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Experimental study on the effect of CRUD-simulated porous structures on pool boiling heat transfer in the vertical orientation

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1. Introduction

Boiling characteristics of high burnup cladding(HBC) are of significant importance to nuclear safety, as they can substantially influence the thermal-hydraulic behavior of a reactor core compared with those of fresh cladding. One of the main characteristics of HBC is the formation of CRUD(Chalk River Unidentified Deposit), which develops a porous a porous structure on the cladding surface. Vapor generated within this porous medium escapes through preferential pathways that minimize pressure drop, promoting heat transfer mechanism known as wick boiling.

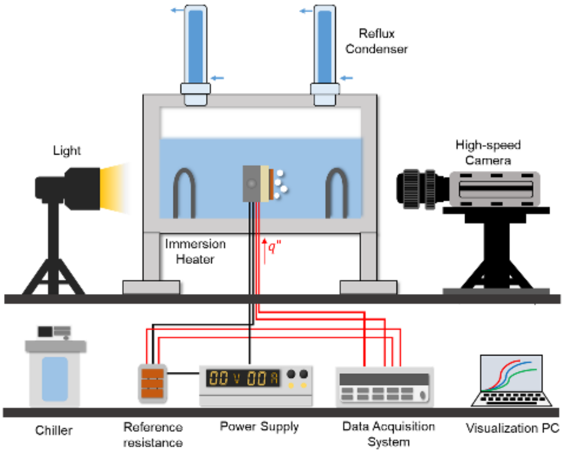
In this heat transfer mechanism, CRUD can enhance critical heat flux(CHF) and boiling heat transfer coefficient(BHTC) [1-2]. However, CRUD can also act as a thermal resistance layer, reducing heat transfer performance [3]. Therefore, understanding the effects of crud on boiling heat transfer is essential.

However, obtaining such an understanding is challenging because fabricating actual reactor CRUD is difficult, making it hard to systematically investigate the effects of individual CRUD parameters. Therefore, an alternative approach is required to study CRUD-related boiling behavior under controlled conditions. In this study, micrometer-thick copper foam with a porous structure similar to CRUD was employed as a surrogate material to simulate CRUD behavior. Pool boiling experiments were conducted under vertical orientation, considering the configuration of fuel rods in an actual reactor. Experimental data obtained from smooth surfaces and porous structures were compared to evaluate the influence of the porous structure on heat transfer performance.

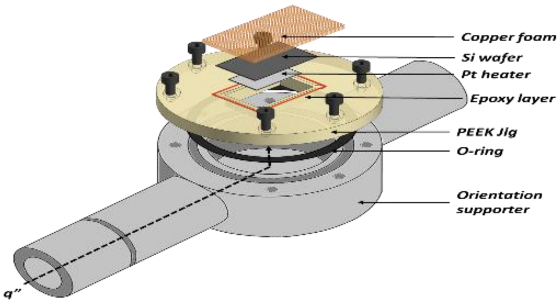
2. Experiments

2.1. Pool boiling setup

Fig. 1 shows the configuration of the pool boiling experimental apparatus using a platinum heater. The edges of the heater were soldered to enable surface heating through Joule heating. As shown in Fig. 1(b), the sample was mounted on a sample holder fixed to a polycarbonate wall, and the experiment was conducted under vertical orientation by rotating the sample holder.



(a) schematic of the test apparatus



(b) schematic of the heater and sample holder assembly
Fig. 1. Pool boiling experimental setup

2.2. Characteristics of copper foam samples

2.2.1. Explicit modeling of ICI

Fifteen copper foam samples were prepared with thicknesses of 50µm, 100µm, and 200µm and pore densities ranging from 90 to 130 PPI at intervals of 10 PPI. The characteristics of the prepared samples are compared with those of CRUD and summarized in Table I. In this study, the thickness and porosity were well replicated; however, accurate simulation of the chimney size was difficult due to the relatively large particle size of the copper foam.

