BUBBLE DYNAMICS IN POOL BOILING OF NANOFLUIDS

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ABSTRACT

Bubble dynamics of pool boiling of nanofluids has been experimentally investigated. The boiling surface was prepared with an average surface roughness of 120 nm. Alumina Oxide-water based nanofluids at a constant concentration of 0.05 wt. % have been used in this investigation.

The bubble growth rate, bubble departure diameter and departure frequency have been observed using high speed imaging during pool boiling of pure water and nanofluids at a wall superheat of 104.4 ºC. Number of nucleation sites was activated in the case of nanofluid against one site for pure water. The bubble diameter observed in the case of nanofluids was about 60 % smaller than that observed for pure water. Nanofluid's bubble departure frequency reached 500 Hz while the bubble frequency observed in the case of pure water was about 23 Hz. In addition, the bubble growth rate showed dependence on the type of working fluid used.

NOMENCLATURE

HTC	[KW/m^{2}K]	Heat transfer coefficient
CHF	[KW/m^2]	Critical heat flux
SIP	[-]	Surface Interaction Parameter
PID	[-]	Proportional Integral Derivative
CMC	[mg/l]	Critical micelle concentration
Ra	[nm]	Average surface roughness
ONB	[º]	Onset of nucleate boiling
Wt.%	[-]	Weight fraction

INTRODUCTION

Nanofluids' boiling has been one of the most attractive research topics in the past two decades. Nanofluids offer enhanced thermal characteristics relative to their base fluids. Heat transfer rates are expected to exceed the values associated with common base fluids. However, the existence of the nanoparticles increased the complexity of the boiling phenomena due to their interaction with active nucleation sites, their spatial concentration, and their effect on the suspension thermal properties close to the heated surface. These interactions resulted in contradicting results as described below.

Kwark et al. [1] investigated pool boiling of various concentrations of nanofluids on a flat horizontal copper heater. The boiling curves of nanofluids showed changing performance with concentration. High concentrations of nanofluids deteriorated the rate of heat transfer and were accompanied with formation of a deposition layer on the heater surface. The deposition layer provided resistance to heat flow. Whereas low concentration nanofluids resulted in rates of heat transfer similar to water except, however, it produced a higher critical heat flux (CHF) that increased with the concentration till it reached a maximum value.

Tang et al. [2] reported maximum heat transfer enhancement at the lowest nanoparticles concentration. They still observed a reduction in heat transfer enhancement and eventually heat transfer deterioration as the nanoparticles concentration was increased. They also used SDBS surfactant to improve the nanoparticles suspension stability. The surfactant addition led to heat transfer enhancement for the same nanoparticles concentration and the magnitude of enhancement was proportional to the surfactant concentration used. Except for the lowest concentration of nanofluids, the surfactant addition caused a reduction in the rate of heat transfer. Kathiravan et al. [3] attributed the heat transfer enhancement after the surfactant addition to early boiling incipience, small bubble departure diameter and an increase in the number of active nucleation sites. In a contradiction to these results, Hopkar et al. [4] reported deterioration of boiling performance after the addition of surfactant to nanofluids.

In order to explore the nanoparticles interaction with the heated surface, Narayan et al. [5] conducted boiling experiment of nanofluids prepared by using different sizes of nanoparticles and using heaters with different surface roughness. Their results showed both heat transfer enhancement and deterioration, based on the ratio of the average surface roughness of the heater surface to the nanoparticles size used, which they called it, the SIP. Values of SIP far from unity resulted in heat transfer enhancement and values close to unity resulted in heat transfer deterioration. Harish et al. [6] reported a similar trend, where smooth surfaces caused heat transfer enhancement and rough surfaces caused deterioration. Wen et al. [7] obtained similar boiling performance to the one reported by Kwark et al. [1] using a rough surface. However, they reported heat transfer enhancement using a smooth surface.

CURRENT WORK

The objective of the current work is to have a better understanding of bubble dynamics during pool boiling of nanofluids. Isolated bubbles have been generated during pool boiling of pure water and nanofluids. Their departure diameter, rate of growth and frequency have been examined using high speed imaging.

EXPERIMENTAL SETUP

The experimental test rig, which is shown in Figure 1, consists of a 20 cm diameter stainless steel vessel (13). It has a stainless steel skirt (16). The skirt holds the heater surface (14) along with its insulation system and the thermocouples in place. The top part of the vessel is wrapped with electric heaters (4) from the outside to help maintain the bulk temperature of the working fluid that is contained inside to a prescribed temperature. There are two glass windows (6) installed at the same elevation of the skirt to observe the boiling phenomena at the heated test surface. The top section includes a condenser coil (2) which is fed with tap water to maintain the amount of liquid constant during the boiling experiment and prevent water vapor escaping from the vessel. The bottom part of the vessel contains the heated surface and it is maintained at a temperature close to the vessel temperature using an electric heater (7) installed around the vessel in order to reduce the heat loss from the working fluid. The electric power provided to each electric heater installed around the boiling vessel is controlled using PID controllers with a feedback signal provided from a thermocouple attached to each heater. An insulation layer (3) is inserted and wrapped around the boiling vessel to minimize heat losses.

