NEUTRON IMAGING STUDY OF BUBBLE BEHAVIORS IN NANOFLUID THROUGH ENGINEERED ORIFICES

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1. Introduction

Nanofluids are engineered fluid consisting colloidal dispersions of nanoparticles, which has been introduced as a new kind of heat transfer fluid. Since it has been reported that nanofluids improve heat transfer characteristics including CHF [1], they are expected to be innovative technique for practical thermal systems such as in nuclear reactor where high heat flux removal is needed. To validate the effects of nanofluids, many experiments have been conducted including pool boiling [2,3] and flow boiling [4]. Most studies focused on the change of surface parameters through deposited nanoparticles, while Vafaei and Wen [5] firstly discussed modification of bubble dynamics by dispersed nanoparticles in fluid as well as deposited ones.

The boiling mechanism, as an effective heat transfer mode, includes bubble generation, growth, departure, and coalescence. Therefore the change of bubble dynamics can lead to the change of boiling heat transfer condition. That is, not only surface characteristics [6] but the dispersed nanoparticles would be the essential parameters of boiling mechanism in terms of bubble dynamics.

Based on the explanation of CHF enhancement mechanism by nanofluids, this study investigate bubble behaviors on engineered orifices in nanofluid, considering both surface characteristics and dispersed nanoparticles in fluid. For advanced visualization of opaque fluids, the neutron imaging technique is introduced.

2. Experimental Setup

The experimental apparatus is made of an aluminum chamber with inner volume of 100 × 150 × 10 mm^3, as shown in Fig. 1. The transparent acrylic front window allows the visualization of bubble behaviors through high speed video camera. Deionized water and 0.01V% Al_2O_3 nanofluid are used for the base fluid. The syringe pump injects air bubble into the chamber at constant flow rate of 0.1ml/s. All the experiments are conducted at atmosphere pressure.

The main parameters of bubble dynamics for this study are departure frequency and departure volume. Each datum was obtained through photographic analysis.

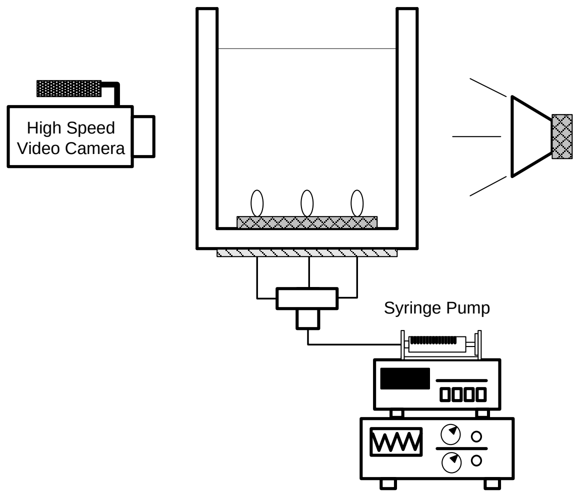


Fig. 1. Schematic diagram of experimental setup

3. Results and Discussion

Considering both surface characteristics and dispersed nanoparticles, two independent experimental conditions are designed. For the surface characteristics, engineered orifices are mounted on the bottom of the chamber, which are related to porosity of the surface. Secondly, water and Al_2O_3 nanofluid were used for the base fluids to investigate the effects of dispersed nanoparticles. Figures 2 and 3 show the averaged experimental results.

3.1 Bubble behaviors through engineered orifices

For the surface characteristics, size and geometry of the orifices were considered. The size of the orifice was varied by 0.4, 0.8, and 1.6 mm diameter with circular geometry. Also three types of orifices were considered; circular, triangular, and square shapes. The hydraulic diameter of each type is set to constant at 1.0mm.

3.1.1 Effect of orifice size

As shown in figure 2, with increasing orifice diameter, averaged bubble departure volume increases for both water and nanofluid. As a result, bubble departure frequency decreases with increasing orifice diameter, as reported also in previous studies [7,8].

For single bubble grown from a submerged orifice, the momentum balance on the bubble which can be considered an equilibrium force balance [9], takes the form;

$$\Sigma F = F_B + F_{CP} + F_C + F_D = 0 \quad (1)$$

where, F_B, F_{CP}, F_C, and F_D are buoyancy force, contact pressure force, capillary force, and dynamic force, respectively. Increasing orifice diameter enhances downward capillary force expressed as:

$$F_C = 2\pi r_o \sigma \sin\theta \quad (2)$$

where, r_0, σ, θ are orifice diameter, liquid surface tension, and contact angle at the triple contact line, respectively. Due to enhanced capillary force, bubble can hold more volume until it departs when the capillary force become equivalent to increasing upward buoyancy force expressed as:

$$F_B = \rho_l g V_B \quad (3)$$

where, V_B is bubble volume. That is, increasing bubble departure volume, or resulted decreasing bubble frequency, indicates enhanced capillary force which can hold bubble longer at the heated surface.

