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Condensation heat transfer on micro and nano structured superhydrophobic surface

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1. Introduction

After Fukushima accident, passive containment cooling system (PCCS) have attracted attention because it can be operated at blackout situation. Condensation phenomena occur during the PCCS operation cooling the containment through phase change heat transfer. Accordingly it is important to enhance the condensation heat transfer performance. Condensation mode is commonly classified as filmwise condensation (FWC) and dropwise condensation (DWC). DWC heat transfer performance has an order of magnitude higher than FWC heat transfer performance. In DWC process, condensed liquid droplets attach to the surface and prevent transfer of heat to the cooled surface. Generally the condensate is removed by gravity. When removal rate of condensate is high, DWC heat transfer performance will be enhanced. In terms of removal rate, superhydrophobic surface, which is recently in the spotlight, is expected to have capability to enhance the DWC heat transfer efficiency by reducing droplet size. In this study, we investigated condensation heat transfer performance on micro and nano structured superhydrophobic surface.

2. Methods and Results

2.1 Fabrication

Superhydrophobicity is able to be achieved by 2 factors: chemical composition on the surface, surface roughness. This wetting characteristics can be explained theoretically by Wenzel[1] and Cassie-Baxter[2]. For fabrication of micro and nano structures on the surface, which is similar to the lotus leaves[3], the specimens were anodized in diluted HF solution.[4] After anodic oxidation, Poly Tetra Fluoro Ethylene(PTFE) was coated on structured surface to promote hydrophobicity. In addition, smooth zirconium alloy plates coated with PTFE were also fabricated for comparison with structured surface. As shown in Fig. 1 (a), the characteristics of structures on the surface were observed by High Resolution Field Emission Scanning Electron Microscope (FE-SEM). The micro-scale structure was composed of nano-scale grains. The spacing between micro structures was about 4μm and radius of nano scale grain was about 10nm. The contact angle was ~117° on the smooth surface and ~152° on the structured surface respectively. That is, smooth surface coated by PTFE showed hydrophobic characteristics and structured surface coated by PTFE showed superhydrophobic characteristics.

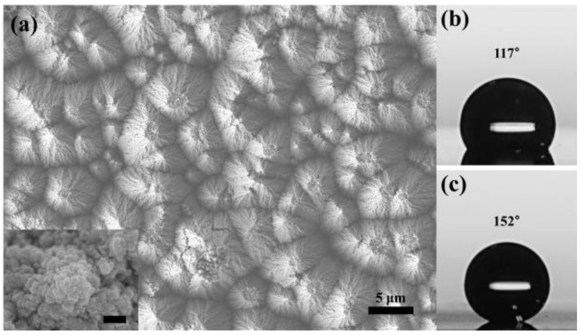

Fig. 1. (a)High Resolution FE-SEM image of the surface from a top view (inset: FE-SEM image with high magnification, scale bar is 100 nm). A deposited droplet on the (b)smooth surface, (c)micro and nano structured surface.

2.2 Experiments

Condensation experiments were conducted in the experiment apparatus shown in Fig. 2. Steam was generated by boiling deionized water in the steam generator and flew into the steam chamber. And then steam was condensed on the specimen surface which was in contact with the copper block being cooled by water flow. During the condensation, we measured wall temperature of the specimen, wall temperature of the copper block and bulk temperature of steam chamber in steady state. Using measured temperatures, heat flux and heat transfer coefficient were calculated as follows.

$$q'' = k\Delta T / \Delta x \quad (1)$$

$$h = q''/(T_{steam} - T_{surf}) \quad (2)$$

Here, q'' is heat flux (kW/m^2), h is heat transfer coefficient (kW/m^2/K), ΔT is temperature difference, Δx is the distance between thermocouples in the copper block or the distance from a thermocouple in the specimen to the surface, T_{steam} is steam-side bulk temperature (K), T_{surf} is wall temperature of the specimen surface (K) and k is thermal conductivity (kW/m/K) of copper or zirconium alloy modified in accordance with the measured temperature. The heat flux and surface temperature were calculated by (1) conduction equation assuming 1-dimension steady state. With calculated heat flux and surface temperature, heat transfer coefficient was calculated by (2).

Special care was taken for maximum removal of noncondensable gas. The experimental conditions in steam chamber are following: Pressure(~140 kPa), and temperature(~108 ℃). The experiments were operated at two different coolant flow rate to change the heat flux. The coolant flow rates were 2.5~3.1 L/min for low heat flux and 6~7 L/min for high heat flux.

