



Control of pool boiling heat transfer through photo-induced wettability change of titania nanotube arrayed surface



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ABSTRACT

In the present experimental study, the pool boiling heat transfer performance was controlled and enhanced through the photo-induced wettability change of titania (TiO₂) nanotube arrayed surface (TNAS). The TNAS was analyzed using various spectroscopic techniques such as the scanning electron microscopy (SEM), energy dispersive spectrum (EDS), transmission electron microscopy (TEM), and water contact angle (WCA) measurements. The WCA of TNAS was tuned by the ultraviolet (UV) light irradiation time. The increase in UV light irradiation time to TNAS decreased the WCA. Enhanced wetting of TNAS had strong impact on the boiling heat transfer performance. As the WCA of TNAS decreased, the boiling curve was shifted to the right (i.e., higher wall superheat condition) accompanying critical heat flux (CHF) improvement. Measured CHF results of TNAS in the present study were different from those of plain TiO₂ surface without the special structures tested in some previous reports. This discrepancy could be caused by the nanotube arrayed structures of the present TiO₂ surface. The surface wettability was an important factor to determine the boiling heat transfer of TNAS. The present CHF measurement data were in good agreement with Liaw and Dhir (1989) correlation in the earlier CHF models tested in this work. Based on this study, it was found that the boiling heat transfer can be controlled and enhanced successfully by the photo-induced wettability change of TNAS through the UV light irradiation.

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1. Introduction

It is well known that the nucleate boiling heat transfer is more effective mechanism than the single-phase heat transfer at given temperature difference. To enhance the nucleate boiling heat transfer, various surface treatment techniques have been developed and applied. In the early stage, a rudimentary surface preparation method such as grit-roughening was widely used [1,2]. Later, a significant progress in surface preparation methods [3–7] has been made. It has led to a few order of magnitude of heat transfer coefficient enhancement.

However, the nucleate boiling heat transfer is limited by certain heat flux condition, which is called critical heat flux (CHF). Beyond the CHF, the boiling regime transits from nucleate boiling to film boiling. In the film boiling regime, heated surface cannot contact with surrounding liquid. That means the heated surface is fully covered with the vapor film with low thermal conductivity. In such a case, the wall temperature of heated surface increases rapidly. It may result in the severe failure of heated surface. Therefore, most thermal-energy systems are desired to be operated in the nucleate boiling heat transfer regime (i.e., below

the CHF). In this regard, the research to achieve the higher CHF is the practically important and valuable contribution to the industrial applications such as the advanced electronic devices [8] and nuclear reactor design [9].

Recently, a lot of attention has been paid to obtain the higher CHF. It is known that the combinations of an extended surface area, capillary-assisted liquid suction, increased nucleation site density, and vapor escape passages from the heating surface are effective to retard or avoid heating surface failure. In order to augment the CHF, extensive investigations using the various types of nanofluids have been performed [10–18]. Based on the previous research, the nanofluid alters the characteristics of heated surface, which contribute to increasing the CHF. However, for nanofluidic CHF applications, the optimal concentration and deposition time can be critical [15]. If the concentration of nanoparticles is too low and the deposition time is short, the thin porous layer is formed. It is not efficient to introduce the large number of active nucleation site density and capillary wicking. On the contrary, at the high concentration and long deposition time, the thicker porous layer is created, which prevents the vapor escape from the surface and increases the thermal resistance. Hence, the formation of optimized porous nanoparticle layer can be a key factor to ensure the CHF enhancement. However, the nanostructure formed on the heated surface by the deposition

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of nanoparticles through the boiling process is not well-controlled with ease. Therefore, the pre-organized structured surface may be an effective way to improve the CHF, and the experiments using the heated surface with the well-designed structures and unique materials should be carried out intensively.

Lately, the photo-catalytic wetting behavior and its applications have been reported [19–23]. The surface wettability can be modified effectively by light irradiation. Among the materials with unique photo-catalytic wetting characteristics, the titania (TiO_2) was utilized for the heat transfer experiments [24,25]. Glavin [24] performed the boiling heat transfer experiment using the sputter-coated TiO_2 thin films. The water contact angle (WCA) of TiO_2 thin film was substantially decreased by the UV light irradiation, which resulted in the boiling heat transfer coefficient reduction. In addition, they insisted that the CHF increases slightly by UV light-exposed TiO_2 surface, but it was not a significant change. On the other hand, Maeng et al. [25] investigated the effect of surface wettability on CHF using TiO_2 surface. They fabricated the TiO_2 surfaces using the direct current (DC) plasma sputtering process, which did not provide the special porous structures. Their WCAs were controlled by the sputtering time, of which range was from 62° to 11° . Surface wettability of TiO_2 surfaces was improved, as compared with the non-treated one (WCA $\sim 82^\circ$). Despite improved surface wettability, the TiO_2 surfaces did not change the CHF obviously. They concluded that the surface wettability was not a main parameter to determine the CHF. In the previous research [24,25], the plain TiO_2 surfaces without any special structure were tested. However, the nanostructured TiO_2 surface may show the different influence on the boiling heat transfer performance, which needs to be examined.

In this study, the effect of photo-induced wettability change of TiO_2 nanotube arrayed surface (TNAS) on the pool boiling heat transfer performance is investigated. The surface wettability (i.e., WCA) of TNAS is controlled by the UV light irradiation time. The boiling curves of TNAS and plain (i.e., non-treated) titanium surface (PTS) are obtained and discussed. In addition, their CHF measurement data are reported and compared with the earlier CHF correlations. Based on the experimental data, the relationship between the photo-induced wettability change of TNAS by the UV light irradiation and pool boiling heat transfer performance (i.e., boiling curve and CHF value) is examined in detail.

