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BOILING FROM A SUPER-WATER-REPELLENT SURFACE

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Abstract

Pool boiling from a super-water-repellent(SWR) surface has been studied. The SWR surface has a coating layer of fine particles of nickel and PTFE. Its contact angle to water is 152° in room temperature. The heat transfer surface is facing upward and the diameter of heated section is 30mm. The boiling feature of the SWR surface is considerably different from those of usual surfaces. The stable film boiling occurs in very small superheating and the nucleate boiling is hardly observed. Bubbles generated on the surface coalesce into a vapor film without departing from the surface. The heat transfer characteristic agrees well with the Berenson's theory.

1. INTRODUCTION

Surface wettability is one of the key effects on phase change heat transfer. In recent years, various types of functional surfaces have been developed. For instance, the surface coated by TiO_2, one of the photocatalyst, shows amazing nature(Fujishima et al., 1999) called *"photo-induced superhydrophilicity"*. When the TiO_2 surface is exposed with UV, the contact angle gradually decreases and finally reaches to zero. By using this nature, we can control the surface wettability by switching on and off of UV illumination, and consequently it enables the control of heat transfer. The authors have proposed the use of TiO_2 coating as the heat transfer surface, and reported a series of experimental studies(Takata et al., 2000, 2001, 2002a, 2002b, 2003a). The first experiment was falling film evaporation around a horizontal cylinder. Very thin stable film appeared in lower flow rate and consequently the heat transfer was enhanced by 40 times at the maximum case. The second experiment was immersion cooling, and the copper specimen coated by TiO_2 was cooled down more rapidly than that of normal copper specimen. The third experiment was pool boiling and it was found that the CHF increased by twice compared to the normal copper surface. The fourth experiment was evaporation of water drop on a hot surface. We found that the wetting limit temperature increased with the decrease in contact angle, and that the lifetime of water drops decreased with the decrease in contact angle.

From the previous experimental results, it is no doubt that the superhydrophilic surface has a big advantage in phase change heat transfer. Alternative method to make a heat transfer surface hydrophilic is a plasma irradiation. When the surface is exposed by plasma for a short while, the surface wettability increases considerably. This effect is not permanent and the surface returns to hydrophobic state in several hours later. We used this technique in the experiment of water drop evaporation and obtained the results similar to those of TiO_2 surfaces(Takata et al., 2003b).

Recently the coating technique has been improved and some super-water-repellent(SWR) surfaces were developed. Watanabe et al.(1999) have been studying the effect of SWR wall on the friction coefficient of water pipes. They found that there is a slip of velocities at the SWR wall and the friction coefficient decreases by about 6% from the theoretical value in laminar and transition flow regions. The coating material they used contains PTFE particles and the thickness of layer is of about 60μm. This is too thick and has too low thermal conductivity to use as a heat transfer surface.

The authors have reported preliminary experiments on boiling feature from a SWR surface(Takata et al., 2004). The SWR surface was formed by means of electrolytic nickel-plating with suspension of PTFE fine particles. Its contact angle to water is over 150°. Boiling heat transfer on the surface of such a high contact angle has not been reported so far. In the previous study, we observed some very interesting phenomena. Bubble nucleation initiated at very low surface superheating and the stable vapor film was observed even at the surface superheating below saturated temperature. These phenomena are described later again in detail. In the previous experiment, however, we could not obtain accurate boiling curve for SWR surface because of the heat loss which was caused by the structural defect of heat transfer block.

In the present paper, we solved the problem in experimental apparatus and could obtained the correct heat transfer characteristics. The boiling features on a SWR surface previously observed are confirmed. The boiling feature is completely different from those of usual surfaces. Some amazing characteristics were obtained through a series of pool boiling experiment.

2. EXPERIMENTAL APPARATUS

A schematic diagram of experimental apparatus is illustrated in Figure 1. Bulk temperature of water in boiling vessel is kept constant by heaters ⑤ and a condenser ④ during measurement. The vessel is also heated from side by air heater ⑧ to reduce heat loss. The detail of heat transfer block is illustrated in Figure 2. The heat transfer surface is a copper cylinder of 30mm in diameter, facing upward, with coating of SWR layer. The block and PTFE plate are sealed with O-ring. The heat transfer surface was coated with nickel and fine PTFE particles of 10μm in thickness by means of electrolytic plating. The contact angle of the SWR surface lies between 150~170°. As seen from the photograph by SEM (Figure 3), the surface has fractal asperity to increase water-repellent nature. Without this asperity the contact angle would be less than 120°. The surface with mirror finish was also used to obtain reference data and its contact angle was 93°.

