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Surface wettability effect on nucleate pool boiling heat transfer with titanium oxide (TiO_2) coated heating surface

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ABSTRACT

Here, we explored the effect of surface wettability on nucleate pool boiling heat transfer performance by employing hydrophilic titanium oxide (TiO_2) layer coated on a cylindrical plain aluminum 6061 (Al 6061) as a reference. The comparative heating surfaces are the plain, TiO_2 coated and TiO_2-water repellent coated surfaces. The water repellent was superimposed on the reference heater before TiO_2 coating on it to depress hydrophilicity nature of TiO_2. The boiling tests were carried out in steady-state condition and in saturated water under one atmosphere during the entire experiment. The nucleate boiling performance depends on the level of surface wettability. Results showed that TiO_2 coated surface contributed to the increasing of nucleate pool boiling performance by 64.1% in comparison to that of the plain surface. The TiO_2-water repellent coated surface gave a less enhanced performance than the TiO_2 coated surface, and it is underperformed over the plain surface when the wall superheat (ΔT) > 12.3 °C. Boiling visualization demonstrated the augmented heat transfer mechanism by showing more active nucleation sites and more bubble departure frequency on the TiO_2 coated surface.

1. Introduction

A lot of effort has been made to investigate extensively boiling heat transfer by many researchers. A number of models and correlations have been proposed to predict the boiling heat transfer coefficient (HTC), as well as critical heat flux under different conditions [1]. Earlier works reveal that major parameters affecting the HTC under nucleate pool boiling conditions are heat flux, saturation pressure, thermophysical properties of a working fluid and surface-fluid combinations, such that the effects of these parameters have been well established. Moreover, the surface effects, for example, shapes, dimensions, thickness, surface finish, micro/nanostructure, porous layers, etc., need more investigations [1–3]. Industrial demands also lead to the development of methods to increase boiling heat transfer performance for a high cooling and heating efficiency. Thermal management such as cooling and boiling, heat dissipation in various systems and nuclear reactors requires better boiling performance in pursuit of safety and efficiency at the same time.

Various techniques for boiling heat transfer enhancement have been implemented by surface modifications on a heating surface such as plasma coating, MEMS fabrication and mechanical surface machining [4,5]. Lee et al. [4] conducted the fabrication and testing of aluminum oxide nano-porous surfaces (NPS). Dhillon et al. [6] worked on the surface texturing using parametrically designed plain and nano-textured micropillar surfaces. Wu et al. [7] investigated the pool boiling of water and FC-72 on silicon oxide and titanium oxide surface. Zhang and his coworkers [8–10] carried out the experiments of various assembled carbon nanotubes and nano-porous structures. Fundamentally, the boiling heat transfer enhancement is facilitated with surface treatments on a heater surface contributing to increasing vapor and liquid entrapment, bubble departure frequency and active nucleation site density. This leads to reducing the incipient and nucleate boiling wall superheat, such that the boiling performance improves.

Titanium oxide (TiO_2) has received a lot of attention because it shows nucleate boiling and critical heat flux (CHF) enhancement with an affinity for water, and in turn reducing water contact angle on a heating surface [7,11–13]. Takata et al. [11,12] first carried out a study of evaporation and pool boiling on the heater surfaces coated with TiO_2 layers that were irradiated by UV light, and showed a boiling enhancement for water. This study reported that the contact angle of the irradiated TiO_2 surfaces decreases nearly to zero. Wu et al. [7] worked on the nucleate boiling and CHF of water and high-wetting FC-72 on a hydrophilic surface modified by TiO_2 nanoparticles. They found that the boiling performance enhancement hinges on the level of surface wettability improvement.

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Nomenclature

A	heat transfer area, m^2
I	current, A
h	boiling heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
L	length of heater, m
Q	electrical power consumption, W
q	heat flux, W/m^2
R	thermal resistance, K/W
T	temperature, K
t	thickness, m
ΔT	wall superheat, K
V	voltage, V
Subscripts	
am	ambient
iw	insulation wall
sat	saturated
tc	thermocouple
w	wall

Suroto et al. [13] examined the superiority of nucleate boiling heat transfer attributable to surface wettability and subcooling with hydrophilic copper surface polished, superhydrophilic copper surface coated by TiO_2 and hydrophobic PTFE surface for water. The TiO_2 coated surface was superior to the other two surfaces at a medium heat flux, while the hydrophobic surface showed a better performance at a low heat flux.

