An experimental investigation on periodic single bubble growth and departure from a small heater submerged in a nanofluid containing moderately hydrophilic nanoparticles

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ABSTRACT

An experimental investigation is carried out on periodic *single bubble* growth and departure from a *small* heater in boiling of nanofluids. The nanofluids are made of moderately hydrophilic silica nanoparticles (having a contact angle of 35–37°), dispersing in deionized water at mass concentrations of 0.05%, 0.1% and 0.15%, respectively. It is found that the bubble departure frequency and boiling heat transfer by latent heat are enhanced with increasing concentration of moderately hydrophilic silica nanoparticles. However, the periodic single bubble departure diameter is not affected by the presence of moderately hydrophilic silica nanoparticles significantly. After boiling experiments of these nanofluids are carried out, it is found that a larger amount of moderately hydrophilic silica nanoparticles are deposited on the heater surface at higher wall heat flux, the morphologies of the small deposition layers are varied with increase of heat flux or concentration. The reason for increasing amount of nanoparticles deposited on the heater surface as the wall heat flux is increased is verified by an analysis of vapor recoil force acting on a moderately hydrophilic nanoparticle at the vapor/liquid interface near the wall.

1. Introduction

In recent years, a great deal of interest has been devoted to experimental investigations of boiling of nanofluids [1,2]. From these experimental investigations, it can be concluded that the presence of nanoparticles has the following two effects discussed in Section 1.1 and 1.2 on boiling of a nanofluid:

1.1. Effects of nanoparticle deposition layer on the heater surface

Nanoparticle deposition on heater surfaces had been found in most of previous experimental investigations on boiling of nanofluids [3–5]. Early work on boiling of nanofluids was focused on effects of nanoparticles on wettability, roughness and thickness of these nanoparticles deposition layers [6–13]. Kim et al. [3,6] found that the wettability of heater surfaces was increased after nanoparticles deposition thus enhancing critical heat flux. Das et al. [7] as well as Narayan et al. [8] concluded that the ratio of the original roughness of a heater surface to the average size of nanoparticles could influence the roughness of a heater surface after nanoparticles deposition. Subsequently, with the aid of SEMs, microstructures of nanoparticles deposition layers were

investigated by Kim and Kim [9], Kwark et al. [10] as well as by Vafaei and Wen [11]. They found that the nanoparticle deposition layer became thicker and rougher due to a larger amount of deposited nanoparticles on heater surfaces by increasing the wall heat flux or nanoparticles' concentrations. Later, Ahmed and Hamed [12] suggested that the concentration of nanoparticles in nanofluids can also affect the roughness of the heater surface after nanoparticles deposition. Recently, Quan et al. [13] found that a surface deposited by moderately hydrophilic nanoparticles is rougher than those deposited by strongly hydrophilic nanoparticles.

1.2. Effects of nanoparticles on bubble dynamics

It has been found that the presence of nanoparticles have effects on bubble dynamics in boiling experiments of nanofluids [13–17]. Vafaei and Wen [14] found that suspended nanoparticles could modify bubble dynamics significantly in flow boiling of nanofluids. Xu and Xu [15] speculated that the structural disjoint pressure resulted from suspended nanoparticles could increase bubble departure frequency and decrease bubble departure diameter in flow boiling experiments of nanofluids containing alumina(Al_2O_3) nanoparticles. Quan et al. [13] were the first

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to point out that wettability of nanoparticles has strong effects on bubble size in boiling of nanofluids. They found that strongly hydrophilic silica nanoparticles had no effect on the size of bubble departure from the heater surface with respect to pure water. But moderately hydrophilic silica nanoparticles could decrease the size of bubble departure from the heater surface due to their effects in preventing bubble coalescence. This is because moderately hydrophilic nanoparticles are adsorbed on bubble interfaces firmly, resulting in a capillary pressure in the liquid between adjacent bubbles to prevent bubble coalescence.

It should be pointed out that most of previous boiling experiments of nanofluids (including those of our previous work [13]) were performed on a large heater where many vapor bubbles were generated simultaneously. Under such experimental conditions, vapor bubbles departure characteristics were not only affected by the presence of nanoparticles but also affected by bubble coalescence as well. Moreover, since a larger area of nanoparticles deposition layer was formed on a large heater by many small deposition layers under multiple vapor bubbles by interlacing and overlapping with each other, it is difficult to identify nanoparticle deposition mechanisms clearly. To exclude bubble coalescence effects on bubble departure diameter or bubble departure frequency as well as the interlacing effects of nanoparticle deposition layers, we have carried out periodic single bubble growth and departure experiments from a small heater in this paper. Effects of moderately hydrophilic nanoparticles' concentration on periodic single bubble departure characteristics are observed by a high speed camera. Effects of heat flux and concentrations on moderately hydrophilic nanoparticles deposition layers are investigated by a SEM. An analysis of the vapor recoil force acting on a single moderately hydrophilic nanoparticle at the vapor/liquid interface near a heater surface is carried out to verify that a larger amount of nanoparticle deposition is formed with the increase of wall heat flux.

