CHF experiments with a plate-type large size of carbon steel heater considering long-term oxidation process

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1. Introduction

During a severe accident in nuclear power plants (NPPs), the reactor core begins to melt and the melted core accumulates at the bottom of reactor pressure vessel in a shape of corium. As a mitigation strategy of NPP severe accident, In-vessel retention external vessel cooling (IVR-ERVC) is operated to remove a huge amount of thermal load from the corium. Numerous researchers have evaluated the thermal load induced on RPV surface during a severe accident and have studied critical heat flux (CHF) using a carbon steel (RPV material) as a function of orientation (Downward-facing to vertical-facing) to evaluate a thermal margin of RPV.

Rempe et al. [1] studied the thermal load generated on RPV inner surface by the corium in several accident scenarios, and the highest heat flux was reported in vertical surface region. Kam et al. [2] conducted CHF experiments using a large size of heater and pool, and showed the CHF trends as a function of heater dimensions, orientations (0~90), materials (Stainless steel, Carbon steel), and pressure (1~10bar). They observed that CHF increases with an increase of orientation and pressure.

During a normal operation of a NPP, RPV surface is exposed to dry and high temperature environment. Since hot leg and cold leg temperature of primary side are around 568.98K and 600.48K in OPR1000, the RPV surface temperature is expected to be as 573.15K (300^{o}C). The hot and dry environment outside of RPV has caused the oxidation on carbon steel surface to be accelerated, and the surface oxidation has a significant influence on a heat transfer performance, especially CHF. Kim et al. [3] considered this normal operation condition into carbon steel and evaluated the CHF with oxidized upward-facing heater surface. They asserted that the CHF decreased despite the surface morphology modification.

For the CHF evaluation under the IVR-ERVC condition, the experiments are required with a relatively large and inclined heater surface considering bubble dynamics generated by the vapor flow along with heater length and its effects on CHF. In this study, a large size of carbon steel heater was oxidized by a box furnace. Using the oxidized heater, CHF experiments were conducted under the vertical orientation condition (90^{o}), and the surface morphology was analyzed by SEM, XRD, and contact angle measurement. As a result, magnetite and hematite oxidation layer were observed on heater surface, and the enhancement of wettability and CHF was confirmed after all.

2. Methodology

Furnace cooking was conducted under 300^{o}C for 7, 14, and 30 days, while thermocouples were installed at the reference heater to manage the temperature of heater surface more accurately in the furnace. Several oxidized heaters were prepared in the same oxidation-period condition for the sake of CHF experiments and surface analyses. After the oxidation, the heaters were stored in a desiccator to avoid additional interaction with humid air and heater surface. When heater temperature was recovered up to room temperature, surface analyses of SEM, XRD, and wettability estimation were performed and CHF experiments was conducted as well.

ASME Gr.3 Cl.1, SA508 carbon steel is well-known as an external surface material of RPV, so that the SA508 carbon steel was purchased from Steelmax company. The large size of heaters in 50mm width and 100mm long were manufactured to consider the vapor flow along with the heater surface and its hydrodynamic effects on CHF. Vertical orientation was considered as the experimental condition since the highest heat flux is induced on vertical part of RPV in practice. For more accurate evaluation, a huge size of deionized water pool, which have approximately 210L of volume, was used to minimize recirculation effects on CHF generated by boiling phenomena. Fig.1 shows the facility used for the CHF experiments in this study.

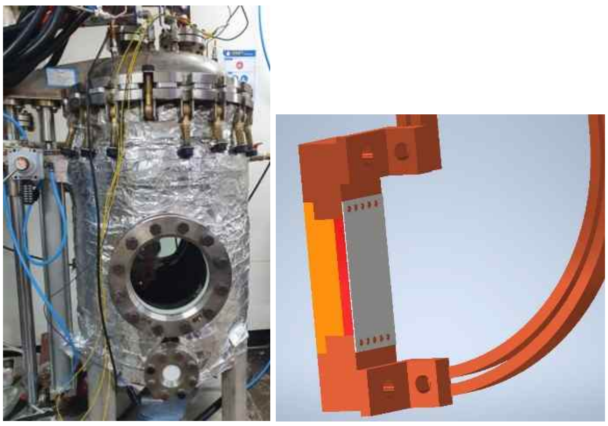


Fig.1 Pool boiling experimental facility (left) and schematic holder assembly of SA508 heater (right)