In this paper, we studied the effect of TiO_2 coating layer on a cylindrical and horizontal Al 6061 heater in nucleate pool boiling heat transfer. For performance comparison, three types of heater surface were adopted through different fabricating processes. They are the plain surface that serves as a reference, TiO_2 coated and TiO_2-water repellent coated surfaces. In particular, the latter was contemplated so that the TiO_2 coating was superimposed on a water repellant [NeverWet^{TM}, (NeverWet LLC, USA) [14]] coated on the plain surface. This was intended to search for nucleate boiling behaviors on a more moderate surface wettability than the other heating surfaces. Distilled water was chosen for saturated pool boiling experiments. All tests were carried out under steady state condition and at atmospheric pressure in the boiling chamber. Bubble dynamics, such as active nucleation site density, bubble departure frequency and bubble sizes, was visualized at discrete heat flux conditions in order to account for the boiling heat transfer enhancement mechanism qualitatively.

2. Experiment

2.1. Pool boiling experimental setup and procedure

The experimental apparatus for tests is illustrated in Fig. 1a and b. It constitutes a boiling chamber, heating system comprising a test heater and an auxiliary heater, reflux condenser, visualization unit, and data acquisition system. The boiling chamber is mainly housed with stainless steel, and at each side end the PTFE plates are attached. The size is a 101.6 mm in both height and width with a length of 177.8 mm. The cylindrical Al 6061 test heater, with a 19.1 mm in diameter and a 101.6 mm in length, is machined to insert a 400 W cartridge heater (McMaster) into the center of it with a high-conductivity thermal paste (Omega 201). Ceramic wool (<0.1 W/m K) is adopted as an insulator that surrounds the entire boiling chamber to depress as much heat leakage as possible to the environment. The auxiliary heater with a capacity of 100 W is immersed in the pool above the bottom of the chamber to preheat the water liquid and to sustain the saturation temperature (T_{sat}) in connection with the reflux condenser, where one atmosphere pressure is maintained through the entire experimental period. One T-type thermocouple is submerged into the liquid pool to measure the bulk temperature, and then to give a feedback to a temperature controller to maintain the saturation condition. The reflux condenser that plays the role of condensing steam generated from boiling is connected to the constant water bath.

