



Temperature measurements near the heating surface at high heat fluxes in pool boiling of 2-propanol/water mixtures



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ARTICLE INFO

Article history:

Received 31 August 2015

Received in revised form 19 October 2015

Accepted 19 October 2015

Available online 21 November 2015

Keywords:

Binary mixture

Pool boiling

Micro-thermocouple

Temperature measurement

Concentration distribution

Critical heat flux

ABSTRACT

To examine the mechanism of CHF enhancement with binary mixtures, this paper measured local temperatures close to a heating surface using a micro-thermocouple at high heat fluxes for pool boiling of a 3 mol% of 2-propanol/water mixture on an upward-facing 12 mm diameter circular surface. The variations in temperature traces measured at various locations above the heating surface indicate that the distributions of 2-propanol concentration have strong non-uniformities in the vertical and radial directions: 2-propanol concentration is higher in the vicinity of the heating surface at the central part of the heating surface and lower in the periphery of the heating surface. The local concentration of 2-propanol was determined based on the assumption that low peak values of temperature fluctuations correspond to the local saturation temperatures of the mixture. This assumption enabled a quantitative representation of the concentration distributions in the vertical and radial directions. The variations in the surface tension of the mixture were evaluated based on the deduced local values of the saturation temperature and the composition of the mixture. It was found that near the heating surface the surface tension increases steeply in the direction of the heating surface, suggesting that intensive Marangoni convection is induced at the liquid/vapor interface near the heating surface.

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1. Introduction

The CHF in pool boiling is often enhanced when binary mixtures are used as working fluids. This characteristic of binary mixtures has potential applications for coolants of thermal devices with high heat flux components. A number of experimental and theoretical studies have been conducted for the CHF of binary mixtures, and various mechanistic models responsible for the CHF enhancement have been proposed. The proposed models are categorized into the following two types.

A first category is based on increases in the effective subcooling around vapor bubbles. In the boiling of mixtures, the concentration of less volatile component around the vapor bubbles becomes richer than that of the bulk liquid due to preferential evaporation of the more volatile component. As a result, the temperature of the liquid near the liquid–vapor interface becomes higher than the saturation temperature (bubble point temperature) of the bulk liquid. This situation is similar to that of subcooled boiling with a single component fluid, and is a cause of the CHF increase. Based

on this idea, McEligot [1], and Reddy and Lienhard [2] have proposed empirical equations to predict the CHF of binary mixtures.

The second category of proposed CHF enhancement models is based on the Marangoni effect occurring at the liquid–vapor interface. In the boiling of binary mixtures, evaporation of the more volatile component from the liquid–vapor interface is more intensive near the heating surface, and hence, concentration of the more volatile component in the liquid phase adjacent to the interface decreases toward the heating surface. This yields a surface tension gradient according to the concentration distribution along the liquid–vapor interface. For the positive mixtures where the more volatile component has the lower surface tension, therefore, Marangoni convection is induced toward the heating surface, and may be a cause of the CHF enhancement. Hovestredt [3], Fujita and Bai [4], McGillis and Carey [5], and Yagov [6] proposed empirical equations for the CHF incorporating the Marangoni effect, although the assumed CHF models are different in the different studies: a bubble merger model [3], a dry-spot model [4,6], and Zuber's instability model [5], respectively.

As above, there are a number of studies on the CHF of binary mixtures, and details of the mechanism of the CHF enhancement are not fully understood. To examine this phenomenon experimentally, the author here and coworkers [7] have investigated the CHF for 2-propanol/water mixtures during pool boiling on an

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upward-facing heating surface under atmospheric pressure. They measured the liquid–vapor behaviors near the heating surface using a conductance probe, and determined the thickness of the liquid layer (a so called macrolayer) formed beneath large vapor masses from the location of disappearance of vapor mass signals. Through these measurements, it was established that: (1) at a 2-propanol concentration of around 3.0 to 4.7 mol% the CHF of 2-propanol/water mixtures is enhanced 1.7 times compared with the CHF of water, (2) the macrolayer thicknesses of a 3.0 mol% 2-propanol/water mixture formed at the center of the heating surface are considerably thicker than those of water at heat fluxes close to the CHF of water, (3) the macrolayer thicknesses of the 3.0 mol% 2-propanol/water mixture show a non-uniform distribution in the radial direction, thicker at the central area and thinner near the periphery of the heating surface, and (4) the change in the macrolayer thickness with the concentration of 2-propanol is similar to that in the CHF: with increasing concentrations of 2-propanol, the macrolayer thickness increases, to reach a maximum at around 3.0 to 4.7 mol% and then decreases.

The above results, (1)–(4), suggest that the formation of a thicker macrolayer at the central area of the heating surface is responsible for the CHF enhancement in 2-propanol/water mixtures. This mechanism is different from the mechanisms assumed in existing models [1–6], however, the formation of thicker macrolayers and the radial non-uniformity of the macrolayer thickness are likely caused by non-uniformities in the 2-propanol concentration in the vicinity of the heating surface as is suggested by the existing models. Therefore, information of local concentrations of 2-propanol close to a heating surface at high heat fluxes is vital to clarify the CHF enhancement mechanism for 2-propanol/water mixtures.