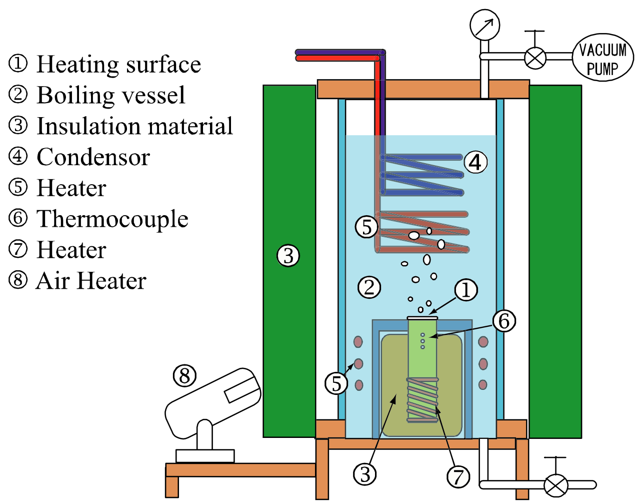


Figure 1: Experimental apparatus

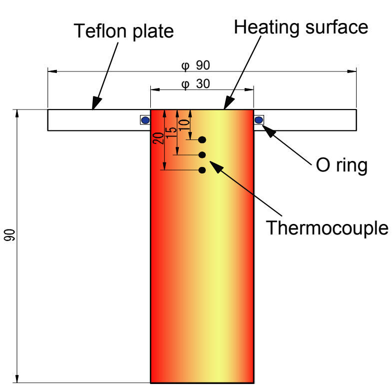


Figure 2: Heat transfer copper block

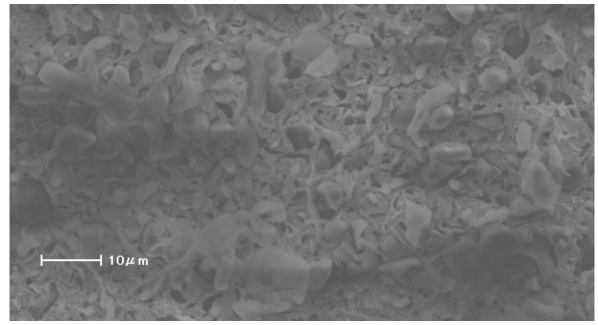


Figure 3: SEM image of SWR surface

Since the SWR surface attracts air, the vessel was evacuated first and then water was poured in it. Before heat transfer measurement, the test liquid was boiled to ensure deaeration. This process was repeated in each experimental run.

Heat flux and surface temperature are measured by thermocouples embedded in the heat transfer block. All measurements have been done in steady state that is judged by monitoring output of three thermocouples. Test liquid is pure water at saturated and at subcooled temperatures. The maximum surface superheating was 150K to protect the SWR coating.

3. EXPERIMENTAL RESULTS

3.1 Saturated boiling

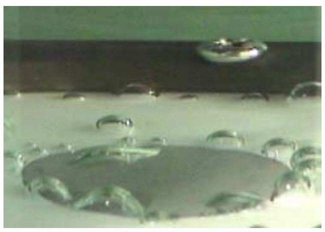
Figure 4 shows photographs of boiling on SWR surface in saturated boiling. The photographs (a)~(d) were taken during increasing surface superheating, whilst those (e)~(h) were during decreasing surface superheating. One of the typical features is that the bubble nucleation occurs at very low temperature. As seen in Figure 4(a), some flat bubbles can be observed on the surface at the surface superheating of 0.23K, at which no nucleation occurs if the surface is a normal copper surface. When the surface superheating was increased up to 1.44K(Figure 4(b)), the whole surface was covered with vapor film and the boiling regime turned to the film boiling. Eventually, the nucleate boiling was hardly observed.

When increasing surface superheating, the size of departing bubble increased as seen in Figure 4(c) and (d). It is noted that, despite the increase in superheating, the heat flux decreased from 22.4 to 15.9kW/m^2 between (c) and (d). As shown later in Figure 5(b), the heat flux at Figure 4(c) was the maximum. In Figure 4(g), the vapor film seems considerably thick, and even below saturated temperature thin stable vapor film still existed as seen in Figure 4(h). Once the surface was covered with the vapor film, it was hard to remove it even if the superheating was decreased.

The boiling curve corresponding to Figure 4 is shown in Figure 5, in which the experimental data for normal copper surface is also indicated for comparison. Arrows in the figure indicates that the measurements were done along these arrows. Figure 5(a), a linear plot, shows how the boiling curve of SWR surface differs form that of the normal copper surface. It is found from the figure that the curve for SWR surface well agrees with the Berenson's theory(1961). Figure 5(b) is a logarithmic plot and one can see the existence of CHF and MHF also for SWR surface. It is interesting to note that the boiling curve for SWR surface had a hysteresis like normal surface in spite that the obvious transition was not visually observed.