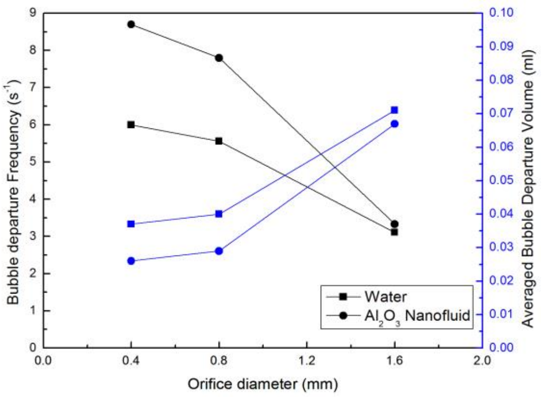


Fig. 2. Bubble departure frequency and averaged bubble departure volume vs. orifice diameter

3.1.2. Effect of orifice geometry

For three geometries of orifices, there are little differences in both bubble departure frequency and averaged bubble departure volume, shown in figure 3. It is inferred that the geometry of orifice, or the shape of pores in the case of nanoparticles-deposited heater surface, gives little effect on bubble dynamics.

An interesting point is that tiny bubbles are emerged from the edges of triangular- and square-shaped orifice, shown in figure 4. Unlikely to circular orifice, the edge in the triangle or square provides locally converged triple contact line. It generates localized small bubbles which are hardly detached from the surface. In an aspect of heat transfer, those tiny bubbles interrupt the bubble generation through boiling process, which deteriorate heat transfer rate. Therefore, the shape of structure, or deposited nanoparticles, can be another parameter which determines effective heat transfer and CHF mechanism.

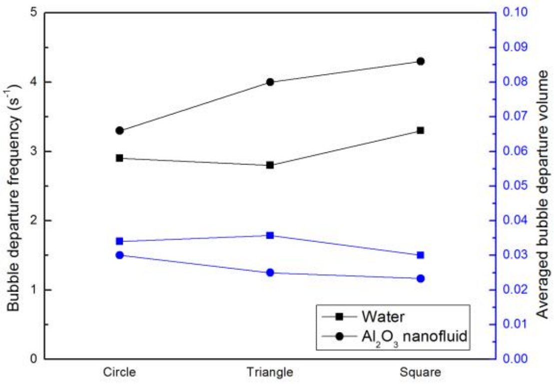
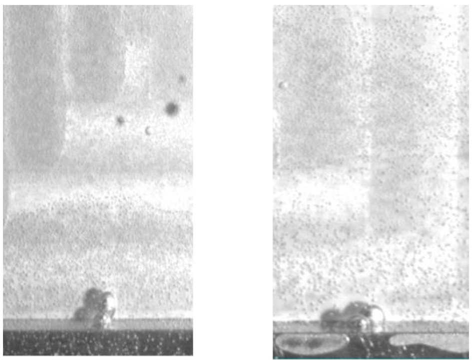


Fig. 3. Bubble departure frequency and averaged bubble departure volume vs. orifice geometry



(a) (b)

Fig. 4. The baby bubbles emerged from the edge of the orifice with; (a) triangle and (b) square

3.2 Bubble behaviors through dispersed nanoparticles

For all the cases, averaged bubble departure volume decreased and resulted bubble departure frequency increased in Al_2O_3 nanofluid. Also there is no tiny bubble emerged from the edge of triangle and square orifices. The results can be attributed to change in physical properties of fluid or/and the interaction between bubble interface and nanoparticles.

In an adiabatic condition, the most powerful properties that determine the bubble dynamics are density, viscosity, and surface tension. Using conventional fluid-solid mixture model, expressed as:

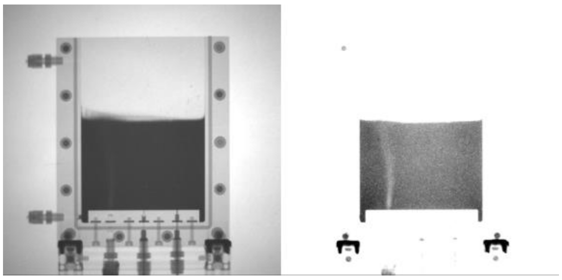
$$\rho_{nf} = \rho_p \phi + \rho_f (1-\phi) \quad (4)$$

the density of 0.01V% Al_2O_3 nanofluid increases 0.0298% compared to that of pure water, which can be negligible. As reported by D. S. Zhu et al. [10], there is no obvious change in the viscosity and surface tension at lower volume fraction of nanoparticle.

