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Effects of SiO_2 nanoparticles on pool boiling heat transfer characteristics of water based nanofluids in a cylindrical vessel

Yanwei Hu, Ziyu Liu, Yurong He *

School of Energy Science & Engineering, Harbin Institute of Technology, Harbin 150001, China

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ABSTRACT

Boiling heat transfer is widely used in energy power equipment, while the poor thermal property conventional fluids cannot meet the increase of heat transfer demand. The addition of nanoparticles into base fluids can modify the properties of base fluids and is a potential way to improve heat transfer characteristics. In present work, amorphous SiO_2 nanoparticles with an average size of 98 nm were synthesized via Stober process. And they were added into water with different mass fractions to investigate the pool boiling heat transfer characteristics. The heat transfer coefficient and critical heat flux were analyzed. Results show that the heat transfer coefficient of all fluids increases rapidly in the natural convective region but then rises gradually in the nucleate boiling region. Moreover, owing to the deposition of SiO_2 nanoparticles, the heat transfer coefficients of SiO_2-H_2O nanofluids are lower than that of the base fluid and reduce as the concentration increase. On the other hand, because of the wettability improvement of the heating wire surface caused by the deposition of SiO_2 nanoparticles, the critical heat fluxes of nanofluids are higher than that of the base fluid. When the concentration is 0.081%, the critical heat flux achieves a peak improvement of approximately 68.8%.

1. Introduction

Boiling heat transfer (BHT) is widely applied in various types of energy power equipment such as heat pumps, boilers, refrigeration and air-conditioning, and microelectronic devices [1–3]. In process engineering applications, BHT is mainly influenced by two parameters, namely heat transfer coefficient (HTC) and critical heat flux (CHF) [4–6]. Above the CHF, the heat surface is covered by vapor rapidly, causing delay in the removal of heat generated and deterioration of heat transfer. This will lead to burning of the heat exchanger surface due to overheating.

Due to the poor thermal properties of conventional working fluids, such as water, engineering oil, ethylene glycol (EG), and so on, the performance of heat transfer systems is significantly low [7,8]. Nanofluids (NFs), proposed by Choi and Eastman [9], were fluids suspending metal particles with excellent performance and diameters <100 nm. In recent years, the heat transfer performance of NFs has been studied worldwide [10–14]. It shows a wide application prospect and huge commercial competitive power in terms of improving energy conversion efficiency. Recently, many researchers have conducted experiments to investigate the effect of nanoparticles (NPs) on BHT by different means and analyzed the change of HTC [15]. Witharana et al. [16] added Au and SiO_2 NPs into water and investigated the BHT of these two kinds of NFs. The results showed that compared with the base fluid, the HTC of Au-H_2O NF (mass fraction of 0.001%) increased by up to 21% while that of SiO_2-H_2O decreased. Wen and Ding [14] investigated the effect of alumina nanoparticles on BHT and significant enhancement of heat transfer was obtained. They thought the effect of interaction between nanofluids and boiling surface was an important issue about BHT. Raveshi et al. [17] conducted a research on nucleate BHT of Al_2O_3-EG/H_2O NF under atmospheric pressure and they found that the HTC of the NF increased by up to 64% when the volume fraction was 0.75%. At the same time, many experiments have been conducted to investigate the difference of CHF between NFs and their base fluids. He et al. [18] investigated the effect of ZnO NPs on BHT of ethylene glycol and water mixture based NFs. They found that CHF was enhanced significantly due to the nanoparticle coating on heater surface. Kim et al. [19] submerged a heating wire horizontally into water and TiO_2/Al_2O_3-H_2O NFs, to conduct a BHT experiment. The results showed that the CHF of NFs was higher and they considered that this change is mainly because the deposition of NPs changes the structure of the surface. By analyzing the SEM image, they also found that the surface roughness of the heating wire increased whereas the contact angle decreased. Liu et al. [20] chose a copper plate with microgroove structure to heat CuO-H_2O NFs of different concentrations under different pressures. The results showed that with a decrease of pressure, the CHF of NFs increased; meanwhile, particle deposition increased the surface roughness and caused a decrease in HTC and an increase in CHF. Coursey and Kim [21] found that the heat transfer performance of a NF is mainly influenced by its concentration and the wettability of the heating surface. At the beginning, the performance of heat transfer improved as the

* Corresponding author.
E-mail address: rong@hit.edu.cn (Y. He).

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concentration increased, while after reaching a certain concentration, the thermal energy storage capacity began to decline.

Currently, most studies are focused on metal and metal oxide NPs [22–24] and less attention is paid on nonmetallic oxides. As the most commonly used liquid with high thermal conductivity, water is widely used in the field of heat transfer. By contrast, SiO_2 is a nonmetallic oxide with excellent thermal energy storage capacity. Here, we proposed to conduct a research on the effect of SiO_2 NPs on BHT characteristics. Instead of purchasing through commercial channels, SiO_2 NPs were self-made to confirm the stability of the SiO_2-H_2O NFs and avoid aggregation during the process of drying. The SiO_2 NPs were synthesized via Stober process and the experiment was designed to explore the BHT characteristics of SiO_2-H_2O NFs with mass fractions of 0.081, 0.163, and 0.325%. We chose platinum wire as heat source owing to its advantage of stable temperature coefficient of resistance. The HTC and CHF of different mass fraction NFs were analyzed and compared with that of base fluids. To explain the change of boiling heat transfer performance, we not only analyzed the change of wettability by testing the surface tension and contact angles of NFs, but also considered the influence of the heat resistance of the coating formed by the deposition of the NPs to the heat transfer.