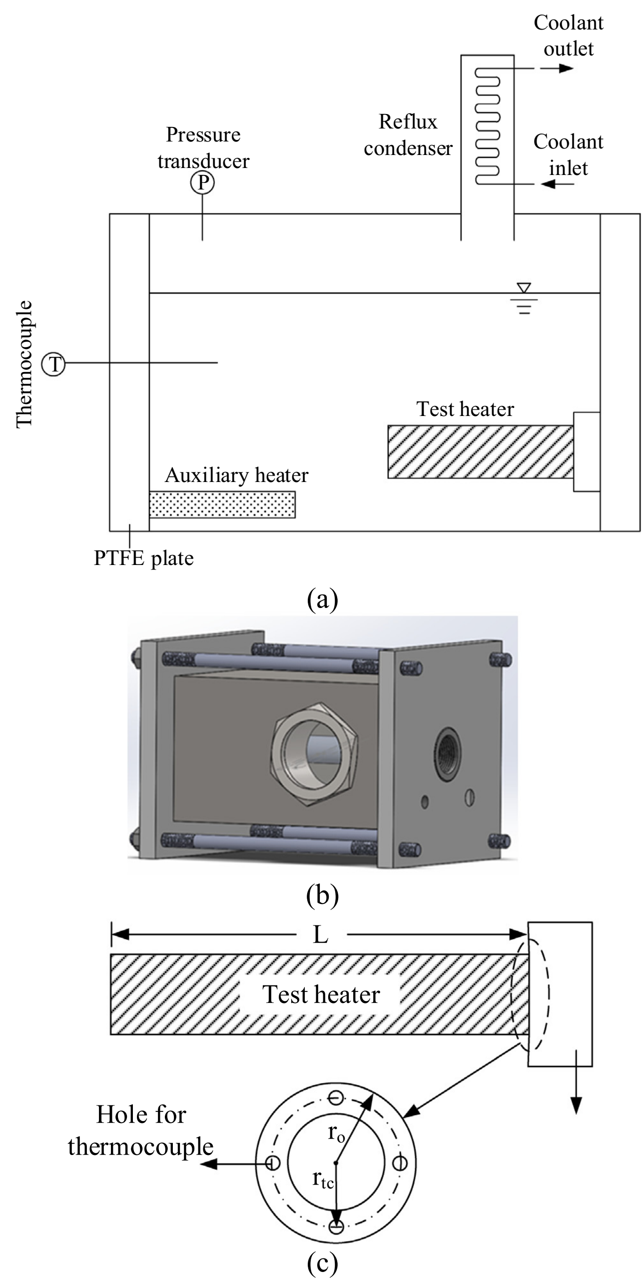


Fig. 1. (a) Schematic of pool boiling apparatus, (b) Boiling chamber, and (c) cylindrical Al 6061 heater substrate and thermocouples location.

There are, as shown in Fig. 1c, four T-type thermocouples equidistantly embedded into along the central circumference between the inner and outer heater walls with the thermal paste (Omega 201). For this, four holes with each 2.4 mm in diameter and 70.0 mm in depth were mechanically drilled 90° apart at the top, middle and bottom. The thermocouples were used to evaluate heat flux across the cylindrical shell by one dimensional pure conduction. The heat transfer rate was evaluated by assuming that a uniform heat flux in the radial direction of the heater is allowed by the cartridge heater. The iOtech data acquisition system was used to record the water and test heater temperatures. The Agilent DC power supplier powered the test heater, and the relevant voltage and current were measured by the Agilent 34410A and Fluke 87 V. A Nikon D40X digital camera and a LW Scientific fluorescent ring light were prepared to visualize boiling phenomena such as bubble generation, departure and its frequency, sizes and distribution.

The experimental procedure started with rinsing the boiling chamber and the test heater with acetone and distilled water. Distilled water was filled in the boiling chamber, and then the test and auxiliary heaters heated the water up to the saturation temperature that corresponds to the atmospheric pressure. Of importance in this experiment is to eliminate non-condensable and dissolved gases effectively in TiO_2 coated surface on the test heater. The degassing procedure was accomplished by boiling the water in the chamber under the ambient pressure for about twenty minutes. The test apparatus was performed to reach a steady state at which temperature readings from the immersed thermocouple in the pool changed within less than one degree Celsius. When the steady state is achieved at an imposed electric power level, all the temperatures were recorded over a period of five minutes. The power was increased by 5 voltages at each test step to investigate boiling curves.

2.2. Sample preparation

To make a TiO_2 coated and TiO_2-water repellent coated surfaces on Al 6061 heater, different fabricating processes were utilized. For the TiO_2 coated surface, Al 6061 heater was polished with a high grit sandpaper, and then it was rinsed with acetone and distilled water. The acetone was employed as a solvent to remove any extraneous deposits off the heater. An aqueous solution, which is a mixture of anatase TiO_2 (wt. 1%) and ethanol (wt. 99%), was prepared and the solution drops were evenly spread on the heater as thoroughly as possible, and subsequently it was heated at a temperature of 200 °C in an oven for over thirty minutes. This process was repeated for four different sides of the heater.

The TiO_2-water repellent coated surface was prepared by a coating process with the water-repellent before applying the aqueous solution that is used for TiO_2 coating on the reference heater. The water repellent is commercially available as water and oils repellent that can keep the treated surfaces clean and dry from the harmful effects of water and oils. It originally works based on two coats, which are composed of a base coat and a top coat. The base coat is sprayed with hydrocarbon resin, and naphtha and ester solvents. The top coat is done solely by acetone solvent. For the present sample, only the base coat was used for the water repellent application.

The different coating fabrications stated above were attempted to focus on nucleate pool boiling effects in terms of surface wettability. Eventually, there are three types of sample surface on the Al 6061 reference heater for the experimental investigations: plain surface that acts as a reference, TiO_2 coated surface and TiO_2-water repellent coated surface.

