

Oxidation Effect on Pool Boiling Heat Transfer in Atmospheric Saturated Water

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1. Introduction

In nuclear power plant (NPP), iron-based alloys are exposed to various corrosive environments. Especially, reactor pressure vessel (RPV) which is an irreplaceable component through the lifetime of NPP experiences natural corrosion on the outer surface in atmospheric environment. In normal operation, it is innocuous on the operation of the NPP, because primary water flowing only inner surface of RPV promotes galvanic corrosion between stainless steel insulator and carbon steel. During the hypothesized severe accidents, however, the modified nature of the oxidized outer surface of RPV may act as a significant heat transfer variable to achieve In-Vessel Retention through External Reactor Vessel Cooling (IVR-ERVC) strategy, which is the one of important mitigation strategies of severe accident to delay occurrence of critical heat flux (CHF) [1-4]. As well understood, the CHF is mainly affected by the two distinctive conditions classified to thermal hydraulic behavior of fluid system and surface characteristics.

In this regard, a CHF test considering oxidation effect on the pool boiling heat transfer of the RPV outer surface has been proposed to evaluate realistic thermal margin of IVR-ERVC strategy.

In this study, pool boiling heat transfer experiment was conducted under the condition of atmospheric saturated water. Oxidized surface characteristics were quantitatively evaluated with measurement of contact angle and roughness.

2. Experimental Description

It is well known that the real raw material of the PWR RPV is low carbon steel alloy, whose grade is SA508. In this study, however, specimen made of stainless steel grade 316 (SS316) was selected as test heater, which is broadly used in energy industries utilizing high temperature steam. This is because the studies related to oxidation boiling heat transfer based on iron alloy are difficult to secure.

The test specimens were polished or not to confirm the effect of chromic oxide, which is formed after the production. Dimension of heated surface is $26 \times 8 \times 2$ mm³ in length, width, and thickness, respectively.

2.1 Oxidation Treatment

In general, SS316L has high corrosion resistivity as having high chromium composition about 18wt%. Chromic oxide barrier forms constantly on the free surface, which plays a role in preventing contact with oxygen in atmosphere. In this circumstance, oxidation on the free surface occurs via diffusion process only. Thus, in order to simulate sufficient oxide layer thickness, high temperature condition was provided using muffler furnace. Table 1 shows four types of specimens oxidized with different processes.

Table 1. Oxidation thickness according to each process

Surface treatment	Specimen number	Oxidation temperature (°C)	Oxidation period (day)	Oxide layer thickness (μm)
Clean	D001 D002	-	-	0
Oxidation	D051 D052 D053	500	5	0.38±0.06 (localized)
	D201 D202	700	20	-
	D251	700	25	0.89±0.28 (flattening)

Figure 1 shows surface morphology after oxidation treatment. In all cases except for a bare specimen, oxide particles were deposited on the free surface. But the extent of oxide layer flattening was different with the oxidation period. In other words, the specimens oxidized for short-term period showed only local pitting corrosion, which may be unacceptable as a continuous oxide layer. On the contrary, the specimens oxidized for long-term period exhibit thin oxide layers distributed continuously on the free surface.

It is considerable by the fact that the chromic oxide layer cannot be perfectly uniform along with the free surface due to some external forces applied to the surface [5]. This indicates that oxidation occurs unequally. It is important because non-uniform oxidation on the heated surface may show some discontinuities of surface characteristics related to boiling heat transfer.

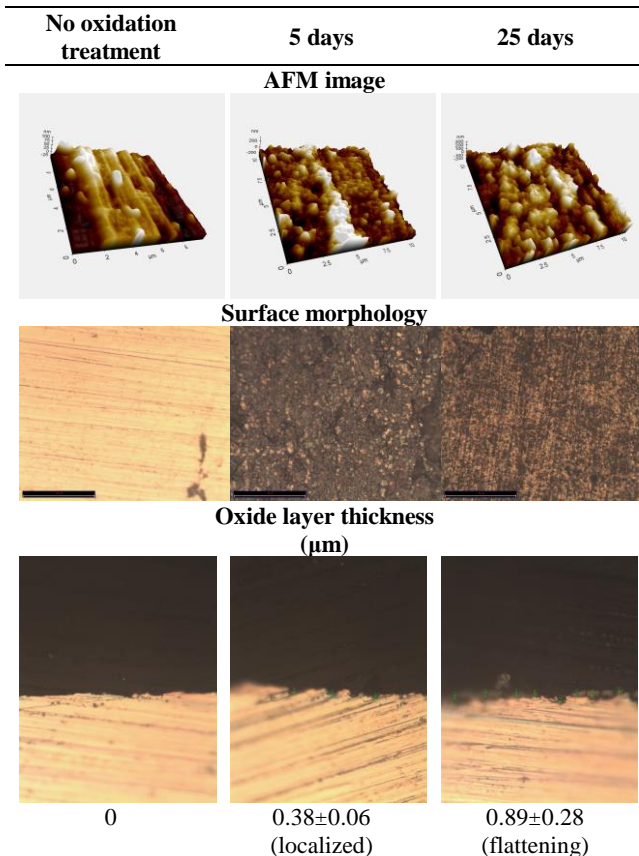


Fig. 1. Atomic Force Microscope (AFM) and optical microscope image of oxide surface and layer (black scale bar in the image of surface morphology indicates 10 μm).