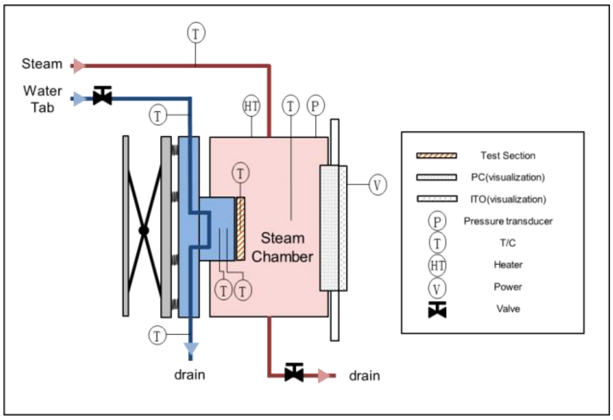

Fig. 2. Experiment apparatus. Blue-colored region indicates cooling region and red-colored region indicates the steam region.

2.3 Experimental Results

The experimental results are shown in the Fig. 3. In opposite to our expectation, heat transfer rates and heat transfer coefficients on structured superhydrophobic surfaces were rather lower than those on smooth hydrophobic surface. In cases of high coolant flow rates, the heat flux difference between structured surface and smooth surface was 92 kW/m^2 and heat transfer coefficient difference was 34 kW/m^2/K on average. For low coolant flow rate cases, the heat flux difference was 48 kW/m^2 and heat transfer coefficient difference was 25 kW/m^2/K. In both surfaces, heat transfer coefficient increases with heat flux which was controlled by coolant flow rate.

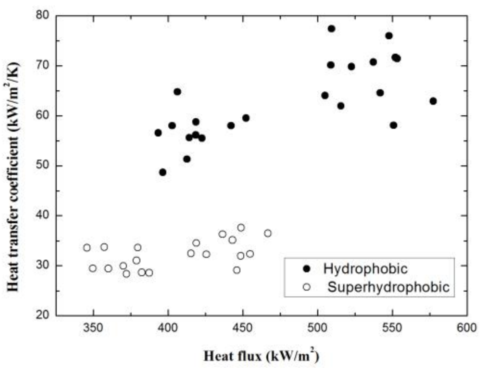

Fig. 3. Heat transfer coefficient with respect to heat flux on hydropboic surface and on superhydrophobic surface.

In order to investigate why heat transfer performance on the structured superhydrophobic surface was lower than that on the smooth hydrophobic surface, we conducted visualization experiments. The condensed droplets on the surface were visualized by using a high speed camera with an endoscope. Through image processing, we measured contact angle hysteresis and the radius of droplets just before being removed from the surface, so called 'departing radius'. Departing radius of condensed droplet and contact angle hysteresis on the smooth hydrophobic surfaces and on the structured superhydro-phobic surfaces are presented in Fig 4. Departing radius on the structured superhydrophobic surface was about 0.4 mm lower compared with that on smooth hydrophobic surfaces. And the contact angle hysteresis on the structured superhydrophobic surface was approximately 20° higher. As a result of visualization experiments, it was found that droplet mobility became lower on the structured superhydro-phobic surface than that on smooth hydrophobic surface during condensation. In other words, the superhydrophobic structured surface lost superhydrophobic characteristics. The condensed liquid penetrated into the spacing between structures and made the surface wet so that superhydrophobicity disappeared. Therefore, departing radius of droplet became larger due to the large the pinned base area. In the same vein, contact angle hysteresis became much larger compared with the hysteresis in case of sessile drop.

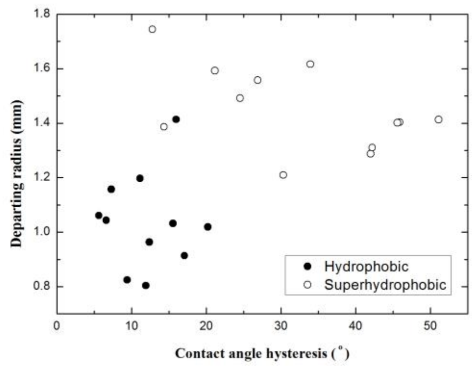

Fig. 4. Radius of departing droplets and contact angle hysteresis measurements using a high speed camera with an endoscope.

3. Conclusions

Condensation experiments on the micro and nano structured superhydrophobic surface were carried out and compared with those on the smooth hydrophobic surface in terms of heat transfer performance and condensed droplet morphologies. Through the experiments, we found that superhydrophobicity disappeared under the condensation circumstance. As a result, heat transfer performance on the superhydro-phobic structured surface decreased compared with that on the smooth hydrophobic surface. In order to enhance the condensation heat transfer performance with superhydrophobic property, condensation mechanism on superhydrophobic surface and the conditions for sustaining superhydrophobicity should be studied more.

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