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BUBBLE COALESCENCE DURING NUCLEATE BOILING OF BINARY MIXTURES FROM ARTIFICAL CAVITIES

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1. ABSTRACT

This study investigates pool boiling and bubble behaviour of Novec7000, Novec649, and their binary mixtures. Utilizing a paired artificial cavity coated with superhydrophobic Glaco, bubbles horizontal coalescence sequences reveal a dependence on the mole fraction of the binary mixture. As the mole fraction (X_i) increases, bubble horizontal coalescence transitions from dual pinning onto the surface to depinning. The evaporative heat flux was calculated across varying mole fractions of the binary mixture. Detailed analysis indicates that binary mixtures significantly impact bubble coalescence compared to isolated bubble dynamics.

2. INTRODUCTION

Coalescence, the process by which bubbles merge, is widely recognized for its role in augmenting heat transfer, attributed to the evaporation of an additional microlayer formed between the merged bubbles' stems. However, existing studies often offer only qualitative descriptions of boiling behaviour, lacking in-depth characterizations of bubble dynamics during coalescence. Previous simulations find that horizontal coalescence amplifies surface heat fluxes between bubbles, whereas reduced coalescence fails to yield similar enhancements [1]. With combining binary mixtures, only few studies proposed that the mixing effect impedes bubble coalescence [2]. Nonetheless, the impact of fluid composition on bubble coalescence and departure diameter remains elusive, with a scarcity of data concerning bubble dynamics and the influence of wettability and local temperature during pool boiling of mixtures.

3. METHODOLOGY

The experimental apparatus is shown in Fig. 1 (a). Pool boiling was conducted in the boiling chamber with four bottom heaters, and two surrounding heating pads to maintain the working fluid at its saturation temperature and avoiding heat loses to the environment. The boiling chamber pressure could be controlled by adjusting the flow rate and temperature of cooling water in the external condenser between 0.5 bar to 3.0 bar. [3]

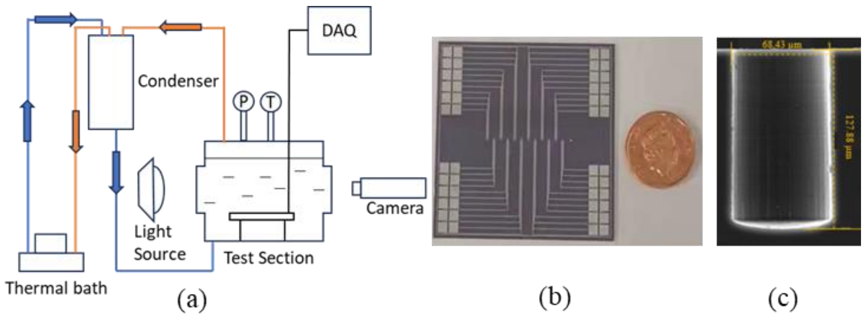

Fig. 1 (a) Experimental setup of the boiling chamber, (b) boiling surface comprising the different artificial cavities arrangements, and (c) Scanning Electron Microscopy (SEM) cross-section of one representative artificial cavity [3].

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The boiling surface is a 50 × 50 mm^2 silicon substrate with twelve micro-fabricated temperature sensors on the front side, as shown in Fig. 1 (b) and a deposited aluminium heater on the backside. Each cavity is equipped with a temperature dependent resistor to measure local superheat, which need four connection pads each. The temperature is determined by measuring the voltage across the changing resistance. An artifice cavity, as shown in Fig. 1 (c), was etched in the centre of each temperature sensor. The boiling surface is coated with Glaco rendering it superhydrophobic. A high-speed camera Chronos 1.4 allowed to record bubbles growth at 1000 fps to 15,000 fps. The bubble diameter and departure frequency data were extracted from the high-speed video recordings. Novec649 and Novec7000 refrigerants were used as working fluids to investigate the effect of concentration on bubbles dynamics.

4. RESULTS

Sequence images of bubble nucleation, growth, and departure on the hydrophobic surface (Glaco) were evaluated using Fiji software. Successful departure bubbles at each degree of superheat were measured three times. In Fig. 2, a sequence of images with 1 ms intervals are shown for two bubbles coalescing process at 3.6 K superheat and 1 bar saturation pressure.

