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Experimental Study on Pool Boiling Heat Transfer in Water Using Sintered Copper Microporous Coatings on Metal Surface

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1. Introduction

Systematic and robust accident management strategies are required to prevent a catastrophic failure in case of a severe accident. One of the mitigation measures is to cool the reactor vessel outer wall to retain the molten corium inside the reactor vessel. In the current cooling technologies, the reactor vessel outer wall is cooled by water, which boils due to the high heat flux from the molten corium. While boiling, the reactor outer wall temperature needs to keep near saturation temperature by avoiding CHF. A key strategy considered herein is to improve the boiling heat transfer on the reactor wall using every technology possible. In order to enhance either nucleate boiling heat transfer (NBHT) or critical heat flux (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 saturated at atmospheric pressure is investigated experimentally on copper surfaces with high-temperature, thermally-conductive, microporous coatings (HTCMC). The HTCMC coatings are created by sintering copper powders on 1 cm x 1 cm copper surfaces in a vacuum or nitrogen environment. A parametric study of particle size and coating thickness effect on the Nucleate Boiling Heat Transfer (NBHT) and the Critical Heat Flux(CHF) was conducted with three average particle sizes (APS's) of 10 μm, 25 μm, and 67 µm and various coating thicknesses and an optimized particle size and coating thickness were determined. 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 67 µm APS and 296 µm coating thickness. Subcooling effects were also investigated for the subcooled water of 10–30 K and compared with the subcooled results of a plain surface.

2. Pool Boiling Experiments

2.1 Experimental Setup and Test Procedure

An aluminium chamber was used for subcooled pool boiling heat transfer study, as shown in Fig. 1 (a). The test heater assembly was located on an aluminium bracket inside the chamber and connected to electric wires and thermocouples. Subcooled pool boiling heat transfer experiments were conducted using the test heater assembly in various subcooled temperatures with increasing heat flux until the CHF condition was reached. During the experiment the heat fluxes were supplied from a DC power supply to the resistive heater of heater assembly and temperatures were measured by a data acquisition system controlled by LabVIEW program after reaching steady states. Heat flux was increased to the next value by computer control until the CHF was measured. The CHF was declared once the instantaneous temperature jump was detected that is larger than 20 K compared to the averaged value in the last heat flux, and DC power supply stopped immediately by the program.

2.2 HTCMC Fabrication

The microporous coating was created by sintering of a copper powder on a copper substrate. The average particle sizes of the powder were measured by image processing of optical microscope images of Cu powders. The average sizes were 10 ± 1.4, 25 ± 9.0, and 67 ± 14.6 µm. The copper powder was mixed with a thinner and spread over a 1 cm × 1 cm copper block and dried. Then the mixture was sintered in a furnace at high vacuum of $\sim 10^{-5}$ hPa or nitrogen environment. 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 porous structures as illustrated in Fig. 1 (b). The porosity of the coating was measured as 65% from the measured volume of the porous layer and the weight of the sintered copper powders.

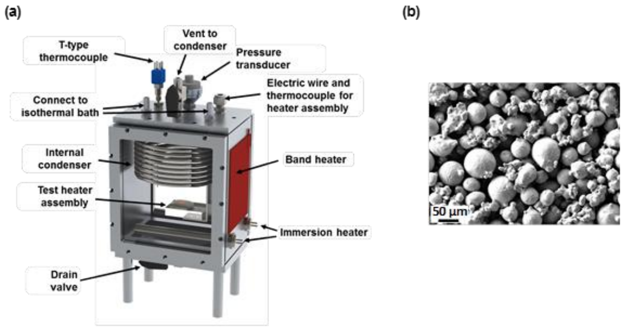

Fig.1. Schematic of the pool boiling chamber (a) and SEM of HTCMC (b).