2.3. Surface wettability measurement

The surface wettability of working liquid on a surface has an important impact on nucleate pool boiling heat transfer. It is determined by contact angle between the surface and liquid droplet. The sessile drops application using KSV CAM 200 goniometer was adopted to measure contact angles of water droplets on the heater surfaces. Multiple trials were conducted to verify the measuring reliability and repeatability, and to ensure the surface coating evenness.

Fig. 2 shows the contact angles of water droplets on the three sample surfaces. The plain surface was used to calibrate the measuring facility, and its contact angle was obtained as 81°. The smallest contact angle, which was measured by 15°, occurred on the TiO_2 coated surface because of water affinity to the surface. The contact angle of the TiO_2-water repellent surface was measured by 65°, which is larger than that on the TiO_2 coated surface due to the water repellent effect.

2.4. Data reduction and experimental uncertainty

The heat flux and surface temperature of the test heater were measured in order to obtain nucleate boiling curves. Heat was transferred to water through the cylindrical shell of the test heater from the cartridge heater by conduction. The overall heat balance is formulated by

$$q = \frac{Q - Q_{loss}}{A} \quad (1)$$

in which q is the net heat flux transited to the water. Q is the total electrical power consumption provided by the cartridge heater, which is defined as $Q = VI$, where V and I are the imposed voltage and current, respectively. Q_{loss} is the heat loss to the ambient. $A(= 2\pi r_o L)$ is the total heat transfer area of the heater interfaced with the water in the pool. Invoking one-dimensional and steady state conduction, the heat flux q is rewritten by

$$q = \frac{T_{tc} - T_w}{R_c \cdot A} \quad (2)$$

where $R_c = \ln(r_o/r_{tc})/2\pi kL$ is the thermal resistance across the heater wall thickness by pure conduction. T_w and T_{tc} are the temperatures of the heater wall in contact with water and the average temperature from the thermocouples embedded into the heater (Fig. 1c), respectively. r_o and r_{tc} stand for the outer radius of the heater and the distance between the heater center and the thermocouple, respectively. k is the thermal conductivity of Al 6061. The water boiling on the heater surface occurs at 10 mm away from the

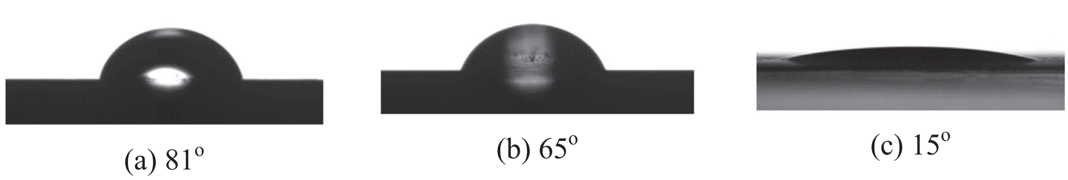


Fig. 2. Contact angle measurement for water droplet: (a) plain surface, (b) TiO_2 coated surface, and (c) TiO_2-water repellent coated surface.

thermocouples. The heater wall temperature T_w is determined by extrapolating the measured average temperature of the test heater as follows,

$$T_w = T_{tc} - R_c \cdot (Q - Q_{loss}) \tag{3}$$

The total heat loss is stated as $Q_{loss} = (T_{iw} - T_{am})/R_{loss}$ in which T_{iw} and T_{am} are the insulated wall and the ambient temperatures during the experiment, respectively. The thermal resistance of heat loss is of a form $R_{loss} = t/k_{iw}A_{iw}$, where t and A_{iw} are the ceramic wool insulation thickness and the relevant area covering the chamber, respectively. k_{iw} is the thermal conductivity of ceramic wool. The average heat loss approaches about 3.0 W during the entire data collection, showing that it increases as the power input increases, while the percentage loss decreases.

The experimental uncertainty of the heat input into the heater can be estimated by the method proposed by Kline and McClintock [15],

$$\frac{\Delta q}{q} = \sqrt{\left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta I}{I}\right)^2 + \left(\frac{\Delta A}{A}\right)^2} \tag{4}$$

where ΔV and ΔI are the variable quantities pertaining to the measured voltage and current, respectively, which are generated by the power supply imposed on the heater surface. The accuracy is 0.2% for each measurement. ΔA for which the measurement accuracy is allowed by 10% is the variable area that may vary relying on surface treatments and modifications such as polishing, coating and chemical rinsing. The heat transfer coefficient uncertainty in association with those of the heat flux and temperature is of a following form, which was proposed by Moffat [16],

$$\frac{\Delta h}{h} = \sqrt{\left(\frac{\Delta q}{q}\right)^2 + \left(\frac{\Delta T}{T}\right)^2} \tag{5}$$

The nominal uncertainty of T-type thermocouple is 0.75%. In the present study, it was found that the overall uncertainties of the heat input and heat transfer coefficient are 5.2% and 5.9%, respectively.