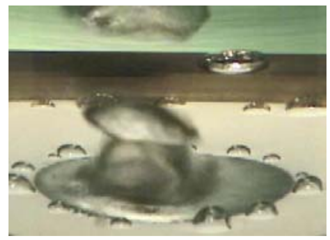
3.2 Subcooled boiling

Photographs of subcooled boiling are shown in Figures 6 and 7 for subcoolings of 5K and 10K, respectively. These are displayed in sequence of measurement. In subcooled conditions, the bubble nucleation initiated at negative superheating (Figure 6(a)) and the vapor film covered the whole surface when the surface superheating was −0.36K(Figure 6(b)). It is surprising that the stable vapor film exists even at the surface temperature below saturated temperature. In subcooled boiling, the vapor film on the surface was so stable that the bubble departure was not observed. As seen in Figure 6(e)~(h), the thickness of vapor film seems to decrease with the decreasing superheating. In Figure (g) and (h), the superheating became negative value again. For the case of subcooling of 10K, as shown in Figure 7(a), many bubbles were formed even at the negative superheating and stayed on the surface without departing from the surface. When increasing superheating,

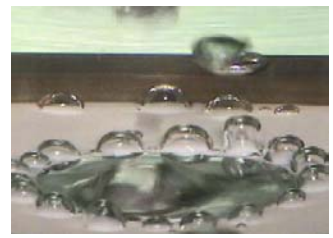


(a) ΔT_{sat}=0.23K q=8.3kW/m^2

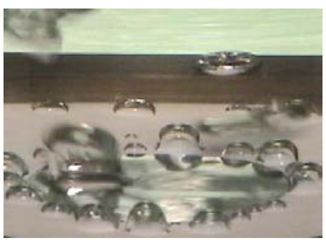
(b) ΔT_{sat}=1.44K q=18.8kW/m^2



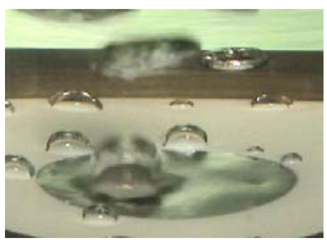
(c) ΔT_{sat}=12.6K q=22.4kW/m^2



(d) ΔT_{sat}=70.0K q=15.9kW/m^2



(e) ΔT_{sat}=60.7K q=23.8kW/m^2

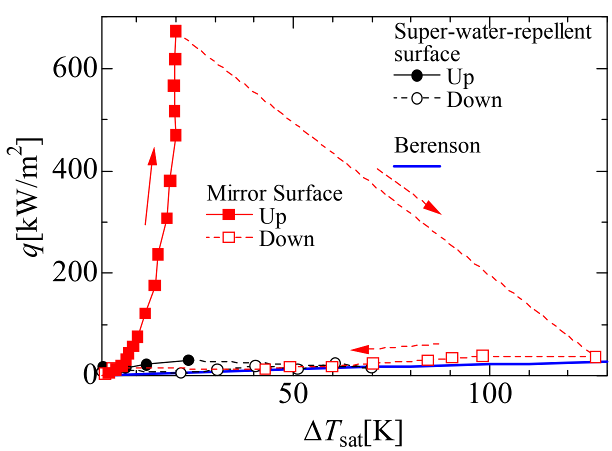


(f) ΔT_{sat}=5.06K q=11.9kW/m^2

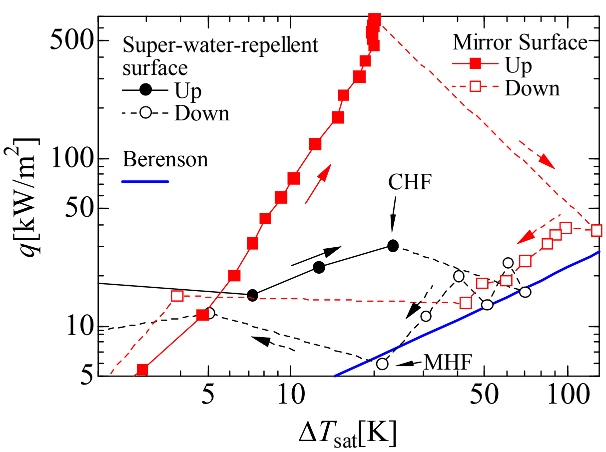
(g) ΔT_{sat}=1.32K q=8.41kW/m^2

(h) ΔT_{sat}= −0.26K q=8.37kW/m^2

Figure 4: Behavior of bubble and vapor film in saturated boiling



(a) linear plot



(b) logarithmic plot

Figure 5: Heat transfer characteristic in saturated boiling

they merged into each other and subsequently formed vapor film. The mechanism of transition to the film boiling is quite similar to the bubble packing mechanism proposed by Rohsenow and Griffith(1956). On the other hand, when decreasing superheating, the vapor film was very stable and remained on the surface even in negative superheating as shown in Figures 7(c) and (d). This is the same as the case for subcooling of 5K.

