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# X-ray imaging analysis on behaviors of boiling bubbles in nanofluids

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ABSTRACT

Nanofluid, a liquid suspension containing nanoparticles, has been widely used to enhance heat transfer. However, the heat transfer enhancement mechanism of nanofluids has not been clearly revealed yet. Therefore, understanding the boiling heat transfer of nanofluids is a challenging research issue in the field of heat transfer. When nanoparticles are added into a base fluid, the thermo-physical properties of the fluid and surface characteristics are modified. Those modifications induce changes in the behavior of boiling bubbles. In addition to the size and number of bubbles, the generating rate of boiling bubbles was newly defined to estimate the heat transfer coefficient directly from bubble behaviors according to nanofluid concentration. As the nanofluid concentration increases, both the generating rate of boiling bubbles and the heat transfer coefficient decrease. Wettability and hydrodynamic size were also employed to reason those degradations. Wettability increase leads to the reduction of activated nucleation sites, which reduces the bubble generating rate and heat transfer coefficient with an increase in nanofluid concentration. In this study, the feasibility and usefulness of synchrotron X-ray imaging and a newly defined boiling generating rate for examining boiling heat transfer were verified by observing boiling-bubble behaviors. Moreover, it was also shown that wettability plays an important role in changes of the bubble behaviors and the heat transfer coefficient as surface roughness modification.



## 1. Introduction

Boiling has been used in various engineering applications, including nuclear power plants, chemical reactors, electronic devices, and heat exchangers of heating, ventilation, and air conditioning (HVAC) systems, for effective heat transfer. Therefore, many studies have been carried out in the past century [1–10]. Boiling heat transfer is a complex process even for nucleate pool boiling of pure water. It is influenced by various parameters, including heat flux, saturation pressure, heating surface characteristics, and thermos-physical properties of working fluids [11]. In addition, additives such as surfactants, solid particles, and dissolved gases affect both macroscopic and microscopic behaviors of boiling heat transfer [12].

To enhance heat transfer in miniaturized systems that require more powerful heat removal, nanofluids, which are liquid suspensions containing nanoparticles, was proposed in 1995 by Choi and Eastman [13]. Since then, numerous studies have been extensively conducted on heat transfer using nanofluids [12,14–30]. Nanofluids were found to significantly enhance thermal transport without any system contamination during the loading of relatively small particles, owing to the small size of individual nanoparticles. Therefore, commercial nanofluids have a strong potential to provide significant improvements in heat transfer performance without significant changes in preexistent systems.

The addition of nanoparticles into base fluids creates two major effects on the boiling heat transfer of nanofluids. The first effect is the suspended nanoparticles modify the thermo-physical properties of the base fluids, including thermal conductivity, viscosity, and surface tensions [31–33]. The second effect is the deposited nanoparticles modify their surface characteristics, such as homogeneity, roughness, and wettability [34–36]. Although the combination of both effects could lead to enhancement or deterioration of boiling heat transfer, they commonly change the behaviors of boiling bubbles.

Compared to the natural convection process, the behaviors of boiling bubbles strongly influence the characteristics of nucleate boiling heat transfer. The departure diameter, departure frequency, and growth rate of vapor bubbles are commonly used to describe bubble behaviors in the nucleate boiling process [11]. The shadowgraph technique has been widely employed to investigate bubble behaviors in dispersed two-phase flows [37]. However, this technique has technical limitations in the measurement of bubble

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behaviors in opaque fluid flows, such as blood flow and nanofluid with high concentration, because visible light cannot transmit through such opaque fluids. Moreover, the optical distortions encountered in the shadowgraph technique are another problem in two-phase flow research.

To overcome these limitations, various non-invasive measurement techniques, such as electrical capacitance tomography [38], ultrasound imaging [39], magnetic resonance imaging (MRI) [40], and neutron radiography [41] have been used to investigate bubble dynamics of two-phase flows. However, it is difficult to identify bubble shape or investigate high-speed bubbly flows owing to low temporal and spatial resolutions. Recently, the synchrotron X-ray micro imaging technique has been utilized to measure the size of microbubbles and void fractions of bubbly flows [42,43]. It has a strong potential for investigating bubble dynamics because of its high spatial and temporal resolutions.

In this study, the relationship between heat transfer enhancement of nanofluid and bubble behaviors was examined by employing a synchrotron X-ray imaging system. The size and number of bubbles were acquired using digital image processing. The bubble generating rate was newly proposed to explain boiling bubble behaviors and heat transfer coefficient according to nanofluid concentration. Finally, the hydrodynamic size and contact angle of nanofluids were also analyzed to ascertain the mechanism of degradation in the heat transfer coefficient. These recent results would be helpful in understanding the relationship between bubble behaviors and heat transfer phenomena in nanofluids.