3. Results

The boiling curves for the non-coated and coated heating surfaces for comparison are obtained in Fig. 3. For given wall superheats, the heat fluxes increase as the wall superheat increases. The performance of the TiO_2 coated surfaces outperforms that of the plain surface, however, from the transition at $\Delta T = 12.3$ K ($q = 109.6$ kW/m^2), the plain surface performs better than the TiO_2-water repellent coated one. The average heat transfer rate on the TiO_2 coated surface is improved by 64.1% in comparison with the plain surface when the superheat ranges from 2 to 13 K.

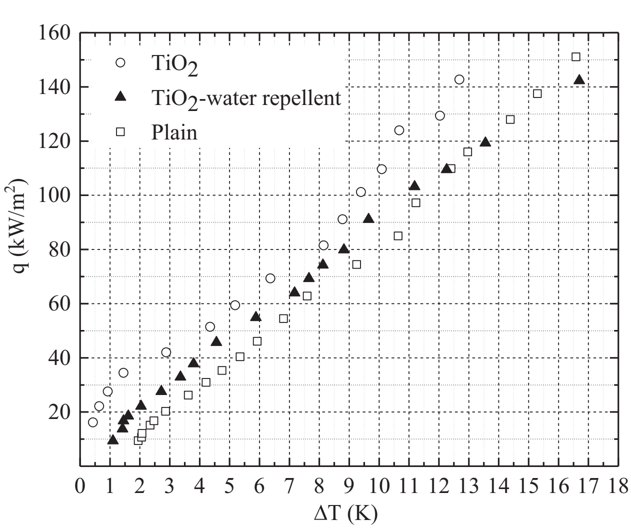


Fig. 3. Boiling curves for the non-coated and coated surfaces.

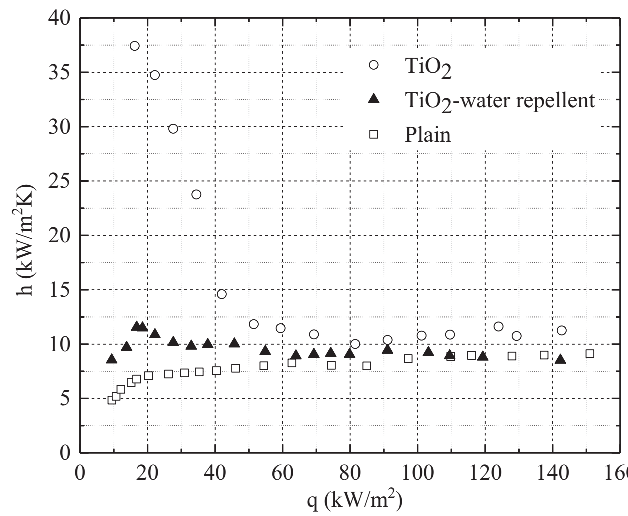


Fig. 4. Relationship between heat transfer coefficients (HTC) and heat flux for the non-coated and coated surfaces.

Heat transfer coefficients, defined as $h = q/\Delta T$, are presented in Fig. 4. At low heat fluxes of the tests when $q < 40$ kW/m^2, the heating surfaces experience dramatic performance changes, after which they show a stabilizing behavior according to increasing heat fluxes. The largest values take place on the TiO_2 coated surface, especially, at the start of boiling tests and having an overall decreasing trend as the heat flux increases. On the other hand, the heat transfer coefficients for the plain surface increase according to increasing heat flux and overcome the performance of the TiO_2-water repellent coated surface from at the heat flux value, $q = 109.6$ kW/m^2, as illustrated in Fig. 4. There exists a maximum heat transfer coefficient on the TiO_2-water repellent coated surface at $q = 16.7$ kW/m^2, which corresponds to the relevant heat transfer coefficient, $h = 11.6$ kW/m^2.