2. Nanofluids preparation and boiling experimental setup

2.1. Nanofluids preparation

As in our previous study [13], nanofluids containing moderately hydrophilic nanoparticles were used in the present boiling heat transfer experiments. Moderately hydrophilic silica nanoparticles can be made from silica nanoparticles modified by polyethylene glycol groups. More detailed discussion on preparation of such a nanofluid and its effects on pool boiling heat transfer can be found in our previous paper [13]. Contact angles of moderately hydrophilic nanoparticles used in the present experiment were about 35–37° and the average diameter of the moderately hydrophilic nanoparticles was 20 nm, which are the same as those of moderately hydrophilic nanoparticles used in our previous study [13].

2.2. Boiling experimental setup

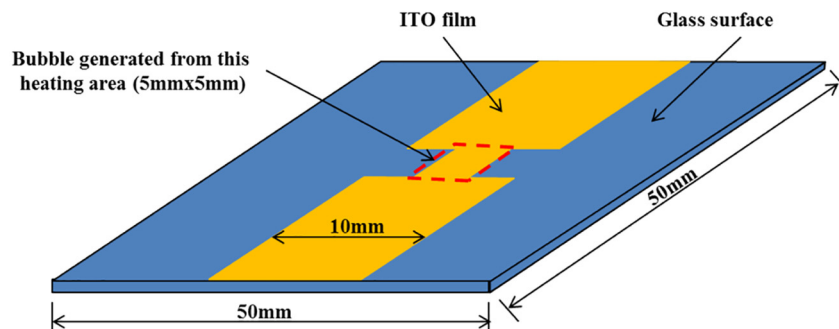Fig. 1 is a schematic of the heater used in this experiment, which

was a glass surface coated with an indium tin oxide (ITO) film, the same as the heater used previously by Gao et al. [16]. The ITO film had good electrical conductivity, and when DC voltages were applied at both ends of the ITO film, Joule heat was generated in the film. The width of the ITO film in the middle was 5 mm while the width of the ITO film in other part was 10 mm. Since the width of ITO film in the middle section was narrower than other part, the electric resistance was the highest in the middle section. When DC voltages were applied at the ITO film, the heat flux in the middle section with an area of 5 mm × 5 mm (indicated by a red square in Fig. 1) was the highest, and a single bubble was generated from this location. The bubble grows and subsequently departs from the heater surface owing to buoyancy force thus forming a periodic bubble growth and departure cycle. The heat flux in the middle section q'' can be calculated as $q'' = P/A$, where P is the heating power at the middle section and $A = 25$ mm^2 is the heating area of the middle section. So, constant wall heat flux conditions were achieved if constant DC voltages (heating powers) were applied to the ITO film.

Fig. 2 is the schematic of the boiling experimental setup used in this paper, where a heater surface with DC voltages applied at its ends was placed at the bottom of a Pyrex glass vessel, which was filled with deionized water or with nanofluids. A single bubble was generated periodically from the small heater surface at a superheated temperature. A condenser coil was installed at the top of the Pyrex glass vessel to condense vapor to liquid during the boiling experiment. The Pyrex glass vessel was submerged in a larger thermostatic oil bath heated by auxiliary heaters. Thus, the temperature inside the Pyrex glass vessel was maintained at the saturation temperature of deionized water or a nanofluid, so that boiling experiments at a saturation condition could be carried out.

3. Experimental procedures and data reduction

Periodic single bubble dynamics were investigated in boiling of deionized water at first, and then deionized water was replaced by nanofluids containing moderately hydrophilic nanoparticles at different concentrations. The process of periodic single bubble growth and departure from a small heater surface was recorded in sequences of photo images by a high speed camera (2500 frames per second). Fig. 3 is a series of photo images during bubble growth period in a nanofluid captured by the high speed camera. These photo images were then used to determine single bubble departure frequencies and bubble departure diameters from the small heater under different experimental conditions. Since single bubble departure frequencies and bubble departure diameters may fluctuate with time although the bubble grew from the same nucleation site, so images for many bubble ebullition cycles were recorded to calculate the average bubble departure frequencies f_{d-ave} and diameters D_{ave}.

The average bubble departure frequency f_{d-ave} is calculated as $f_{d-ave} = 1/t_{ave}$, where t_{ave} is the average bubble cycle time which is defined as $t_{ave} = \sum_{i=0}^{n} t_i/n$, where n is the total number of the recorded

Fig. 1. A schematic of the heater.