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Abstract. The nanoparticle layer detachment during nucleate pool boiling and its influences on heat transfer surface properties were explored experimentally. The material of the heat transfer surface was copper and the nanoparticle layer was formed on the heat transfer surface by nucleate boiling in the water-based TiO_2 nanofluid. It was found that the detachment of the nanoparticle layer during nucleate boiling in pure water is significant. In the present experiment, more than half of nanoparticles deposited on the heated surface were detached before the CHF condition was reached. The thickness and roughness decreased accordingly. However, the wettability and wickability that are the influential parameters on the CHF value were maintained even after the occurrence of nanoparticle layer detachment and deteriorated only after the CHF condition was reached. It is therefore considered that the onset of CHF brings qualitative change to the capillary suction performance of the layer of nanoparticles. In exploring the effect of the nanoparticle layer properties on the nucleate boiling heat transfer, sufficient attention should be paid to the variation of the nanoparticle layer properties during nucleate boiling.

1. Introduction
In nucleate pool boiling in nanofluids, the heat transfer coefficient (HTC) and the critical heat flux (CHF) are different from those in pure liquids. In particular, since CHF usually increases in the nanofluids, its applications to the emergency cooling in nuclear power plants and the heat removal from the high-power-density electronic devices are considered promising [1-4]. The variations of HTC and CHF in nanofluids are mainly attributed to the change in the heat transfer surface properties due to the formation of the layer of nanoparticles [5, 6]. Thus, extensive measurements have been carried out not only for HTC and CHF but also for various properties of the nanoparticle layer [7, 8]. However, the effects of each nanoparticle layer property on HTC and CHF are not sufficiently elucidated.

If the effects of each nanoparticle layer property such as the roughness, thickness, wettability, and wickability are elucidated, high-performance heat transfer surface of improved HTC and CHF may be designed efficiently. However, since the nanoparticle layer properties vary during nucleate boiling, experimental determination of the relation between the nanoparticle layer properties and the boiling heat transfer characteristics is not easy. In particular, it is known that since adhesion of the nanoparticle layer on the heated surface is not always very strong, detachment of the layer may occur during nucleate boiling [7]. In the present work, pool boiling experiments are performed to explore quantitatively the

significance of the nanoparticle layer detachment during nucleate boiling and its influence on the nanoparticle layer properties.

2. Description of the experiment

The photo and schematic of the experimental apparatus are displayed in Fig. 1. The circular end face of a copper block containing nine cartridge heaters were used as the heat transfer surface. The heat transfer surface was 20 mm in diameter and set at the bottom of the cylindrical polycarbonate vessel of 144 mm in diameter. The experimental procedures are described as follows. First, 0.15g of TiO$_2$ nanoparticles (Aeroxide TiO$_2$ P25, Aerosil Corporation) were dispersed in 200 ml of distilled water using an ultrasonic bath to obtain the nanofluid. Next, the heat transfer surface was cleaned using metal polishing paste and acetone. To prepare satisfactorily identical initial surface, it was confirmed that the contact angle was within 85-95° at five positions within the surface. Then, 1300 ml of distilled was supplied to the experimental vessel and the immersion heater in the vessel was switched on for degassing for 1h. The nanofluid was added to the test liquid to form the layer of nanoparticles on the heat transfer surface. From the mass of nanoparticles (0.15g) and the liquid volume (1500 ml), the particle concentration was calculated 0.1 kg/m^3. The heat flux to the heat transfer surface was kept at 600 kW/m^2 for 1h. After the formation of the nanoparticle layer, the test liquid was replaced by distilled water to avoid further deposition of nanoparticles. The heat flux q_w and the wall superheat ΔT_w were calculated from the temperature data of the four calibrated thermocouples accurate to within ±0.3K embedded in the copper block. The measurement errors of q_w and ΔT_w were estimated within 16 kW/m^2 and 0.5 K, respectively.