The heater configuration, has been used to generate isolated bubbles to investigate bubble dynamics during pool boiling of pure water and nanofluids, is depicted in Figure 2. It consists of a flat sheet of copper (20) with a thickness of 1 mm was attached to the top surface of the skirt (16) and a cone-shaped heating element (21) made from copper touched the back or the dry side of the sheet in a very small area. The cone heating element was connected to a precise threading mechanism (22) that controlled its axial location. In this configuration, there was only one heater of 250 W used. The surface temperature of the sheet was measured by using a self-adhesive, fast response type-E thermocouple. The whole mechanism was insulated with Teflon (23) to minimize heat losses. The copper heater's surface roughness has been maintained at an average value of 120 nm by using hand polishing technique.

Nanofluid is prepared using Alumina (Al_2O_3) nanoparticles with a nominal size of 10 nm with deionized water as the base fluid. Details of nanofluids preparation method used in this study can be found in [8].

RESULTS

The growth of a single isolated bubble has been observed during pool boiling of pure water and nanofluids. A single concentration of 0.05 wt. % of nanofluids has been used with no surfactant added to avoid multiple bubbles generation, because of the lower surface tension associated with the use of the surfactant. Images of the growing bubble in deionized water captured by using the high-speed camera. The shape of the water bubbles was not spherical and it was similar to the shape reported by Hetsroni et al. [9].

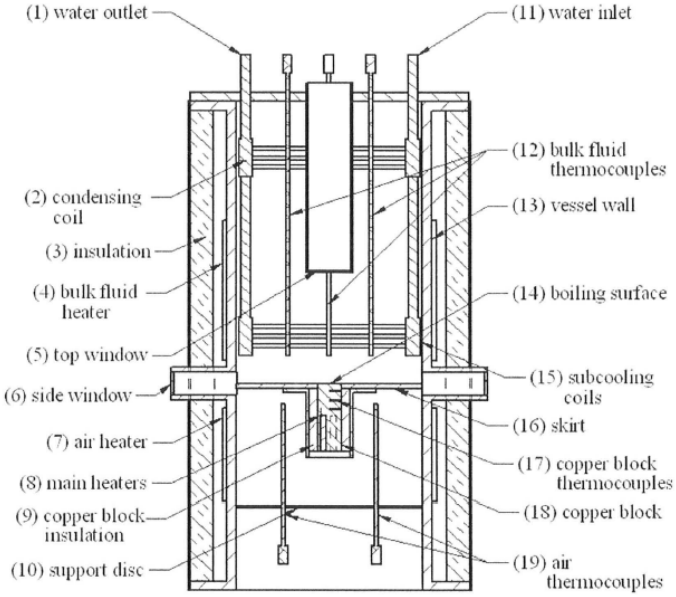

Figure 1: Schematic of the boiling vessel.

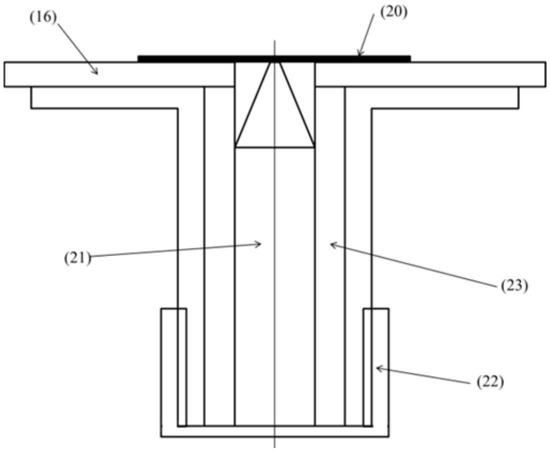

Figure 2: Schematic of the heater configuration.

The bubble growth rate in the case of deionized water at a wall superheat of 104.4 °C is shown in Figure 3. The change in bubble diameter as function of time was fitted using an empirical power law equation. The resulting power value was 0.33. In contrast, the theoretical models of Plessent and Zwick [10] and Forster and Zuber [11] proposed a power of 0.5. This difference is believed to be due to the assumptions made in the development of these models. The models assumed a spherical bubble growing within isothermal liquid layer above the heated surface. Neither of the assumptions was verified experimentally. The actual bubble shape is not spherical, as observed here. Also, temporal and spatial temperature variations do exist around the bubble nucleation sites, as confirmed experimentally using IR thermography in [12]. Theoretical models predicted a slower growth rate prior to bubble detachment. However, the actual growth rate and the bubble size remained almost unchanged till detachment. Figure 4 shows a comparison between growth rate results reported by Gerardi et al. [12] and current results, both for pure water. It is observed that the water bubbles had a very long waiting time that caused the departure frequency to be as low as 4.54 Hz.