The carbon steel heater was assembled with copper electrode, and silicone rubber was used to make an insulation at the bottom of heaters. Three thermocouples and two copper voltage measurement line were installed between the heater and the silicone rubber. With the measured data, heat flux and heater surface temperature were calculated by following equations, (1) and (2), respectively. V and I indicate voltage and current, and T_s, L_{th}, k_s, and T_m mean surface temperature, heater length, and measured temperature, respectively.

$$q' \ (kW/m^2) = \frac{V \times I}{Heated \ \ Area} \quad (1)$$

$$T_s = \frac{q' \, L_{th}}{2k_s} + T_m \quad (2)$$

3. Results

The heater surface oxidized under 300°C of dry air shows red and brown surface which appears as oxidation layer. First of all, contact angle was measured using 5μL of deionized water and SEO contact angle device, and low contact angle was observed for even 7day-oxidized heater surface as shown as Fig.2. XRD analysis was conducted in order to clarify the components of oxidation layer, and hematite (Fe2O3) and magnetite (Fe3O4) layer were confirmed on heater surface (Fig.3). In addition, through the SEM and EDS analyses, the morphology modification was observed in a needle-shaped iron oxide as shown in Fig. 4. This surface morphology modification causes contact angle to decrease: an increase of wettability.

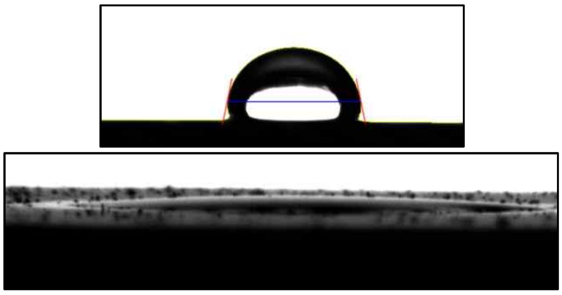


Fig. 2. Contact angle measured for bare-heater (top, 80°) and 7 days-oxidized heater surface (bottom, super hydrophilic ~5°)

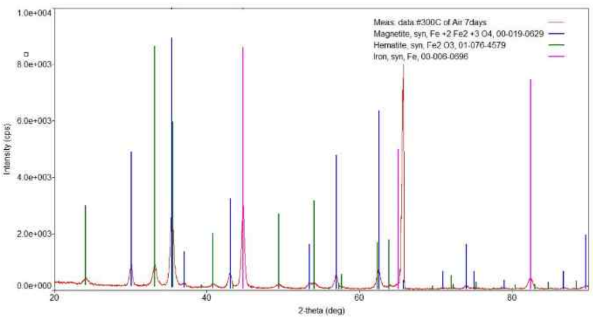


Fig. 3. XRD results of the oxidized heater surface (Blue: Magnetite, Green: Hematite, Pink: Iron)