(a) Photo   (b) Schematic diagram

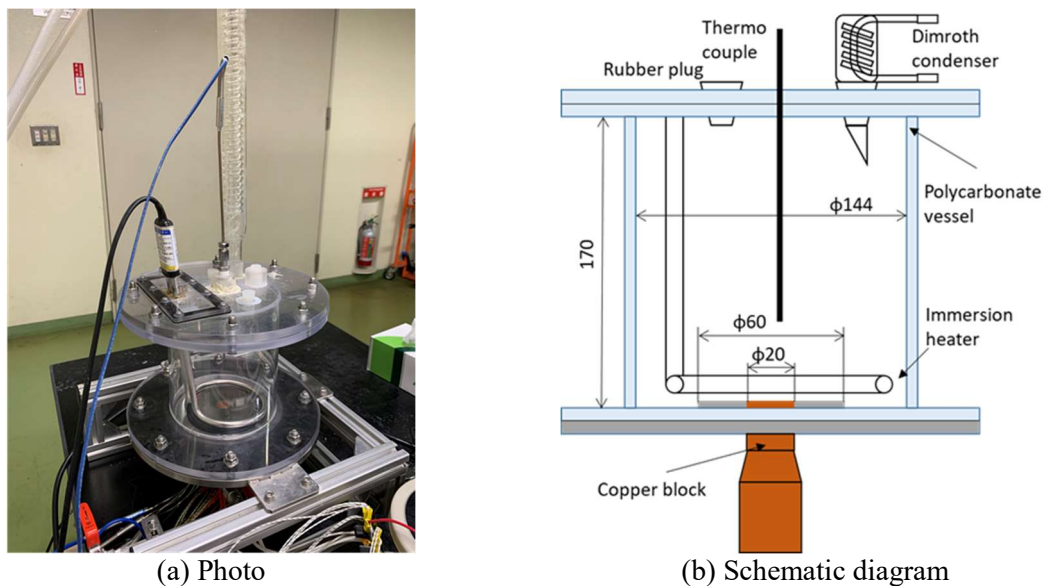**Figure 1.** Photo and schematic diagram of the experimental apparatus.

3. Results and discussion

3.1. Boiling curve

After replacing the test liquid with distilled water, q_w was increased step by step to obtain the boiling curve. The results are presented in Fig. 2. For the bare surface without the nanoparticle layer, the boiling curve is in good agreement with the correlation by Rohsenow [9] while the critical heat flux (CHF) was lower than the correlation by Zuber et al. [10]. The reason of lower CHF is unclear but a small amount of nanoparticles remained in the nucleation cavities. For the TiO$_2$ nanoparticle layer coated surface, it can be seen that the heat transfer coefficient (HTC) is deteriorated but the CHF is improved. These trends are consistent with the results reported by previous investigators [2, 7, 8].

3.2. Nanoparticle layer properties

As important properties of the nanoparticle layer, its total mass M_0, thickness d, roughness Sa, contact angle θ, and wickability Wi [11] were measured. The experimental data are displayed in Figs. 3-7, respectively. The nanoparticle layer properties may change continuously during nucleate boiling or abruptly at the onset of CHF. Thus, these measurements were conducted three times when the nanoparticle layer was formed (fresh surface), the value of q_w reached 90% of CHF, and the CHF was exceeded. After CHF, several defects where the nanoparticle layer detached significantly were found. Hence, the thickness and roughness were measured at the defect area as well as the normal area.

Figures 3 and 4 indicate that M_0 and d decreased continuously with an increase in the value of q_w. These are clear evidences that not only deposition but also detachment of the nanoparticles occurs during nucleate boiling in nanofluids. Figure 5 shows that the surface became smoother with progression of the detachment. It can also be seen that the values of d and Sa are smaller in the defect area.