The observed nucleation process for nanofluids was quite different from the one observed for pure water. One active nucleation site was observed in the case of pure water, while a number of active nucleation sites were observed on the same small local heated area. Bubbles generated in the case of nanofluids were more spherical and much smaller in size than pure water (~60% smaller). The bubble growth rate in the case of nanofluids is presented in Figure 5. The bubble growth time in nanofluid is 2.3 ms, which is shorter than in pure water. The waiting time of nanofluid bubble was negligible which resulted in high bubble departure frequency of 430 Hz. The high departure frequency causes fast surface rewetting which enhances the heat transfer. The nanofluids bubble growth rate fit very well with the empirical power law equation. The resulted power was 0.38. Because of the smaller bubbles observed in the case of nanofluids, one might hypothesize that the presence of the nanoparticles caused a reduction in the surface tension, which caused a similar trend of reduction in the growth rate similar to the trend described by Forster and Zuber [11].

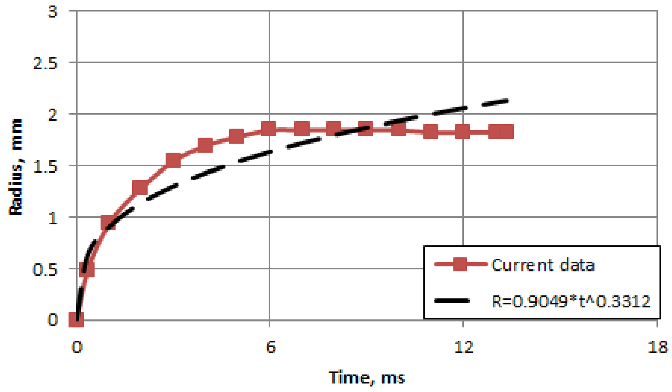

Figure 3: Bubble growth rate in the case of pure water at wall superheat of 104.37 ºC.

CONCLUSION

An experimental study has been carried out to investigate bubble dynamics during pool boiling of pure water and nanofluids. Number of nucleation sites varied based on the type of working fluid where nanofluid caused an increase in the number of active sites for the same heating surface. Nanoparticles altered the surface tension of the base fluid and reduced the size and growth time of the departing bubbles. Heat transfer enhancement experienced by using nanofluids is due to the significant reduction in waiting time with respect to pure water. The nanofluids bubble growth rate showed better agreement with the theoretical models than in the case of water.

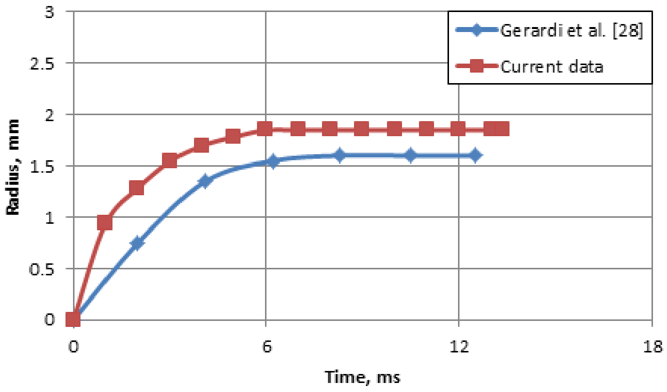

Figure 4: Comparison of the current bubble growth rate with the one reported in [12] in the case of pure water.

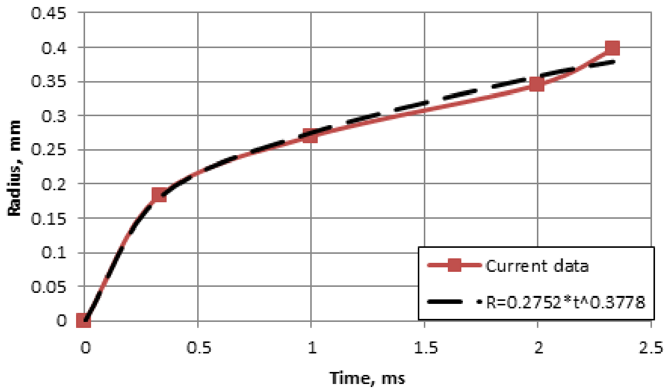

Figure 5: Bubble growth rate in the case of nanofluids at wall superheat of 104.33 ºC.

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