The modified surface characteristics including roughness and wettability were shown in Tables 2 and 3. As far as the roughness, any large difference between the specimens was not shown because all measured roughness is in the range of nano-scale [6]. Unlike the roughness, Table 3 shows the remarkable change of wettability in terms of the contact angle.

Table 2. Surface roughness for clean and oxide surfaces

Specimen No.	Oxidation Period (day)	Surface Roughness			Surface Statistics
		R _q (nm)	R _a (nm)	R _z (nm)	Surface Area Ratio (%)
D001	0	20.1	16.5	137.0	0.11
D051	5	69.4	46.9	491.7	5.05
D053	5	83.6	62.7	532.4	5.02
D202	20	79.9	64.0	574.7	7.48
D251	25	83.5	62.7	657.6	10.00

Specially, receding angle of the oxidized specimens was almost the same regardless of the oxidation period. This indicates that once a metal specimen is oxidized, receding force of water on the free surface may be the same by oxide particles, which have high surface tension with water, deposited to the upmost boundary of the effective surface. But the effect of oxide layer on the

receding angle was not confirmed because the receding angle closed to 10 degrees was the lowest value to measure. In other words, the receding angle alone may not represent wettability due to the measurement limit in the low range.

Table 3. Contact angle for clean and oxide surfaces

Specimen No.	Oxidation Period (day)	Receding angle (°)	Static contact angle (°)
D001	0	-	77.8±0.3
D002	0	44.4±4.1	98.2±0.6
D051	5	15.6±3.6	68.8±3.7
D052	5	16.4±2.2	50.8±4.5
D053	5	17.2±3.4	50.4±5.5
D201	20	14.0±1.3	50.3±3.8
D202	20	16.4±2.2	50.8±4.5
D251	25	11.6±1.0	33.0±2.1

2.2 Experimental apparatus and procedures

Pool boiling heat transfer experiment was conducted with saturated deionized (DI) water in the atmospheric pressure. The boiling heat transfer apparatus consists of an isothermal bath, a DC power supply of 10V-1200A, a high speed camera, and data acquisition system. A full schematic diagram of the apparatus is shown in Fig. 2.

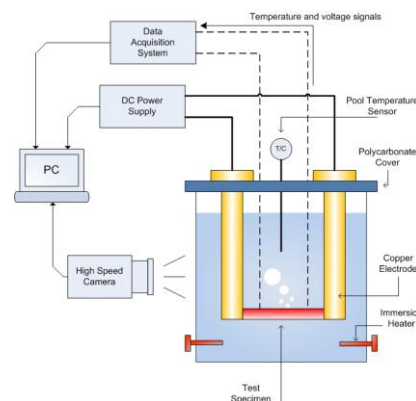


Fig. 2. Schematic diagram of pool boiling heat transfer apparatus.

Experimental procedure follows two major steps. First, saturated temperature at atmospheric pressure was achieved using the preheaters equipped in the isothermal bath. To remove non-condensable gas affecting bubble performance, saturated state was maintained for approximately one hour. Second, power input was increased in step of 40 kW/m² until the heat flux reached 70% of the predicted CHF. Closed to the CHF, smaller heat flux of 20 kW/m² was applied to prevent sudden vapor film formation.

Voltage drop was measured in each back end of the heater to remove unintended heat loss. Measurement uncertainty was measured using a propagation of error method. The uncertainties on the current (U_I/I), voltage (U_V/V), and heated length (U_L/L) and width (U_W/W)

values were less than 0.5, 0.5, 2.5, and 0.8 %, respectively. The final measurement uncertainty calculation of 2.7 % was evaluated.

3. Results and Discussion

3.1 CHF Comparison according to oxidation period

Test matrix introduced in this study is summarized in Table 4. Two surface finish conditions of polishing and non-polishing were introduced. Oxidation periods up to 25 days were applied.

Table 4. Test matrix

Test material	SS316L
Test condition	Saturated at atmospheric pressure
Working fluid	DI water
Surface finish	Polished: PD Unpolished: NPD
Oxidation period (day)	0, 5, 20, 25

Figure 3 shows the CHF change according to oxidation period. The CHF of bare specimen is about 600 kW/m^2 , which is lower than the typical CHF value of 1070 kW/m^2 reported by Zuber [7]. Nevertheless, a relative comparison for each case is available to confirm oxidation effect on the CHF.