## 2. Experimental apparatus and methods

### 2.1. Nanofluid preparation

A two-step method was employed to prepare $Al_2O_3$ nanofluid solutions [44]. Nanofluid with four different concentrations (0.05, 0.1, 0.5, and 1% in weight) were prepared by dispersing 20% $Al_2O_3$ nanofluid solutions (SIGMA-ALDRICH, USA) in 50 mL of deionized water. The density of the 20% $Al_2O_3$ nanofluid was 1.06 g/mL at 25 °C and its molecular weight was 101.96 g/mol. The diameters of $Al_2O_3$ nanoparticles were distributed in the range of 30–60 nm. After dispersing nanofluid solutions, an ultrasound sonication bath (JAC-2010, SONIC, Republic of Korea) was utilized to bake the nanofluids for 1 h at 30 °C. In this study, no dispersant or stabilizer was used to prevent any additional changes in chemical properties of the prepared nanofluids. No significant sedimentation by gravity of 1% $Al_2O_3$ nanofluids was observed for 24 h, as illustrated in Fig. 1.

### 2.2. X-ray imaging

Fig. 2 shows the experimental set-up of the synchrotron X-ray imaging system. The experiments were conducted at the 6C biomedical imaging beamline (6C BMI) of Pohang Light Source II (PLS-II). The beam storage energy was 3 GeV and the corresponding beam current was 360 mA. A monochromatic X-ray beam with a beam flux of $1.2 \times 10^{12}$ photon $s^{-1}$ $mm^{-1}$ was used in this study. The X-ray beam passing through a 1 mm-thick silicon wafer was 24 keV. The X-ray beam size was adjusted to 8 mm (h) × 5 mm (v). The test model was positioned at approximately 30 m downstream from the X-ray source. A CsI scintillator having a thickness of 450 μm was utilized as the scintillator crystal. The distance between the scintillator and the test model was fixed at 50 cm. Five hundred X-ray images were consecutively recorded with a high-speed camera (SA 1.1, Photron, Japan) at 1000 fps for 0.5 s. A 20× objective lens was attached in front of the camera in the X-ray imaging experiments and the corresponding field of view was 973 μm × 973 μm (1024 × 1024 pixels).

### 2.3. Boiling nanofluid

The boiling test facility is also depicted in Fig. 2. A heating chamber with an observation window was made of SUS 304 steel. The chamber size was 100 mm × 100 mm with a 5 mm thickness. The 50 mm × 50 mm observation window was made of acryl plate. A hot plate (GPHPS-D, Global lab, Republic of Korea) was placed at the bottom of the chamber to heat $Al_2O_3$ nanofluids. All experiments were conducted under atmospheric pressure.

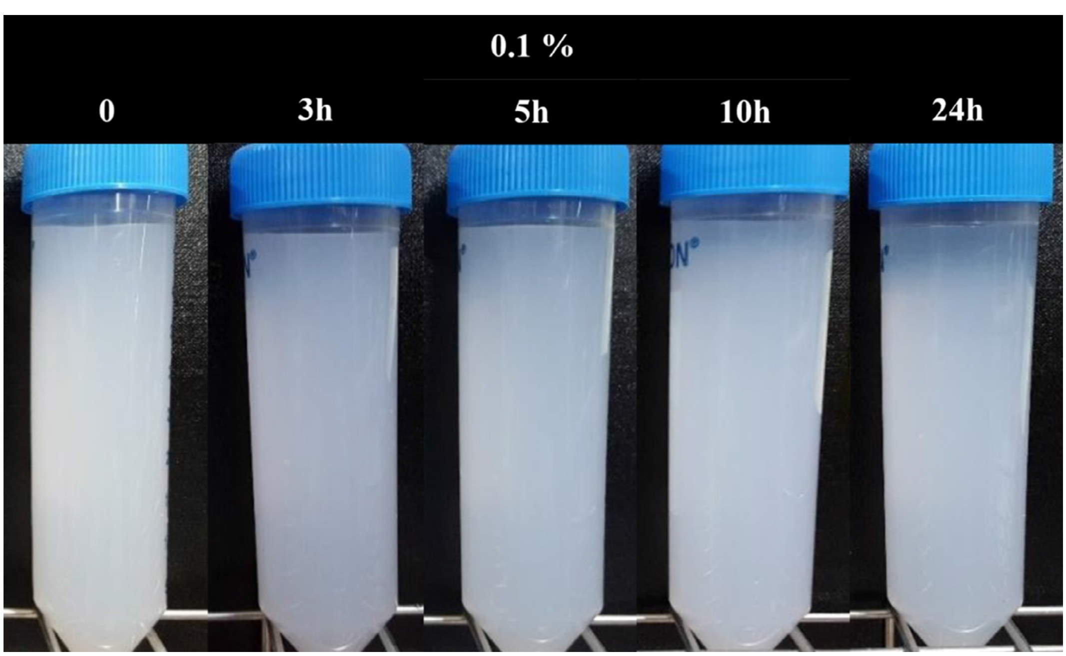


**Fig. 1.** Photographs of $Al_2O_3$ nanofluids at various times.