As demonstrated in Fig. 3, the boiling curve migration of the TiO_2 coated surfaces towards the upper left side from the reference boiling curve of the plain surface results in a better heat transfer augmentation for which a lower superheat is achieved for the same heat flux transited. Furthermore, the onset of nucleate boiling (ONB) on the coated surfaces can be conjectured to take place earlier than on the plain surface. Fig. 5 shows the boiling curve hysteresis on the TiO_2-water repellent coated surface when the wall superheat increases and then decreases at the maximally imposed superheat. For water, the heater provides almost identical boiling curves independently of increasing and decreasing wall superheat conditions. Better consistency occurs for smaller wall superheats.

It is demonstrated that the boiling curve migration coincides with surface wettability. As the surface wettability increases with a smaller contact angle formed by water droplet on the surface, better boiling performance is pursued due to superior hydrophilicity, i.e., water affinity, on the heater surfaces. But, the boiling curves for the plain and TiO_2-water repellent coated surfaces show that the decrease in contact angle is not linear with nucleate boiling heat transfer performance, which indicates that it is necessary to take into account applied heat flux ranges to discover optimal boiling regimes.

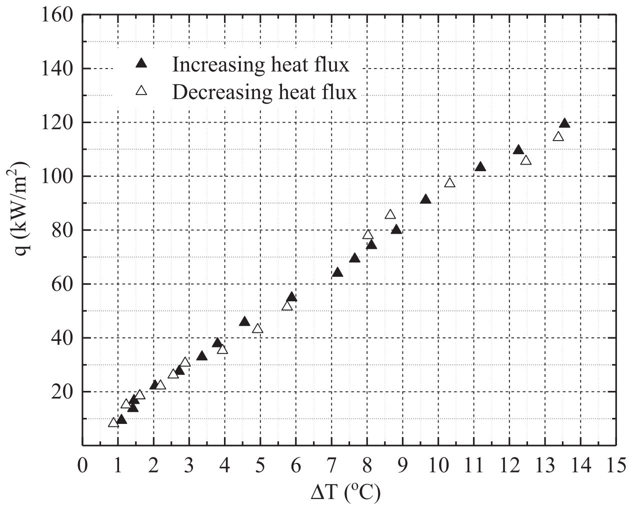


Fig. 5. Boiling curve hysteresis for the TiO_2-water repellent coated surface.

The nucleate boiling visualization for the plain and TiO_2 coated surfaces, as shown in Fig. 6, reinforces the boiling heat transfer enhancement mechanism for the boiling curves that appear in Figs. 3 and 4. For the given distinguishable heat input, the bubble population density, bubble departure frequency and bubble sizes increase as the heat flux increases. The TiO_2 coated surface has more bubble population density, faster bubble departure frequency than on the plain surface, however, the bubble sizes are relatively smaller compared with those on the plain surface for the same heat fluxes because of faster bubble removal off on the TiO_2 coated surface. For the low and intermediate heat fluxes at $q = 40$ and $60\ kW/m^2$, respectively, isolated bubbles separated from the surface participate in nucleate boiling heat transfer such that heat exchanges from the heater surface to liquid flow near the heater [17,18]. At the high heat flux condition at $q = 120\ kW/m^2$, active nucleation sites on the TiO_2 coated surface are intensified so bubble coalescences are observed on it. Based on this boiling visualization combined with the boiling curves, it is proved that more dynamic bubble behaviors on the heater surface lead to enhanced boiling heat transfer.