Second, the interaction between bubble interface and nanoparticles may be the reason. It is assumed that nanoparticles interrupt into interactions between liquid, gas, and solid, which lead to unstable condition of triple contact line of bubble. However further investigation of dispersed nanoparticles should be needed to clarify this.

3.3 Visualization using Neutron Radiography

Neutron radiograpy is a visualization technique using the characteristics of the neutron beam which is high transmission rate through metallic material. For a higher concentration of nanofluid, visualization of bubble behaviors using high speed video camera, or any optical technique, is impossible due to opaque fluid itself. For extended experimental conditions, neutron radiography is used to visualize the bubble behaviors in the higher concentration of nanofluid. Figure 5 shows the image of bubble jet inside the water using neutron radiography. Since the overall shape of bubble jet can be distinguished, next step should be to check the feasibility of visualizing single bubble by neutron radiography.



(a) (b)

Fig. 5. Image of bubble jet inside the water by neutron radiography: (a) raw image; (b) processed image

4. Conclusion

In the present study, the bubble dynamics in nanofluid through engineered orifices was studied. The main parameters of engineered orifices are size and geometry. Photographic analysis of bubble departure frequency and averaged bubble departure volume provides as follows:

(1) With increasing orifice diameter, averaged bubble departure volume increases, while bubble departure frequency decreases. The results are attributed to enhanced capillary force by increasing contact perimeter.

(2) Averaged bubble departure volume and bubble departure frequency remain similar for three different types of orifices. But edges of the triangle and square orifice produce small bubbles which interrupts bubble generation. The converged triple contact line due to the edge may be a reason for the emerged baby bubbles.

(3) Nanofluid shows less averaged bubble departure volume and higher bubble departure frequency. Considering little change in physical properties of the fluid, interaction between bubble interface and nanoparticles may be in charge of the results.

REFERENCES

[1] S. M. You, J. H. Kim, K. H. Kim, Effect of nanoparticles on critical heat flux of water in pool boiling heat transfer, Appl. Phys, Lett., 83 (16), p.3374–3376, 2003.

[2] I. C. Bang, S. H. Chang, Boiling heat transfer performance and phenomena of Al2O3-water nano-fluids from a plain surface in a pool, Int. J. Heat mass Transfer, 48 (12), p.2407-2419, 2005.

[3] H. Kim, J. Kim, M. Kim, Experimental studies on CHF characteristics of nano-fluids at pool boiling, Int. J. Multiphase Flow, 33(7), p.691-706, 2007.

[4] H. Ahn, H. Kim, H. Jo, S. Kang, W. Chang, M. Kim, Experimental study of critical heat flux enhancement during forced convective flow boiling of nanofluid on a short heated surface, Int. J. Multiphase Flow, 36, p.375-384, 2010.

[5] S.Vafaei, D. Wen, Flow boiling heat transfer of alumina nanofluids in single microchannels and the roles of nanoparticles, J. Nanopart Res, 13, p.1063-1073, 2011.

[6] S. Siedel, S. Cioulachtjian, J. Bonjour, Experimental analysis of bubble growth, departure and interactions during pool boiling on artificial nucleation sites, Experimental Thermal and Fluid Science, 32, p.1504-1511, 2008.

[7] J. Xie, X. Zhu, Q. Liao, H. Wang, Y. Ding, Dynamics of bubble formation and detachment from an immersed micro-orifice on a plate, Int. J. Heat Mass Transfer, 55, p.3205-3213, 2012.

[8] S. D. Bari, A. J. Robinson, Experimental study of gas injected bubble growth from submerged orifices, Experimental Thermal and Fluid Science, 44, p.124-137, 2013.

[9] E.S. Gaddis, A. Vogelpohl, Bubble formation in quiescent liquids under constant flow conditions, Chemical Engineering Science, 41(1), p.97–105, 1986.

[10] D.S. Zhu, S.Y. Wu, N. Wang, Surface Tension and Viscosity of Aluminum Oxide Nanofluids, AIP Conference Proceedings 1207 p.460-464, 2010.