Interesting observation is found in Figs. 6 and 7. The values of θ and Wi that are considered to have large impacts on the CHF are fairly constant before the onset of CHF and significant variations are found after the onset of CHF. These results indicate that capillary suction performance of the nanoparticle layer is maintained during nucleate boiling in spite of the occurrence of the detachment and deteriorated at the onset of CHF.
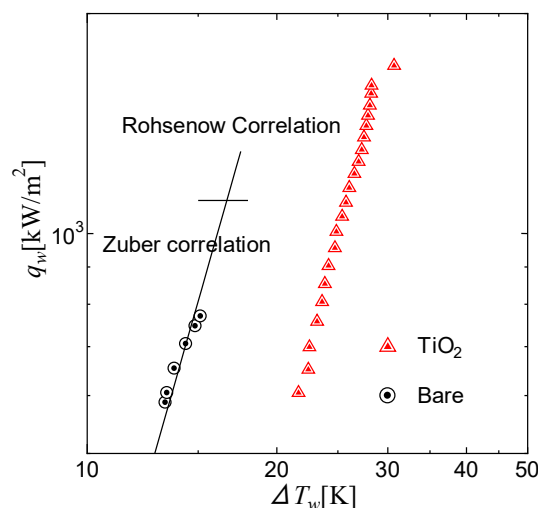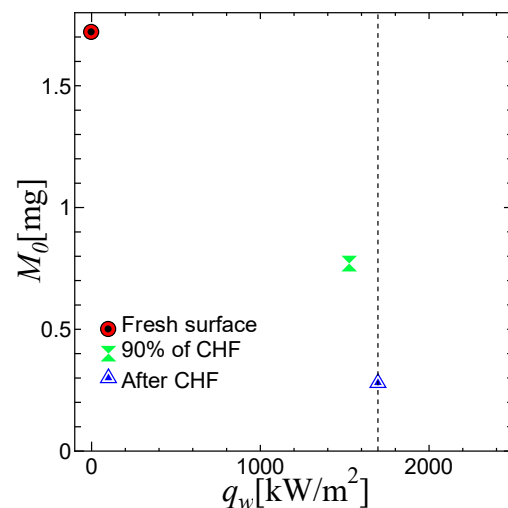

Figure 2. Boiling curvaes
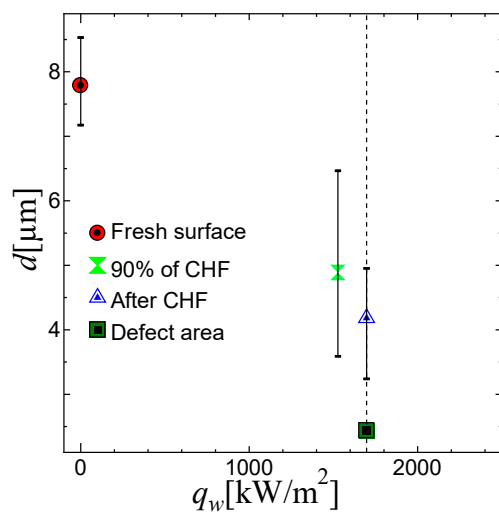

Figure 3. Mass of nanoparticle layer

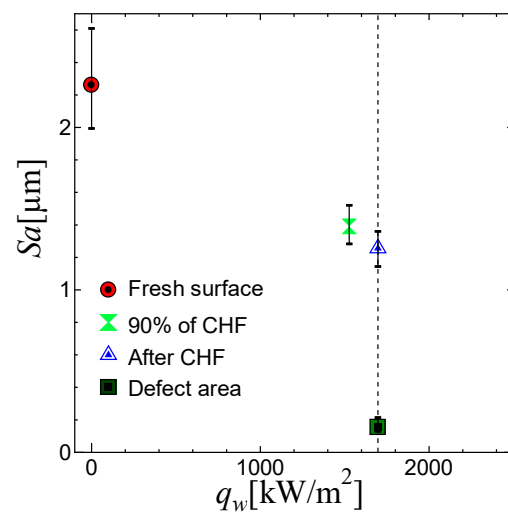**Figure 4.** Nanoparticle layer thickness
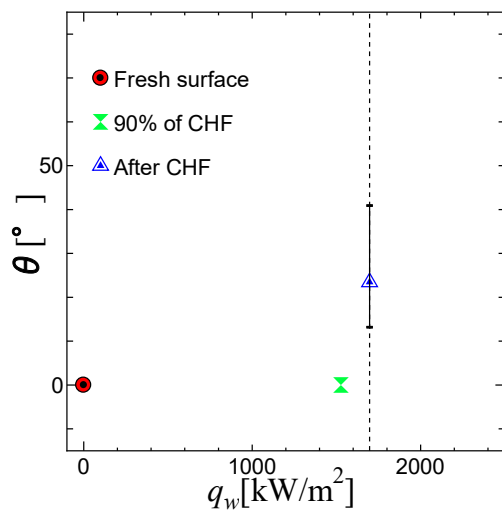