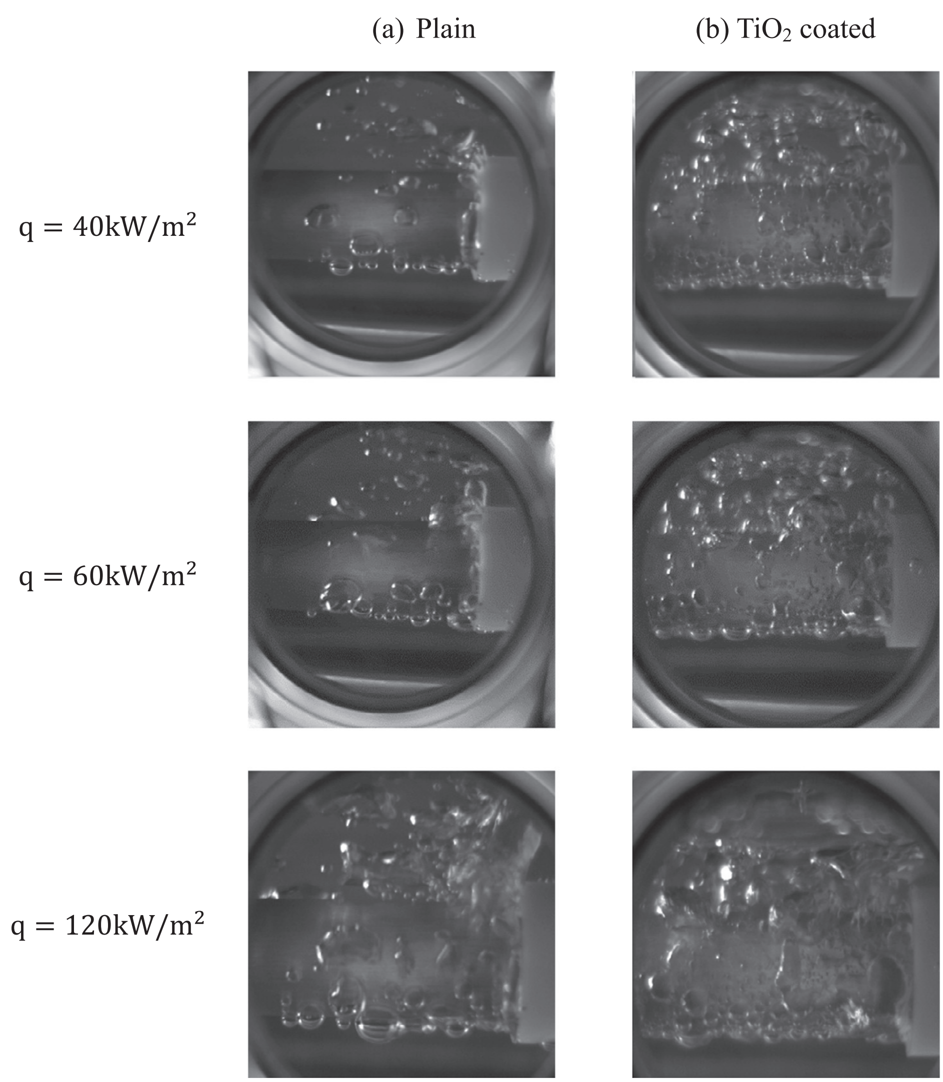


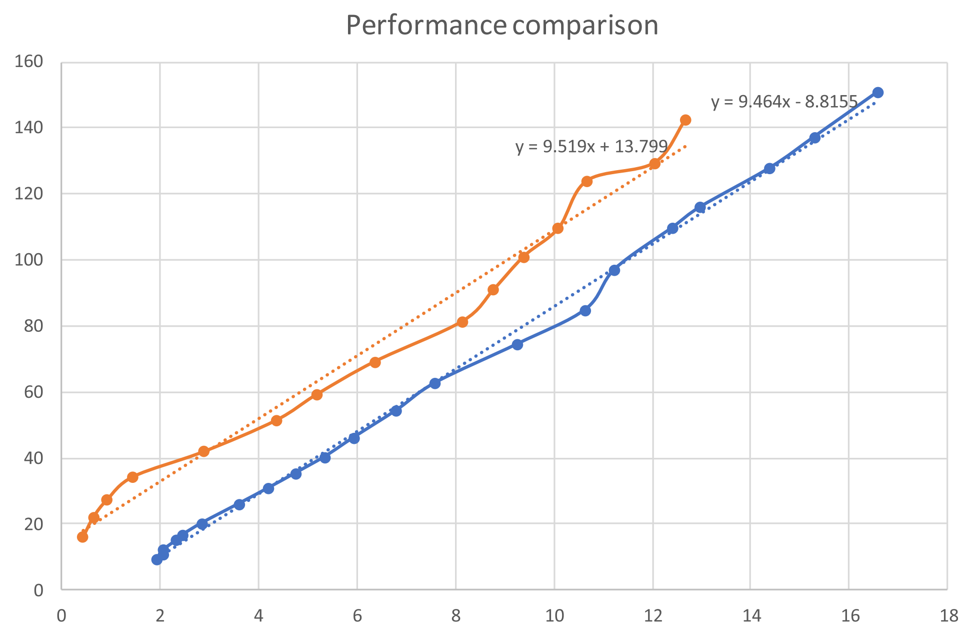
Fig. 6. Visualization of nucleate pool boiling on the plain and TiO_2 coated surfaces.