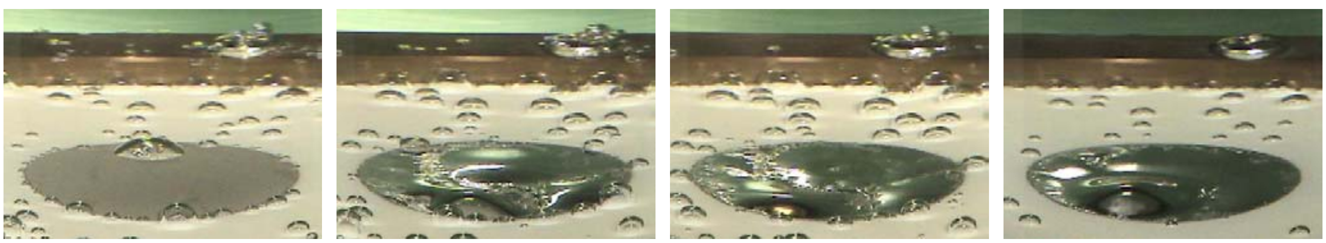
The boiling curves corresponding to Figures 6 and 7 are shown in Figure 8, in which the result for saturated boiling is also plotted. The tendency of the boiling curves in the figure is almost the same as that in Figure 5. Again, it is confirmed that the maximum and the minimum heat fluxes exist in the case of subcooled boiling and for higher surface superheating the boiling curve for SWR surface agrees with the Berenson's theory(1961). The maximum heat flux for SWR surface increased with the increase in subcooling.

It is a big question why vapor film exists even in the negative superheating as shown in Figures 4, 6and 7. If we consider a small cavity which traps vapor inside, the shape of the liquid-vapor interface may be concave because the contact angle is over 150°. Laplace equation is given by

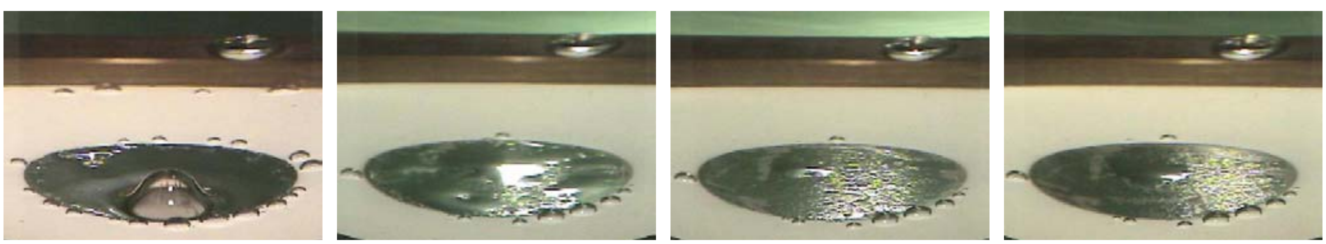
$$p_l - p_v = \frac{2\sigma}{R} \tag{1}$$

where σ is the surface tension and R the curvature of liquid-vapor interface which is positive value for concave interface. The vapor pressure inside the cavity, p_v, must be lower than liquid pressure, p_l and, hence, the saturation temperature becomes lower than that of atmospheric pressure. Assuming that the size of cavity be 5μm, the saturation temperature calculated using equation (1) is 92.7°C. This means that the vapor film can exist in the negative superheating.