Figure 5. Roughness
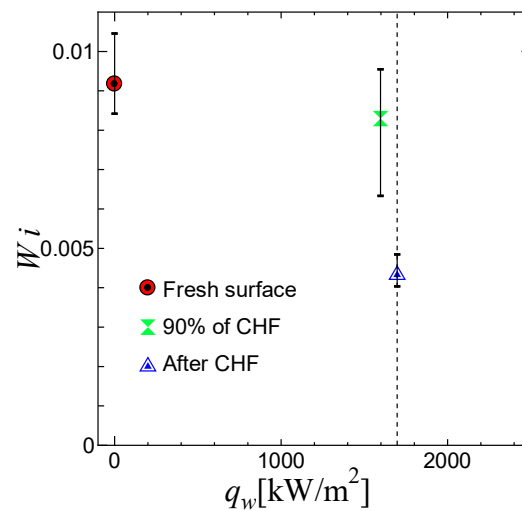
Figure 6. Contact angle

Figure 7. Wickability

4. Conclusions

The nanoparticle layer detachment during nucleate pool boiling and its influences on heat transfer surface properties were explored experimentally. The material of the heat transfer surface was copper and the nanoparticle layer was formed on the heat transfer surface by nucleate boiling in the water-based TiO_2 nanofluid. It was found that the detachment of the nanoparticle layer during nucleate boiling in pure water is significant. In the present experiment, more than half of nanoparticles deposited on the heated surface were detached before the CHF condition was reached. The thickness and roughness decreased accordingly. However, the wettability and wickability that are the influential parameters on the CHF value were maintained even after the occurrence of nanoparticle layer detachment and deteriorated only after the CHF condition was reached. It is therefore considered that the onset of CHF brings qualitative change to the capillary suction performance of the layer of nanoparticles. In exploring the effect of the nanoparticle layer properties on the nucleate boiling heat transfer, sufficient attention should be paid to the variation of the nanoparticle layer properties during nucleate boiling.

References

[1]   Kim H D, Kim J and Kim M H 2007 Experimental studies on CHF characteristics of nano-fluids at pool boiling *Int. J. Multiph. Flow* **33** 691-706

[2]   Okawa T, Takamura M and Kamiya T 2012 Boiling time effect on CHF in pool boiling of nanofluids *Int. J. Heat Mass Transf.* **55** 2719-2725

[3]   Kulkami D P, Vajjha R S and Das D K 2008 Application of aluminum oxide nanofluids in diesel electric generator as jacket water coolant *Appl. Therm. Eng.* **28** 1774-1781

[4]   Bang I C, Heo G, Jeong Y H and Heo S 2009 An axiomatic design approach of nanofluid-engineered nuclear safety features for generation III+ reactors *Nucl. Eng. Technol.* **41** 1157-1170

[5]   Kim S J, Bang I C, Buongiorno J and Hu L W 2007 Surface wettability change during pool boiling of nano-fluids and its effect on critical heat flux *Int. J. Heat Mass Transf.* **50** 4105-4116

[6]   Kim H D and Kim M H 2007 Effect of nanoparticle deposition on capillary wicking that influences the critical heat flux in nanofluids *Appl. Phys. Lett.* **91** 014104

[7]   Watanabe Y Enoki K and Okawa T 2018 Nanoparticle layer detachment and its influence on the

heat transfer characteristics in saturated pool boiling of nanofluids *Int. J. Heat Mass Transf.* **125** 171-178

[8]   Zuhairi Sulaiman M, Matsuo D, Enoki K and Okawa T 2016 Systematic measurements of heat transfer characteristics in saturated pool boiling of water-based nanofluids *Int. J. Heat Mass Transf.* **102** 264-276

[9]   Rohsenow W M 1952 A method of correlating heat transfer data for surface boiling of liquids *Trans. ASME* **74** 969-976

[10]   Zuber N, Tribus M and Westwater J W 1961 The hydrodynamic crisis in pool boiling of saturated and subcooled liquids *Proc. 2nd Int. Heat Transf. Conf. (Boulder, Colorado)* pp 230-236

[11]   Rahman M M, Olceroglu E and McCarthr M 2014 Role of wickability on the critical heat flux of structured superhydrophilic surfaces *Langmuir* **30** 11225-11234