3. Results and Discussion

3.1 Particle Size and Coating Thickness Effect

Three average particle sizes (APS), 10, 25, and 67 µm with various coating thicknesses were tested. For each particle size, the coating thickness was varied to find the most enhanced NBHT and the CHF. The boiling curves of different particle sizes are plotted with various coating thickness as shown in Fig. 2. The optimized coating thickness for NBHT which has smallest wall superheat at prior to CHF was found and the results were shown in Fig. 2(a-c) red square symbols. For APS 10 µm, the optimized coating thickness was 78 µm which is ~8 times thicker than particle size. For APS 25 and 67 µm, the coating thickness was 94 and 296 µm, respectively and those are ~4 times of particle size. The wall superheat in the nucleate boiling heat transfer regime near the CHF at the optimized thickness was ~6.5, 4.5, and 5.0 K for APS 10, 25, and 67 µm, respectively.

Fig. 3(a) shows the CHF values with various particle size and coating thickness. The maximum CHF of APS 10 µm was 1,575 kW/m^2 at the coating thickness of 155 µm. This value is a ~60% enhancement compared to that of the plain copper surface case. It is noted in the figure that the CHF increased further from ~1,500 kW/m2 as the coating thickness increased for a 25 µm particle size of the APS. For the largest particle size of APS 67 µm, the CHF was consistently ~2,100 kW/m2 for the range of the tested thicknesses. For the 25 and 67 µm APS cases, the maximum CHF enhancements showed a ~100% enhancement compared to that of plain copper. Fig. 3(b) shows the NBHT coefficients with various particle size and coating thickness. The maximum NBHT coefficients increased as the particle size increases. The values were obtained 227, 383, and 399 kW/ m^{2}K for APS 10, 25, and 67 µm, respectively at the optimized coating thickness and are enhanced 4.7, 7.8, and 8.2 times compared to that of the plain Cu surface.

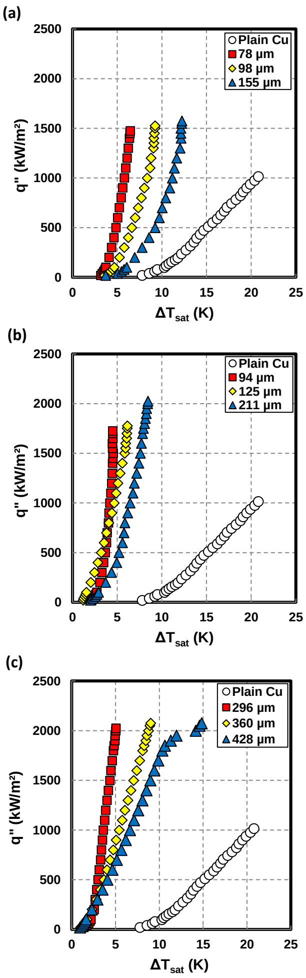

Fig. 2. Pool boiling curves of water with the change of HTCMC coating thickness for (a) APS 10 µm, (b) APS 25 µm, and (c) ASP 67 µm.

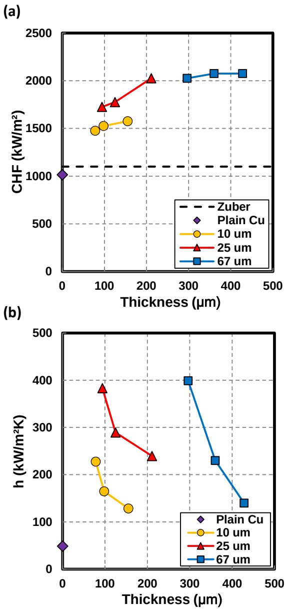

Fig. 3. (a) The CHF and (b) the maximum NBHT coefficient with coating thicknesses.

The particle size effect on pool boiling curves and NBHT coefficients are more clearly seen by comparing the optimized coating thickness of each particle size as shown in Fig. 4. The boiling curves show that the CHF increases from 1,475 kW/m^2 to 2,025 kW/m^2 as the particle size increases from 10 to 67 µm (Fig. 4(a)). The NBHT coefficient increases as particle size increases as well but the maximum NBHT coefficients of APS 25 and 67 µm have similar values as ~400 kW/m^2 K (Fig. 4(b)). From the results, it appears that the larger particle size has higher NBHT coefficient and CHF values.