Above discussion, however, cannot explain why bubble nucleation occurs at surface temperatures below 100°C as seen in Figures 6(a) and 7(a). When a bubble grows from a cavity, the liquid-vapor interface must have convex shape at the cavity exit. The convex interface means that the curvature in equation (1) is negative. Hence, p_l<p_v and the corresponding saturation temperature in the bubble

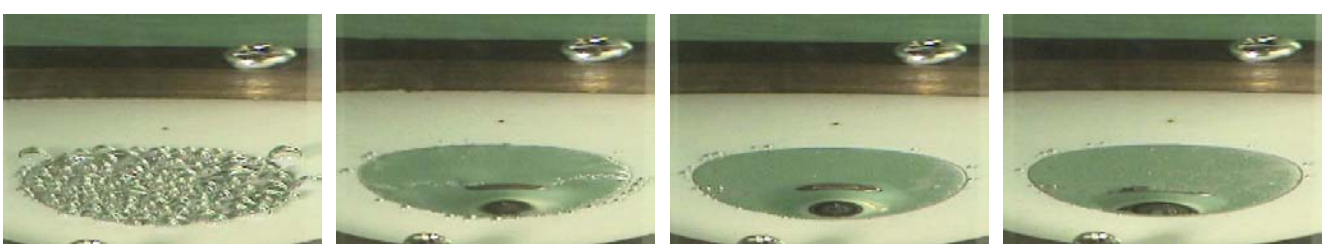


(a) ΔT_{sat}=–5.78K q=6.20kW/m^2 (b) ΔT_{sat}=–0.36K q=5.45kW/m^2 (c) ΔT_{sat}=3.93K q=19.3kW/m^2 (d) ΔT_{sat}=21.6K q=54.2kW/m^2



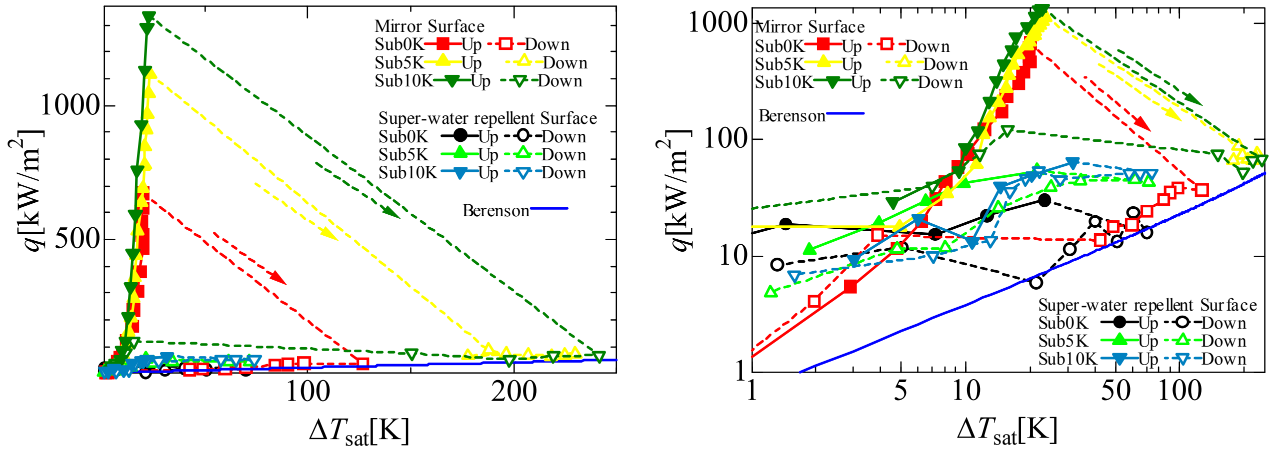
(e) ΔT_{sat}=71.7K q=43.5kW/m^2 (f) ΔT_{sat} =1.23K q=4.90kW/m^2 (g) ΔT_{sat} =–3.54K q=4.90kW/m^2 (h) ΔT_{sat} =–5.06K, q=0.00kW/m^2

Figure 6: Behavior of vapor film for subcooling of 5K



(a) ΔT_{sat}=–4.79K q=14.2kW/m^2 (b) ΔT_{sat}=31.6K q=64.7kW/m^2 (c) ΔT_{sat}=–5.28K q=2.01kW/m^2 (d) ΔT_{sat}=–9.45K q=0.00kW/m^2

Figure 7: Behavior of vapor film for subcooling of 10K



(a) linear plot (b) logarithmic plot

Figure 8: Heat transfer characteristic in subcooled boiling

nuclei must be larger than that of atmospheric pressure. Another possibility may be the deposition of dissolved air. However, before each experimental run, the vessel was evacuated to reduce the trap of air in the cavity and, subsequently, the test liquid was boiled for several minutes for deaeration. At this moment, the reason has not yet been clear.

4. CONCLUSION

(1) Bubble nucleation occurs at very low surface superheating and, however, the nucleate boiling region exists only in narrow range.
(2) The film boiling takes place from very low surface superheating and the boiling curve agrees well with Berenson's theory. The CHF and MHF also exist in the boiling curves for SWR surface.
(3) Very stable vapor film is observed even in the negative superheating.

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