Attempts to estimate the local concentrations of binary mixtures in pool boiling have been conducted by Van Stralen and Sluyster [8], Copper and Stone [9], and Utaoka and Sai [10] at low heat fluxes (the isolated bubble region). These studies measured the temperatures inside the isolated bubbles detached from the heating surface, and showed that the temperature inside the bubbles is higher than the saturation temperature of the surrounding bulk liquid. (Concentration of the more volatile component is lower in the bubble than in the bulk liquid). However, there have been no attempts addressing an evaluation of the concentration of binary mixtures in the vicinity of the heating surface at high heat flux conditions. The study here measured the local temperatures close to a heating surface with a micro-thermocouple at high heat fluxes for pool boiling of 3 mol% 2-propanol/water mixture on an upward-facing surface, and estimated the vertical and radial distributions of the 2-propanol concentrations based on the measured local temperatures.

2. Experiments

2.1. Experimental apparatus

The experiments were carried out in saturated pool boiling of 3 mol% 2-propanol/water mixture at atmospheric pressure. Fig. 1 shows the experimental apparatus, which is the same as that used in the previous study [7], except for a thermocouple probe and temperature measurement arrangement. The heating surface is the upper end of a cylindrical 12 mm diameter copper block. A 0.5 mm thick stainless steel flange was silver-soldered around the copper heating surface. The surfaces of the copper and the surrounding flange were machined to be flush, and then Ni was plated over the two surfaces to avoid nucleation of bubbles at the interface between the copper surface and the flange. The surface heat flux and surface temperature were determined with two 0.5 mm

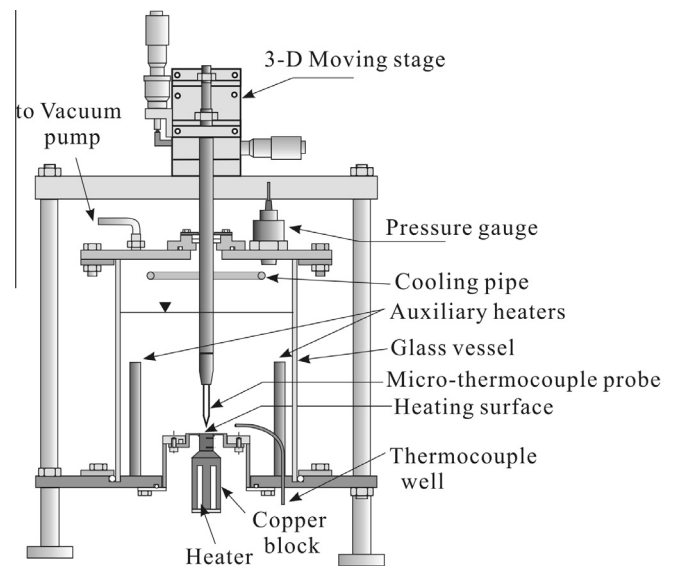


Fig. 1. Experimental apparatus.

diameter thermocouples, embedded in the copper block 4 and 12 mm below the surface. The boiling vessel is made of Pyrex glass with an inner diameter of 150 mm. Two auxiliary heaters were installed in the boiling vessel and were used for heating and degassing the mixture. The liquid temperature during the measurements was monitored with a sheathed thermocouple placed 7 mm above the heating surface and 25 mm from the center of the heating surface, the temperature measured in this manner was defined as the saturation temperature of the mixture.

Fig. 2(a) shows a photo of the micro-thermocouple used in the present experiment, and Fig. 2(b) is an enlarged illustration of the tip of the micro-thermocouple. The micro-thermocouple was manufactured from 25 μm diameter chromel and alumel wires, insulated with polyimide resin except at the junction. The two parallel wires were welded at the ends, and finished as a needle type thermocouple with a v-shaped junction. The dimensions of the junction part are about 30 μm long and 50 μm in diameter, as shown in Fig. 2(b). This micro-thermocouple was inserted in a conical capillary quartz tube with very low thermal expansion coefficient, and exposed about 2 mm from the tip of the quartz tube, as shown in Fig. 2(a). The time constant of the thermocouple probe was investigated in [11] using temperature traces measured during subcooled pool boiling of water, and estimated as about 0.7 ms for the measurement in liquid phase. The micro-thermocouple probe was connected to a three-dimensional moving stage with a positional accuracy of 0.5 μm in the vertical direction and 10 μm in the horizontal direction. The noise level in the output signal of the thermocouple was less than 0.2 K, and no process to remove the noise from the signals was included.

The voltage of the output signals from the micro-thermocouple was amplified 100-fold and sent to a PC through an A/D converter. The height of the thermocouple tip was calibrated by detecting the electrical contact between the tip of the micro-thermocouple and the heating surface using a short detection circuit.

2.2. Phase equilibrium of 2-propanol/water mixtures

Fig. 3 shows the phase equilibrium of 2-propanol/water mixtures. For the boiling of the mixture with a 2-propanol mole fraction of x , the saturation temperature of the bulk liquid is given by T_{bp} (Point A). Near the heating surface, however, local saturation temperatures become higher than T_{bp} due to preferential

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