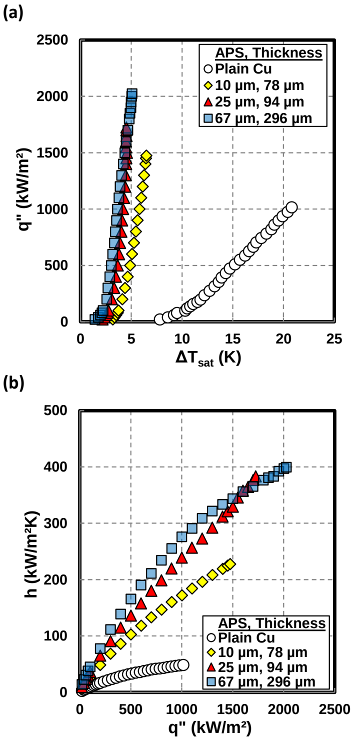

Fig. 4. (a) Pool boiling curves and (b) the NBHT coefficients at the optimized coating thicknesses of each particle size.

3.2 Heater Orientation Effect

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. 5. 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.

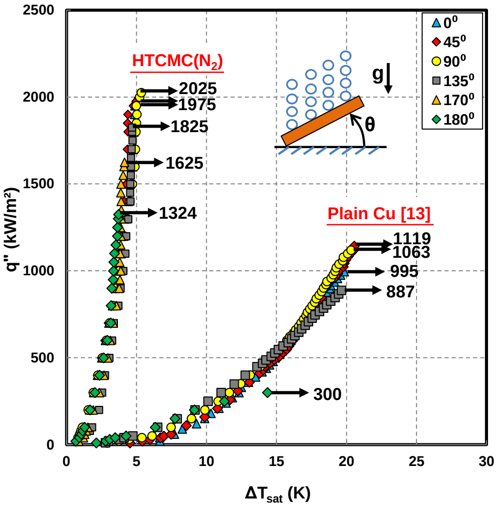

Fig. 5. Boiling curves of HTCMC sintered in nitrogen environment and a plain Cu surface at different orientations.

Fig. 6 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.

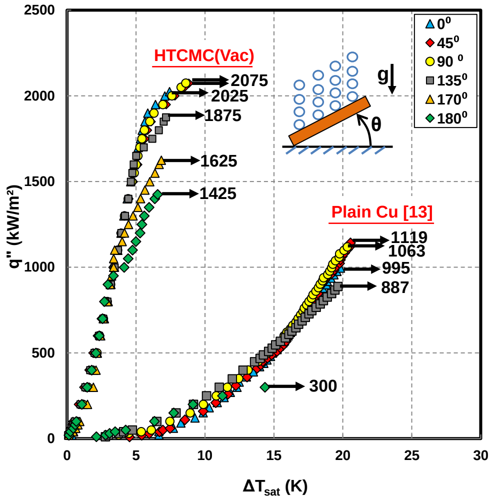

Fig. 6. Boiling curves of HTCMC sintered in vacuum environment and a plain Cu surface at different orientations.

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.

3.3 Subcooling Effect

Fig 7(a) shows the subcooled pool boiling curves of HTCMC and plain copper surfaces. In the HTCMC tst, 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. As shown in Fig. 7(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.

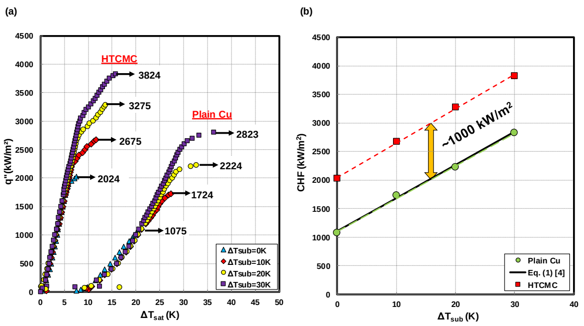

Fig.7. Boiling curves of HTCMC and a plain Cu surface at subcoolings (a) and CHF comparison of HTCMC and plain surface with subcooling (b).

4. Conclusions

In the parametric study of particle size and coating thickness effect, the maximum NBHT coefficient was measured to be ~400 kW/m^2 k with 67 µm APS and 296 µm coating thickness. This value is about 8 times higher than that of a plain copper surface. The maximum CHF observed was 2.1 MW/m^2 at APS 67 µm and 428 µm coating thickness, which is about 2 times higher than CHF of a plain copper surface. 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.

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