2. Experimental

2.1. Preparation of TNAS

Titanium heater was obtained from McMaster Carr. Before anodic oxidation, the titanium surface was electropolished at 20 V in 0.3 M phosphoric acid in order to remove any organic residue or contamination. Organic-based electrolytes were prepared in glycerol, and 3 wt% ammonium fluoride (NH_4F) was used as a fluoride source. After the addition of the fluoride source to the solvent, the mixture was stirred for 2 h to fully dissolve the NH_4F salt at room temperature. Anodic oxidation was performed at 30 V in a potentiostatic mode. After anodic oxidation, the heater surface was thoroughly rinsed with the isopropyl alcohol couple of times. Finally, the TNAS was obtained. In Section 3.1, the characterization results of TNAS were provided and discussed.

2.2. Experimental set-up for pool boiling heat transfer

The pool boiling experimental set-up described in our previous report [26] was used, which was briefly summarized in this section. The preparation of titanium heater with TNAS was described in Section 2.1. The heating surface has 10 mm in diameter. A cartridge heater (McMaster Carr, 120 V and 400 W) was inserted into the center hole of the titanium heater and four T-type thermocouples (Omega) were installed with 6 mm interval from the top. Nominal uncertainty of thermocouple was 0.5°C . DC power supply (Agilent, DC5500) was used to control the power applied to the cartridge heater. Three reflux

condensers connected to a constant temperature controller (Polyscience) were adopted to condense the vapor generated inside of the boiling chamber. All temperatures were monitored and stored by data acquisition system (Iotech). The experimental uncertainties of heat flux and temperature were evaluated to be within 8.1% and 8.6%, respectively.

3. Results and discussion

3.1. Characterization of TNAS

In order to obtain the TiO_2 nanotube arrayed structure on the surface, the pristine titanium heater surface was anodized as introduced in the previous section. It is known that the characteristic features (e.g., pore diameter, wall thickness of nanotube, interspacing between pores, and length of nanotube) of TiO_2 nanotube arrayed structure are varied depending on the anodic voltage and anodizing time.

The surface morphology of TNAS is displayed in Fig. 1, which was obtained using the scanning electron microscope (SEM, Hitachi S-4700). Fig. 1(a) shows the top view ($\times 150,000$ magnification) of TiO_2 nanotubes, which were densely populated at given surface area. The number of TiO_2 nanotubes per given area was approximately $29/\mu\text{m}^2$. Inset ($\times 500,000$ magnification) in Fig. 1(a) displays that the pore diameter and wall thickness of TiO_2 nanotubes are approximately 200 nm and 30 nm, respectively. Fig. 1(b) shows the cross-sectional view ($\times 20,000$ magnification) of TiO_2 nanotubes. Average length (or height) of the TiO_2 nanotubes was approximately $2\mu\text{m}$ and the bundled TiO_2 nanotubes formed the micro-sized bumps. Overall, the TNAS had the combination of different length-scaled (i.e., micro- and nano-scaled) cavities.

In order to confirm the chemical composition of TNAS, energy dispersive spectrum (EDS, INCA Energy Oxford instruments) analysis was carried out. In Fig. 2(a), the oxygen (O) $\text{K}\alpha$ peak and intensive titanium (Ti) $\text{K}\alpha$ peak were observed at 0.53 and 4.51 keV, respectively. Elemental analysis confirmed the presence of TiO_2 by integrating peak area (Ti:O = 61:39 by wt% and 66:34 by atomic%). Fig. 2(b) shows the ring pattern from selected area electron diffraction (SAED) measured using the high resolution transmission electron microscopy (TEM, JEOL 1400) image. The electron diffraction pattern of TNAS (See Table 1) could be indexed to the anatase phase of TiO_2 (JCPDS-21-1272).

3.2. Wettability change of TNAS by UV light irradiation

When the TNAS is exposed to UV light irradiation, the mobile charge carriers (electron pair holes) are generated on its surface. During the photo-catalytic reactions, the oxygen vacancy is produced and reacts with the adsorbed water molecules in atmosphere. A hydroxyl group on the surface increases the affinity of chemisorbed water in the air. It leads to a hydrophilic surface. It is notable that the generation of charge carriers and recombination process are reversible. That means that during UV light exposure, the surface becomes hydrophilic, whereas its hydrophobicity is slowly recovered and becomes (super)hydrophobic when the UV light irradiation is removed.

Fig. 3 shows the WCA measurement results of TNAS with PTS. Here, the numbers of data points in the graph correspond to those of WCA images. The WCA of PTS was 68° (Image ①). On the other hand, the WCA of TNAS was 158° (Image ②) before UV light irradiation. It exhibited the superhydrophobic nature. As shown in Fig. 1, the TNAS consists of micro- and nano-sized cavities and pores. These hybridized structures can escalate its wetting properties into the hydrophobic regime. In other words, the combination of surface roughness and enhanced surface area effectively entraps the air into cavities, which may lead to the Cassie-Baxter state of water droplet. During photo-catalytic reaction, the hydroxyl group is generated on the TNAS and its population is proportional to the irradiation time. Therefore, the WCA of TNAS was drastically decreased with the UV light irradiation time. After 1, 2,

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