4. Conclusions

The purpose of this paper is to experimentally evaluate the effect of TiO_2 coating layer on a cylindrical Al 6061 substrate in nucleate pool boiling heat transfer. For nucleate boiling performance comparison, the heaters with Al 6061 plain surface as a reference, TiO_2 coated and TiO_2-water repellent coated surfaces were prepared and tested under steady-state condition and in saturated water under one atmosphere during the entire experiment. Surface wettability was measured and taken as a key factor to estimate the effect of TiO_2 and water repellent towards boiling curve migration.

The heater surface with TiO_2 coating showed an enhanced performance of boiling heat transfer consistently compared to the plain surface, ascribed to better hydrophilicity and consequently leading to a significant increase in active nucleation sites and bubble departure frequency with smaller bubble sizes. The boiling performance was improved by 64.1% (Fig. 3 and Appendix A). In the case the water repellent was superimposed with TiO_2 on the reference heater to mitigate water affinity, the boiling curve experienced a performance transition at $\Delta T = 12.3\,^{\circ}C$, after which the plain surface was outperformed. All the heating surfaces considered showed more vigorous changes in the heat transfer coefficients for the low heat flux conditions when $q < 40\ kW/m^2$, as shown in Fig. 4. However, as the heat flux increases, the heat transfer coefficients are stabilized, which indicates that the boiling heat transfer is dominantly governed by wall superheat, ΔT. The boiling curve hysteresis is insensitive for water and showed more consistency for lower wall superheats. The boiling visualization strengthens the reason of boiling curve migrations in Figs. 3 and 4, showing that more active bubble removal rate contributes to the enhancement of boiling heat transfer.

The results address the importance of heating surface conditions to make a difference in boiling curves. It was proven that more hydrophilicity is preferred in improving the nucleate pool boiling performance. Superhydrophilic surface with a nearly 0° contact angle, which is manipulated by exposure time of UV



ΔT	Plain(q)	TiO2 coated(q)	%
2	10.1125	32.837	224.717
3	19.5765	42.356	116.361
4	29.0405	51.875	78.6298
5	38.5045	61.394	59.4463
6	47.9685	70.913	47.8324
7	57.4325	80.432	40.0461
8	66.8965	89.951	34.4629
9	76.3605	99.47	30.2637
10	85.8245	108.989	26.9905
11	95.2885	118.508	24.3676
12	104.753	128.027	22.2186
		Average	64.1215

Fig. A1. Performance improvement of the TiO_2 coated surface compared with the plain surface (The values written were calculated by the two trend lines.) Y-axis and X-axis are q (kW/m^2) and ΔT (in K), respectively.

irradiation on a TiO_2 coated heater surface [12], is an ideal candidate for heat transfer surface with various heat transfer phenomena affected by surface wettability. Similar researches have been conducted with square flat heaters and for copper substrates [12,19]. However, it will be very intriguing to observe boiling dynamic characteristics for superhydrophilic surface with a cylindrical aluminum substrate. It is noteworthy that optimal combination of surface wettability with surface roughness level can be a critical coating criterion to explore the enhancement opportunity of nucleate pool boiling heat transfer. Strictly, surface roughness should be included as an indicator to account for boiling performance better when coating on a heater surface is applied, because a rougher surface serves as relatively large cavity sites and makes boiling inception possible at low wall superheats. Moreover, boiling inception is strongly in association with active cavity size ranges, i.e., favorable cavity size ranges for effective nucleation sites, depending on kind of working fluid used in nucleate pool boiling. Accordingly, analysis for active cavity size range is necessary [7,20].

Acknowledgements

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Appendix A

See Fig. A1.

Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ijheatmasstransfer.2018.12.075.

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