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Enhancement of Pool Boiling Heat Transfer with an Optimum Sintered Copper Microporous Coating on Copper Surface

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1. Introduction

As a result of the Fukushima Daiichi Nuclear Power Plant disaster, there is a worldwide concern regarding the safety of nuclear power plants. When natural disaster like an earthquake or a tsunami occurs, the normal operation of the nuclear power plant is paralyzed, which may result in discharge of the molten corium outside the reactor vessel. Robust technology is required to confine the molten corium inside the reactor vessel even in case of a catastrophic failure. IVMR (In-Vessel Melt Retention) through ERVC (External Reactor Vessel Cooling) is one of the mitigation measures to retain the molten corium inside the reactor vessel. A key strategy considered herein is to improve the NBHT (Nucleate Boiling Heat Transfer) and CHF (Critical Heat Flux) on the reactor vessel wall. In order to enhance either NBHT or CHF on a metal substrate, numerous surface treatments have been developed so far. Among them, microporous coating is one of the most effective surface treatment due to the micron size pores including reentrant cavities.

In this study, pool boiling heat transfer of water at atmospheric pressure is investigated experimentally on copper surfaces with HTCMC (High-temperature, Thermally-Conductive, Microporous Coatings). The HTCMC coatings are created by sintering copper powders on 1 cm x 1 cm copper surfaces in a vacuum or nitrogen environment. An optimized particle diameter of 67 µm and a thickness of 296 µm were determined based on numerous tests[1]. Heater orientation effects on pool boiling heat transfer of saturated water were investigated with the change of inclination angles of 0^{o} (horizontal upward) – 180^{o} (horizontal downward) using the HTCMC coatings by copper powder with the optimized particle diameter and thickness. Subcooling effects were also studied in gassy subcooled water of 10 K, 20 K, and 30 K at one atmospheric pressure by comparing with a plain copper surface case. In addition, pool boiling heat transfer was studied in borated water with the change of boric acid concentration from 0.0 to 5.0 volume percent (vol %) to see the effects of borated water from copper microporous coating.

2. Pool Boiling Experiments

2.1 HTCMC Fabrication

Copper powder with an average particle size of 67 µm was used in order to create HTCMC. It was mixed with a thinner and spread over a 1 cm × 1 cm copper block and dried. Then the mixture was sintered in a tube furnace at high vacuum pressure of $\sim 10^{-5}$ hPa. After sintering, the sample was cleaned with 5% acetic acid by sonication, followed by acetone cleaning, and rinsed with distilled water. SEM image shows that HTCMC has microscale porous structures as illustrated in Fig. 1 (a). The porosity of the coating was calculated as 65% by measuring the volume of the porous layer and the weight of the sintered copper powders.

2.2 Experimental Setup and Test Procedure

In order to study pool boiling heat transfer with borated water, an aluminum chamber was used shown in Fig. 1 (b). The test heater assembly was located on an aluminum bracket inside the chamber and connected to electric wires and thermocouples. Two immersion heaters were installed in order to heat and degas the liquid water and two band heaters were attached to two side walls of the aluminum chamber to maintain the bulk liquid water at a steady saturation temperature. After vigorous degassing at saturation, pool boiling experiments were conducted using the test heater assembly in borated water under increasing heat flux conditions until the CHF condition was reached. During the experiment, the heat fluxes were supplied by a DC power supply to the resistive heating element of the heater assembly, and temperatures were measured by a data acquisition system controlled by LabVIEW program after reaching a steady state. Heat flux was increased to the next value by the program until the CHF was measured. The CHF was declared once the instantaneous temperature jump of greater than 20 K was detected when compared to the average wall temperature at the last heat flux value. Furthermore, the DC power supply was stopped immediately by the program as soon as CHF was detected.

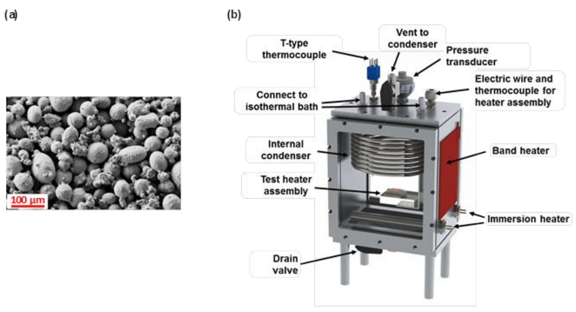

Fig. 1 SEM of HTCMC (a) and schematic of the pool boiling chamber (b).

