux values ranging from  $20 \text{ kW}/\text{m}^2$  to  $400 \text{ kW}/\text{m}^2$  and observed that at higher values of heat flux, the change in mole fraction affects degree of superheat significantly. In the present study, for the range of mole fraction and heat flux considered, the maximum change in degree of superheat due to change in mole fraction at given heat flux is about  $2 - 2.5^{\circ}\text{C}$ . On the other hand, the change in degree of superheat predicted by Fujita and Tsutsui correlation [5] for higher values of heat flux is as high as  $10 - 12^{\circ}\text{C}$ . In an attempt to find a better correlation that shows improved match for experimental data in the considered range of heat flux and mole fraction, a suitable modification in the correlations proposed by Fujita and Tsutsui [5] is suggested. The suggested modification is such that the nature of variation proposed in the original correlation is preserved. Equation 2 above can therefore be written in a more general form as below (Eqs. 3.), where  $a=0.96$  and  $b=0.25$

$$\frac{h_{id}}{h} = \left[ 1 + \left[ 1 - a \exp\left(\frac{-q}{10^5}\right) \right] \left( \frac{\Delta T_{bp}}{\Delta T_{id}} \right)^b \right] \quad (3)$$

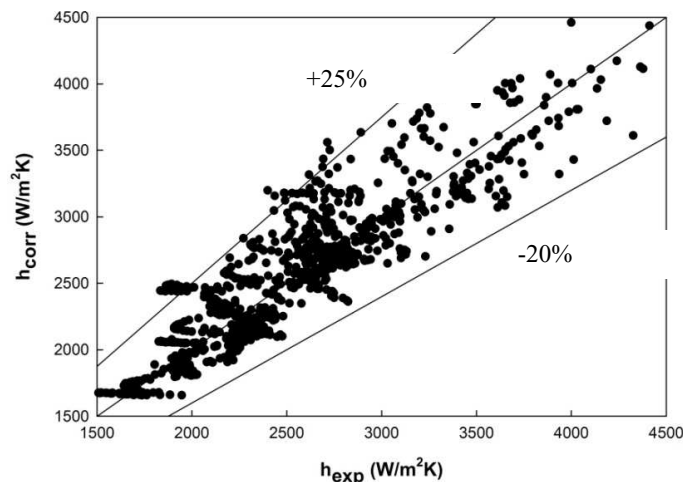


Fig. 5. Comparison of heat transfer coefficient values from experimental results and proposed correlation over entire range of heat flux and mole fraction considered

Here a total of 984 data points are available from the experiment. The entire experimental data shows a good match with the proposed new correlation within +25% and -20% as shown in Fig. 5. Separate and detailed investigation is required to test the nature of these correlations for wider fluid database and higher heat fluxes upto critical heat flux.

#### 4. Conclusions

An experimental study of nucleate pool boiling of water and water-miscible binary mixtures is carried out at low values of heat flux. The rate of change of mole fraction of lower boiling liquid in the mixture is calculated and a comparative study is made between ethanol-water mixtures and 2-propanol-water mixtures for the same values of heat flux. Two distinct regimes are identified, one  $0 < X < 0.3$  and  $q > 20 \text{ kW/m}^2$  or  $X > 0.3$ , in which the experimental data agrees with Fujita and Tsutsui correlation [5] within  $\pm 25\%$  and the other  $0 < X < 0.3$  and  $q < 20 \text{ kW/m}^2$  in which the experimental data is under-predicted by the Fujita and Tsutsui correlation [5]. A modification to the correlation is suggested which shows a good agreement with the present data within +25% and -20% over complete range of heat flux considered.

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