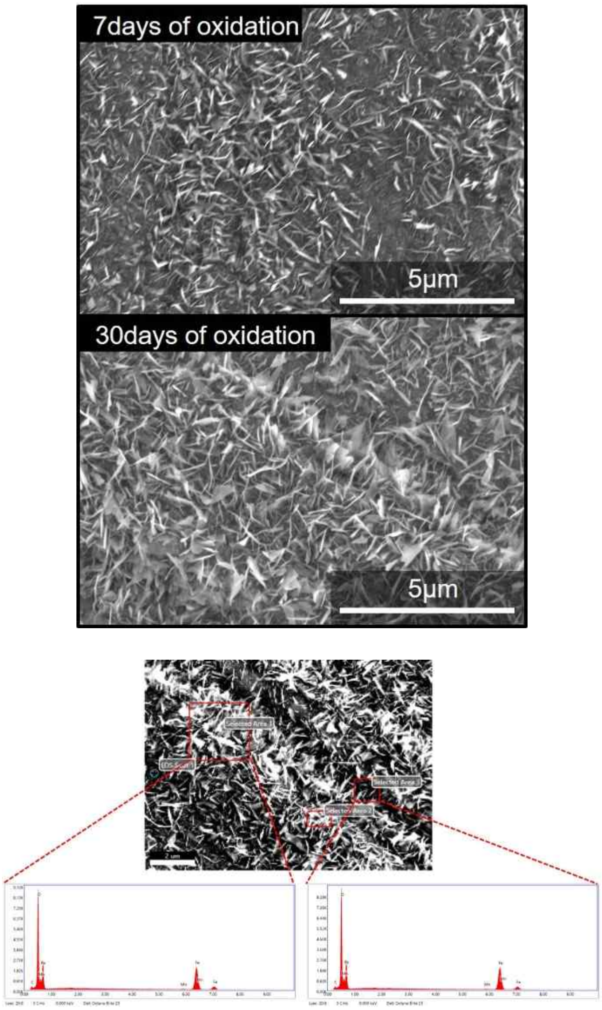
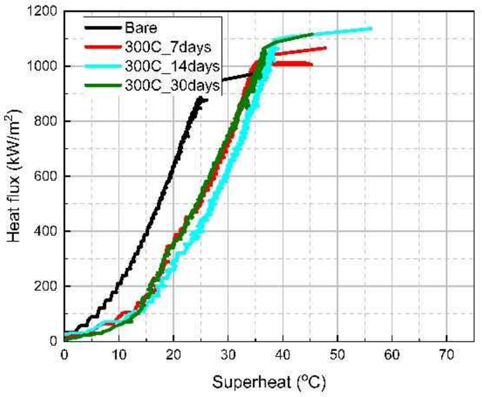


Fig. 4. SEM image of the heater surface oxidized for 7 and 30 days, and EDS results of needle-shaped adsorbate

CHF values were obtained by calculating with voltage and current data measured in real time. Temperature was measured at a rate of 2Hz, and boiling curve was obtained using the superheat and heat flux data (Fig. 5-(a)). As results, a decrease of boiling heat transfer coefficient (BHTC) is observed due to the oxidation layer. Oxidation period appears not to be dominant on BHTC, while it affects CHF enhancement. CHF appears to be enhanced as oxidation period increases from 7 to 30 days (Fig. 5-(b)). Furthermore, the enhancement in CHF is observed to become saturated over the oxidation time.



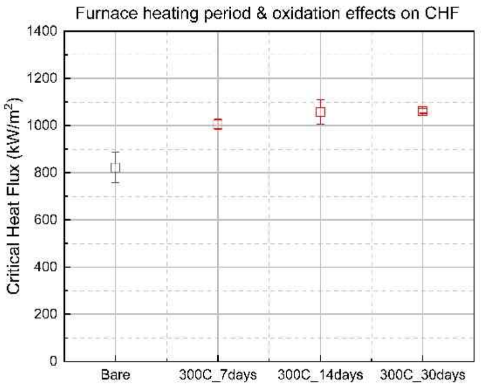


Fig. 5. (a): Boiling curve depending on oxidation period (Superheat versus heat flux), (b): CHF results depending on oxidation period

4. Conclusions

Oxidation effects of a carbon steel on CHF and BHTC was evaluated by pool boiling experiments in order to reflect the RPV surface oxidized during normal operation under hot and dry environment. On this basis, carbon steel oxidation and pool boiling experiments were conducted using a large size of heater and pool. As results, through the oxidation process, the oxidation layer of magnetite and hematite was formed on the surface, confirmed by XRD and SEM. The surface morphology modification has an influence on an increase of wettability, and it shows a decrease in BHTC, but an increase in CHF.

ACKNOWLEDGEMENT

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REFERENCES

[1] J.L. Rempe, K.Y. Suh, F.B. Cheung, S.B. Kim, In-Vessel Retention Strategy for High Power Reactors Final Report, INEEL/EXT-04-02561, Idaho Natl. Lab. Rep. (2005).

[2] D.H. Kam, Y.J. Choi, Y.H. Jeong, CHF experiment with downward-facing carbon and stainless steel plates under pressurized conditions, Int. J. Heat Mass Transf. 125 (2018) 670–680.

[3] H.H. Son, U. Jeong, G.H. Seo, S.J. Kim, Oxidation effect on the pool boiling critical heat flux of the carbon steel substrates, Int. J. Heat Mass Transf. 93 (2016) 1008–1019.