2.3 Uncertainty Analysis

The experimental uncertainties for the current study were estimated using the Kline and McClintock method[2]. Heat flux measurement uncertainty caused by the voltage, current, and surface area of the heater was estimated to be less than 5% with a 95% confidence level. From numerical simulation, the heat loss through the epoxy and Lexan insulation of the heater was estimated to be less than 0.5%. The temperature measurement uncertainty was estimated to be ±0.5 K.

3. Results and Discussion

3.1 Heater Orientation Effect[3]

The experimental results of heater orientation effect on pool boiling heat transfer of HTCMC sintered in nitrogen environment with the heater orientations of 0^o, 45^o, 90^o, 135^o, 170^o, and 180^o are compared to those of a plain copper surface as depicted in Fig. 2. Copper powders with 67 µm APS and 296 µm coating thickness were used. The wall superheat of all the boiling curves of HTCMC were less than 5.0 K throughout the whole nucleate boiling process which are significant enhancement compared to those of the plain surface which have the wall superheat up to ~20 K in most cases. It was observed, in the current study, however that the NBHT of the HTCMC showed almost the same wall superheat values for all orientations throughout all heat flux ranges.

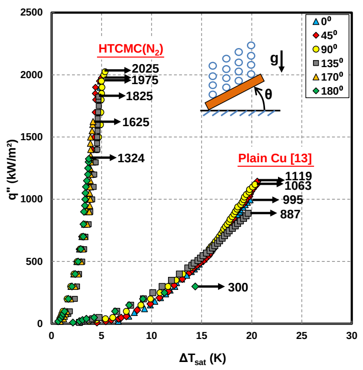

Fig. 2. Boiling curves of HTCMC sintered in nitrogen environment and a plain Cu surface at different orientations.

Fig. 3 shows that the pool boiling results of HTCMC sintered in vacuum environment are similar boiling heat transfer characteristics to the HTCMC sintered in nitrogen except for high heat fluxes (> 1,000 kW/m^2) where the wall superheat increases 2-3 K more because of higher contact angles. However, the heat fluxes up to ~1,000 kW/m^2 the boiling curves of HTCMC are very close for all orientations.

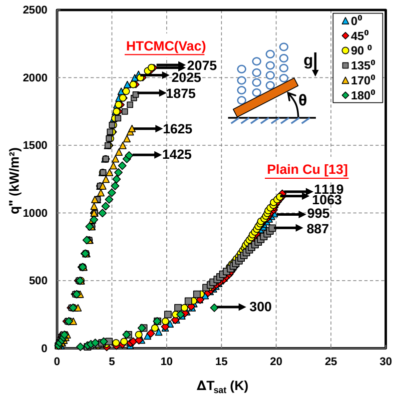

Fig. 3. Boiling curves of HTCMC sintered in vacuum environment and a plain Cu surface at different orientations.

The CHF values for both HTCMC's sintered in a nitrogen and vacuum environment from 0° to 90° showed ~2,000 kW/m^2 and the CHF decreases as the orientation angle increases greater than 90°. The CHF values for the plain Cu surface were ~1,000 kW/m^2 at a 0° inclination angle and slightly increased to ~1,100 kW/m^2 at 90° then decreased drastically as the inclination angle increased further.

3.2 Subcooling Effect[4]

Fig 4(a) shows the subcooled pool boiling curves of HTCMC and plain copper surfaces. In the HTCMC test, copper powders with 67 µm APS and 296 µm coating thickness were used. It is revealed that the wall superheats at different subcoolings were close each other at various heat fluxes up to ~2,000 kW/m^2 for the HTCMC test and ~1,000 kW/m^2 for the plain test. The wall superheats of HTCMC for subcooled boiling remained less than 5.0 K for the heat flux of 1,500 kW/m^2. This is a significant enhancement of nucleate boiling of HTCMC compared to the plain copper surface case that showed about 24 K of wall superheat at the same heat flux. The enhancement of the nucleate boiling heat transfer in HTCMC is attributed to its porous structure of micron-scale cavities and existence of reentrant types. These microporous cavities would create vapor bubbles at extremely low wall superheat values by combining their geometry and thermodynamic aspects of the fluid. As shown in Fig. 4(b), the CHF values linearly increased with the similar rate of ~60 kW/m^2 per degree of subcooling for both surfaces. As a result, the CHF values of HTCMC were maintained about ~1,000 kW/m^2 higher than those of plain surface throughout the subcoolings tested. In case of 30 K of subcooling, the CHF of plain surface was 2,823 kW/m^2 and that of HTCMC was 3,824 kW/m^2. The current study showed that HTCMC is an efficient way of enhancing CHF by subcooling.