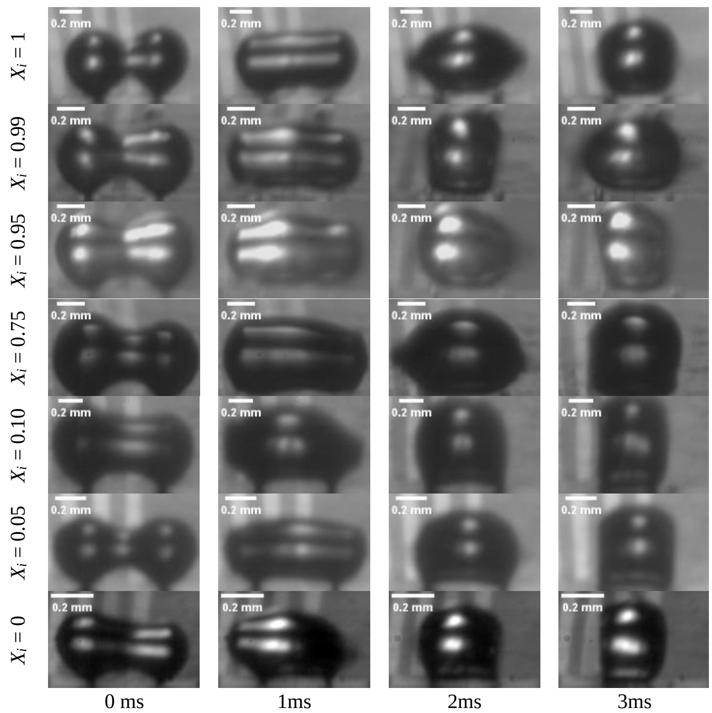

Fig. 2 Bubbles coalescence from a 70 µm diameter cavity and cavities spacing of 0.75 mm at different concentrations, 4 K superheat and 1.01 bar saturation pressure for (top) pure Novec649 and (bottom) pure Novec7000, and (middle) their binary mixtures with concentrations of 0.99, 0.95, 0.75, 0.1, and 0.05.

Figure 2 illustrated the horizontal coalescence of bubbles in various mixture concentrations. It is evident that when the mole fraction (X_i) was 0.1, 0.05, and 0, the merged bubble retained both pinning sites with two thin pinning necks before departing at 2 ms. When the pair of merging bubbles to allow the successful pinch-off from their impaled vapour neck, the work of adhesion is calculated as [4]:

$$W_{AD} = 4\gamma\pi {a_0}^2 \qquad (1)$$

where a_0 is fixed contact radius of pinned neck and γ is surface tension of binary mixture. Due to low viscosity of 0.421 cP at boiling point, the oscillatory viscous dissipation energy was negligible. These phenomena only occurred where work of adhesion was larger than 9.839× 10^{-12} (J/m^2) . However, as X_i increases, the merged bubble promptly departed at 1 ms where the work of adhesion is smaller than 9.003× 10^{-12} (J/m^2) in the case of X_i= 0.75, 0.95, 0.99, and 0. Analysis of the differing wall superheat degrees at X_i= 0.1, 0.05, and 0 revealed an independence of pinning behaviour.

Bubble departure frequency during horizontal coalescence was then investigated. The evaporative heat flux per unit area has been estimated and compared for mixtures. The evaporative flux Q_e (W) per unit area A (m^2) referred to as q_e (W/m^2) can be estimated from the bubble volume leaving the surface using Equation (2) [3]:

$$q_e = \frac{Q_e}{A} = 2D_d \rho_v h_{fg} f/3 \quad (2)$$

where D_d is the bubble departure diameter (mm), ρ_v is the density of bubble vapour (kg/m^3), f is the departure frequency (Hz), and h_{fg} is the latent heat of vaporization (J/kg). The calculation is based nominally on the projected area of the bubble (horizontal cross-sectional area of the bubble at its widest point projected) onto the substrate.

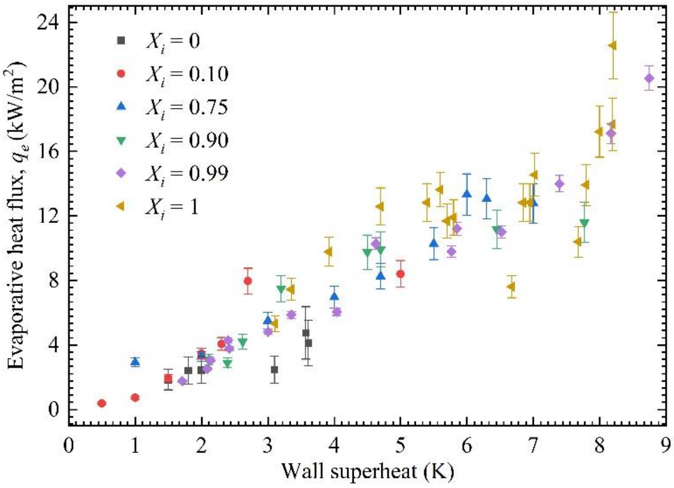

Fig. 3 Evaporative heat flux q_e for cavities spacing is 0.75 mm (S/D is 1.04) at different concentrations as functions of wall superheat.

It is worth noting that the evaporative heat flux was higher under conditions where the mole friction X_i equals 1 compared to other scenarios, primarily due to horizontal bubble coalescence with a small adhesion effect. As X_i increased, horizontal bubble coalescence became more frequent at higher wall superheats, consequently leading to an increase in heat flux. Uncertainties arose from direct convection from the projected bubble area.

5. CONCLUSIONS

The present investigation investigated bubble behaviour of Novec7000, Novec649 and their binary mixtures during pool boiling from artificial cavities. Boiling from a paired artificial cavity coated with superhydrophobic Glaco has yielded valuable insights in bubble dynamics. The analysis of bubble horizontal coalescence sequences indicates the dependence of bubble dynamics (growth, coalescence and departure) on the mole fraction of the binary mixture. Bubble horizontal coalescence changes from dual pinning onto the surface to depinning as X_i increases. The evaporative heat flux is calculated for various mole fractions of the binary mixture and reported as a function of the superheat. Detailed analysis shows that binary mixture affects bubble coalescence when compared to isolated bubble dynamics.

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