Table I. Properties of CRUD [4] and samples

Properties	Reactor CRUD	Copper foam
Composition	Fe_3O_4, NiO, $NiFe_2O_4$, ZrO_2	Cu
Thickness [µm]	10-100	50,100,200
Wettability [˚]	10-30	53-131
Porosity [%]	40-50	45-50
Pore size [µm]	0.1-1	15-30
Chimney Diameter [µm]	2-10	150-460

2.3. Experiment methods

Fifteen The silicon wafers attached to the copper foam are fabricated by the Microelectromechanical Systems process. A silicon oxide layer is deposited on a 500µm silicon wafer for electrical insulation. The film heater is fabricated by depositing a thin film of platinum on one side of the wafer using photolithography process. The silicon wafers and the copper foam are attached to the jig using an epoxy.

The pool boiling experiments were conducted by using deionized water as pool liquid at atmospheric pressure and saturation temperature. The silicon wafer was heated by applying direct current (DC) to wires connected to both ends of a platinum thin film.

The heat flux is calculated by Eq. (1) where V_h, V_{ref}, A_h, and R_{ref} are the voltage of the heater, the voltage of the reference resistor, the heated area, and the resistance of the reference resistor, respectively.

$$q" = \frac{V_h I_{circuit}}{A_h} = \frac{V_h V_{ref}}{A_h R_{ref}} \qquad (1)$$

The wall temperature is calculated by the property that the resistance of platinum varies linearly with temperature. In this study, the wall superheat is calculated as the difference between the wall temperature and the saturation temperature.

$$\Delta T_{super} = T_{wall} - T_{sat} = \frac{q"}{h} - \frac{q"t}{k_{si}} - T_{sat} \qquad (2)$$

The power is increased for 1 minute and data is collected for 3 minutes. To identify the ONB point, the power is increased at intervals of 5 kW/m2 from immediately after the start of the experiment to 50 kW/m2 and then at intervals of 50 kW/m2 to the CHF point. CHF is assumed to be the heat flux just before the rapid temperature rise. Uncertainties were calculated using Eq. (3). The voltage uncertainty of the power supply was 0.2%, the current uncertainty was 0.4%. Additionally, the DAQ had a DC voltage accuracy of 0.004% and AC voltage accuracy of 0.06%. The uncertainty of reference resistance was determined to be 0.32%. Considering all instrument errors and measurement uncertainties, the maximum uncertainty of the heat flux was 13kW/m2, and the maximum uncertainty of wall superheat was 1.15℃.

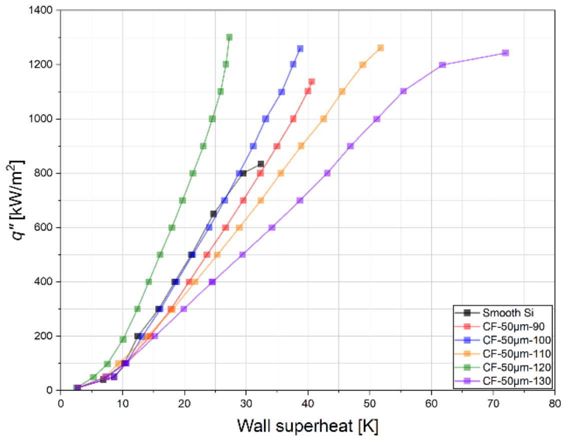
$$\frac{U_{q"}}{q"} = \sqrt{\left(\frac{U_{v_h}}{V_h}\right)^2 + \left(\frac{U_{v_{ref}}}{V_{ref}}\right)^2 + \left(\frac{U_{R_{ref}}}{R_{ref}}\right)^2} \qquad (3)$$

3. Results and discussion

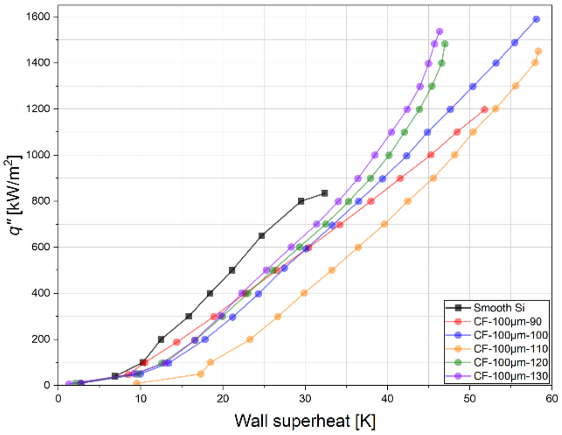
Pool boiling experiments were conducted on a smooth silicon surface under vertical orientation for comparison with the CRUD-simulated surfaces. To ensure reproducibility, each dataset was obtained from five repeated experiments. For the smooth silicon surface, the measured CHF was 834kw/m2. The average deviation in CHF was within 4%, demonstrating high experimental reliability.