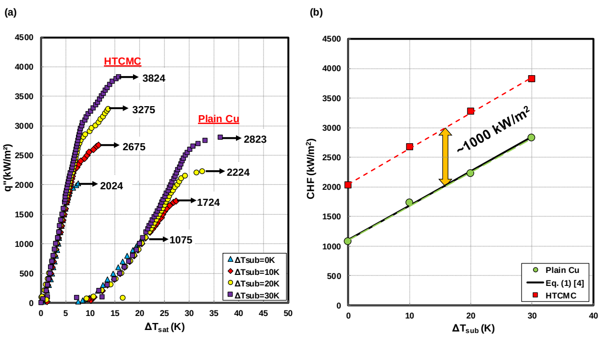

Fig. 4. Boiling curves of HTCMC and a plain Cu surface at subcoolings (a) and CHF comparison of HTCMC and plain surface with subcooling (b).

3.3 Boric Acid Concentration Effect[5]

The pool boiling experiments of HTCMC surface were conducted in borated water with the concentration of 0.5-5.0 vol.% at one atmospheric pressure. The highest heat flux value in each curve of the following figure (Fig. 5. (a)) indicates the CHF point. The results showed that the nucleate boiling heat transfer of HTCMC was significantly enhanced compared to those of a plain surface for all the tested boric acid concentrations. This is due to micron scale pores with reentrant cavities within HTCMC that created numerous active nucleation sites during nucleate boiling. The nucleate boiling heat transfer was slightly degraded as the concentration of boric acid increased for both HTCMC and the plain surface. On the other hand, the CHF values of HTCMC maintained at ~2,000 kW/m^2 up to 1.0 vol.% then started to decrease gradually down to ~1,700 kW/m^2 at 5.0 vol.% -- see Fig. 5 (b). The opposite trend was observed for a plain surface that had the CHF increase sharply from ~1,000 kW/m^2 to ~1,900 kW/m^2 for 0.0-1.0 vol.%, and then it increased slowly to ~2,000 kW/m2 at 5.0 vol.%. The enhancement of CHF of a plain surface in borated water was due to the wettability increase. However, the CHF of HTCMC did not increase further, although the wettability increased as the boric acid concentration increased to 1.0 vol.%. This means that the HTCMC is insensitive with wettability and also that the CHF enhancement of HTCMC is due to the microporous structures. The CHF rather decreased slightly as the concentration even further increase from 1.0 vol.%. It was caused by the fact that the micro-scale pores in HTCMC were blocked by high boric acid concentrations during the nucleate boiling process, so that the smaller size bubbles, created by breaking the vapor through the connected passage ways in the porous structure, were not effectively created as the boric acid concentration increased. However, it should be noted that the boric acid concentration is typically less than 4,400 ppm in nuclear power plants and this value is equivalent to only 0.3 vol.% (shown by the red dashed line in Fig. 5 (b)). The CHF of HTCMC was not degraded at all within the typical concentration range used, so that the CHF of HTCMC was still maintained at a much higher value than that of a plain surface at the same boric acid concentration.

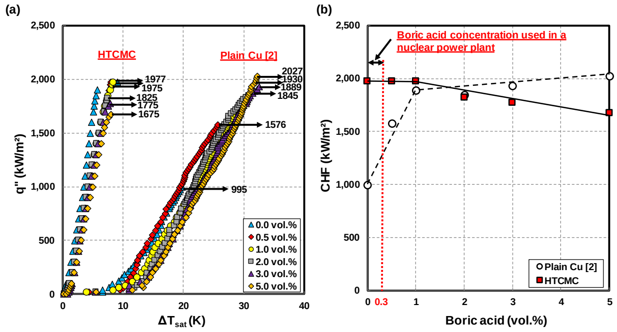

Fig. 5. Boiling curves of HTCMC and a plain Cu surface at different concentrations of borated water (a) and CHF comparison of HTCMC and plain surface (b).

4. Conclusions

In the heater orientation effect test, the CHF values of HTCMC were maintained as ~2 MW/m^2 at upward inclination angles from 0^o to 90^o, whereas the CHF values decreased as the inclination angle changed from 90^o to 180^o. The CHF values were ~1.4 MW/m^2 at 180^o. In the subcooling effect test, the NBHT did not change up to ~2,000 kW/m^2 for the HTCMC test and ~1,000 kW/m^2 for the plain test with the degree of subcooling. The CHF values of HTCMC were maintained about ~1,000 kW/m^2 higher than those of plain surface throughout the subcoolings tested. In the boric acid concentration effect test, the NBHT of HTCMC became slightly less enhanced as the concentration of boric acid increased but the NBHT coefficient values were still significantly higher than those of plain surface. The CHF values from 0 to 1.0 vol.% maintained ~2,000 kW/m^2, then gradually decreased down to ~1,700 kW/m^2 as the concentration increased to 5.0 vol.%.

ACKNOWLEDGMENT

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