2. Experiment

2.1. Preparation of SiO_2 NPs and SiO_2-H_2O NFs

The SiO_2 NPs used to prepare the SiO_2-H_2O NF were synthesized via sol-gel processing [25]. The TEOS (≥99.9%), ethanol (C_2H_5OH, ≥99.9%), and ammonia water ($NH_3 \cdot H_2O$, 25–27 wt%) were all obtained from Shanghai Aladdin Reagent Company. An ultrasonicator (PS-100A Jiekang Ultrasonic Instrument *Co*., Ltd., Dongguan) with a working frequency of 40 kHz was used to sonicate the samples. Firstly, we mixed specific quantities of water and ethanol and sonicate the mixture for 10 min. Then, we added TEOS of a particular mass concentration rapidly into the solution and sonicated it for 1 h to accelerate the rate of hydrolysis of TEOS. The diluted ammonia (8 wt%) was then added into the mixture to promote the rates of hydrolysis and condensation. After sonicating for 2 h, the SiO_2 NPs were obtained. In the experiment for synthesizing SiO_2 NPs, the concentrations of TEOS, H_2O, and NH_3 were 1.2 mol/L, 5 mol/L, and 1.4 mol/L, respectively.

After the synthesis of SiO_2 NPs, the solution remains as ethanol, ammonia, and residual TEOS. To avoid the effect of these chemicals, we performed a centrifugal treatment on the white turbid liquid and cleaned the NPs with pure water repeatedly. Then we dispersed the NPs in water and finally obtained stable NFs through ultrasonic shock. In the entire process, the NPs were in the solution and kept wet.

2.2. Characterization

Before the test, the NPs were centrifuged three times using water and the solution was subjected to ultrasonic treatment for 30 min. The components of the NPs were identified by using X-ray diffraction (D8 Advance, Bruker AXS GmbH, Germany). Scanning electron microscopy (SEM, FEI Quanta 200 FEG, 200 V–30 kV, America) analysis at an operating voltage of 200 kV and a beam current of 101 μA was conducted to examine the NPs. The samples were prepared via repeated centrifugation and alcohol cleaning. Then, they were dropped onto a silicon wafer and sprayed with gold after drying. The size of the NPs was measured and analyzed using the Nano Measure 1.2 software (Fudan University, China). The surface tension of the NFs was measured by an automatic surface tension meter (BZY-1, Shanghai Hengping Instrument and Meter Factory) based on platinum board method. The JCY series contact angle meter (Shanghai Fangrui Instrument *Co*., Ltd.) was used to measure the contact angles of the NFs, and the substrate used was a glass slide.

2.3. Experimental bench setup

In this experiment, the BHT characteristics of SiO_2-H_2O NFs were measured by hot wire method. The schematic diagram of the BHT research experimental bench is shown in Fig. 1. The bench consists of a reaction pool, heating system, cooling system, and data acquisition system.

A reagent bottle is used as a reaction pool. The procedure for the experiment is as follows:

a) Pour the NF to be measured into a 200 mL reagent bottle and submerge the heating wire into the NF.
b) Surround the reagent bottle with oil at high temperature to attain saturated condition of the NF.
c) Adjust the oil temperature so that the heat absorption rate of the NF matches with the heat dissipation rate. The hot oil can preheat the NF to shorten the heating time to boiling temperature and remove the gas from the liquid.
d) Weld the heating wire (WRP, Kaitai Instrumentation *Co*., Ltd., Shanghai) between two copper conductors, and use a direct current power supply (RXN-305D, Zhaoxin Electronic Instrument Equipment *Co*., Ltd., Shenzhen) to make the current pass through the heating wire and heat the NF. The heater wire is a platinum wire, which has a purity that exceeds 99.99%. It has a diameter of 0.07 mm and the temperature coefficient of resistance is 0.00374/°C. The heating wire, copper conductor, and DC power supply compose the heating system. The cooling system, which includes a glass reflux condenser, joint pipe, and low-temperature thermostat bath, reduces the temperature of the water flowing into the reflux condenser to 15 ± 0.5 °C and condenses the vapor back to the reagent bottle. The data acquisition system consists of a thermocouple, digital multimeter, and data acquisition instrument.
e) Run the power supply under voltage-controlled condition. The voltage began from 0.5 V and increased with an interval of 0.5 V for every 10 min until the critical point. For water, the critical point is about 5.8 V and for SiO_2-H_2O NFs, it is <10.0 V and varies with NP concentrations.
f) Insert a T-type thermocouple (SMCL-1, Zenith International Trade *Co*., Ltd., Changzhou) into the NF to monitor the temperature. A 6 1/2-digit digital multimeter (DM 3064, RIGOL Technologies, Inc., Beijing) was used to monitor the current flows through the heater wire. Then, data of voltage across the hot wire and temperature of the NF were obtained using the data acquisition instrument (Agilent 34972A, USA) connected to a computer.

2.4. Data reduction

Based on the temperature coefficient of the resistance (TCR) method, the heater wire temperature T_w was calculated using reference resistance R_{ref}, reference temperature and TCR of the Pt wire, the expression was shown as:

$$T_w = \frac{R_w/R_{ref} - 1}{\alpha} + T_{ref} \tag{1}$$

The resistance of Pt wire R_w was calculated using the voltage of the heating loop U and the current I, as shown:

$$R_w = \frac{U}{I} - R_s \tag{2}$$

where R_s is the resistance in the loop without R_w.

The heat flux can be calculated as follows:

$$q = \frac{I^2 R_w}{\pi D L} \tag{3}$$