Fig. 2 presents the pool boiling performance of copper foam surfaces with different thicknesses. As shown in Fig. 2(a) (50µm), the CHF reached 1300kW/m^2 at 120PPI, corresponding to a maximum enhancement of 54% compared with the smooth silicon surface. In general, CHF increased with increasing pore density; however, beyond a certain condition, an increase in surface temperature was observed, resulting in a reduction in the HTC.

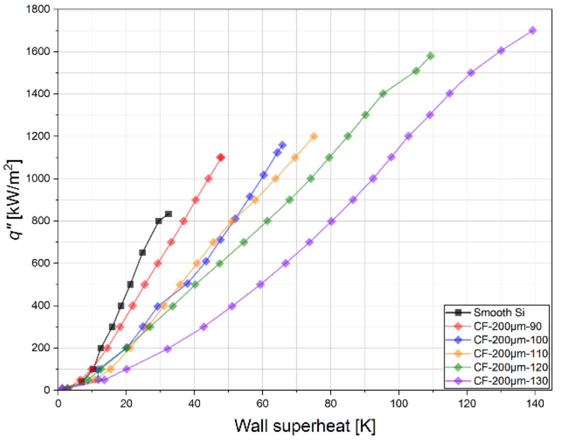
For the 100µm thickness shown in Fig. 2(b), the maximum CHF of 1590kW/m^2 was obtained at 100PPI, representing an enhancement of 88% relative to the smooth Si surface. Although the 200µm thickness shown in Fig 2(c) is outside the typical CRUD thickness range, experiments were conducted to provide data for future development of CHF prediction correlations. At 130PPI, the CHF reached 1700kW/m^2, corresponding to a maximum enhancement of 101%. However, a significant increase in wall superheat was observed, leading to the lowest HTC among all tested conditions.



(a) 50µm copper foam



(b) 100μm copper foam



(c) 100μm copper foam

Fig. 2. Boiling curve of copper foam

Although higher CHF values were obtained with increasing foam thickness, the corresponding wall superheat reached approximately 140K, resulting in a relatively low HTC of about 12 kW/m^{2}K. This behavior may be attributed to the formation of a thin vapor layer near the base of the porous structure, which increases thermal resistance and shifts the boiling mechanism toward evaporation-dominated heat transfer.

However, as illustrated in Fig. 3, the vapor layer was not continuous and could be intermittently disrupted by hydrodynamic effects such as Kelvin-Helmholtz (K-H) instability. In addition, under vertical orientation, intermittent liquid rewetting and bubble nucleation may influence the HTC, potentially contributing to the observed high CHF despite the elevated wall superheat.

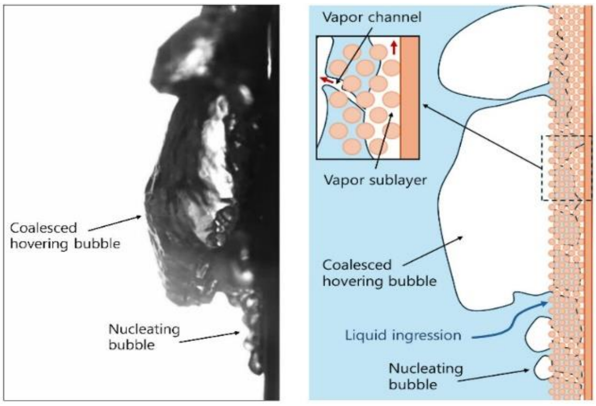


Fig. 3. Schematic of boiling phenomena on porous structure

4. Conclusion

In this study, pool boiling experiments were conducted using copper foam with a porous structure to simulate reactor CRUD, investigating the effects of thickness and pore density under vertical orientation. The result showed that both the thickness and pore density of the porous structure significantly influence boiling performance. As the thickness increased, the CHF increased, reaching the maximum value at 200μm and 130PPI; however, this condition also exhibited the lowest HTC. This behavior is attributed to the formation of a vapor layer near the vase of the porous structure, which increases thermal resistance.

Further experiments covering a wider range of conditions are required to clearly distinguish and understand this phenomenon.

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