In case of D053 oxidized for 5 days, no change of CHF was shown despite the fact that the oxidized surface is more wettable than bare. However, more oxidized specimens above 20 days showed the CHF enhancement clearly by 30%. It is remarkable because the oxide layer thickness of D202 and D251 is just $1 \mu\text{m}$, which is considered as lower than that of the outer surface of RPV. In a typical industrial environment, natural corrosion rate of low carbon steel is approximately to 0.025 mm/yr [8]. Thus, we may expect that as natural corrosion continues more conservative thermal margin under implementation of IVR-ERVC strategy may be accomplished [9].

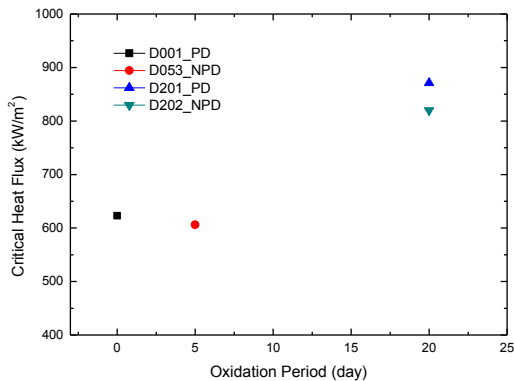


Fig. 3. CHF according to oxidation period.

3.2 Oxidation effect on CHF

It is generally known that wettability and roughness increase the CHF [10]. In Fig. 4, however, these variables do not show consistent positive effect on the CHF. Moreover, the remarkable result is shown in D053. Although D053 was rougher and more wettable than the bare specimen, the CHF was not increased but remained as unity. On the contrary, the CHF of D202 was enhanced by 30% in spite of the same receding angle and roughness with D053. These results disagree with general belief that the more wettable or rougher surface may delay the CHF with enhancement of rewetting process which can break the coalescence of vapor at the high heat flux.

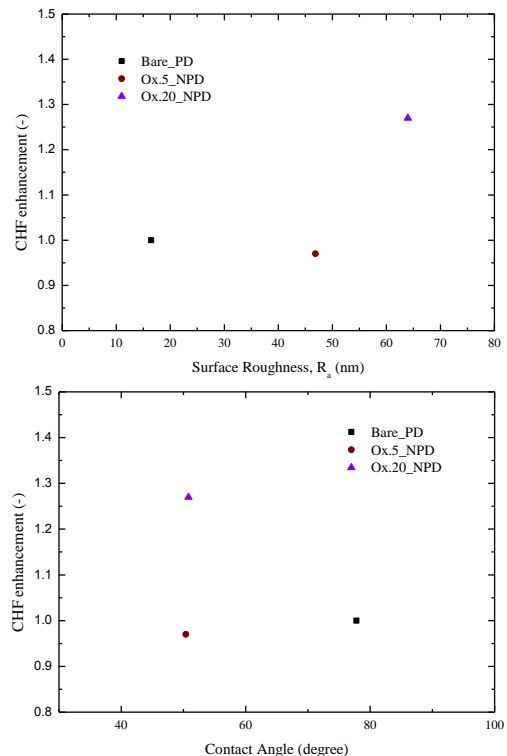


Fig. 4. CHF enhancement with respect to (a) surface roughness (b) contact angle.

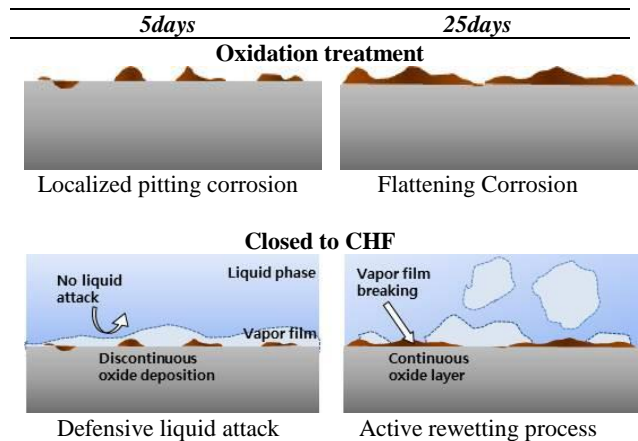


Fig. 5. The difference of rewetting process according to the existence of the porous channel.

Fig. 5 presents the conceptual schematic of what might happen during current experiment. Active rewetting process occurs mainly when connected porous channel is formed under the oxide layer. On the contrary, disconnected oxide group may not break vapor film smoothly due to lack of capillary wicking force even though it is more wettable and rougher.

O'Hanley et al. suggested that the effect of wettability and roughness hardly acts on the non-porous surface. The study provides a case of clue that dominant surface parameter affecting the CHF is porosity. In addition, the effect of wettability and roughness may be considerable when correlated with porous channel [12].

4. Conclusions

In this study, oxide layer formation on the heated surface was investigated and experimentally simulated to find out its effect on the pool boiling CHF. Several SS316L substrates were oxidized in the corrosive environment under the condition of high temperature with different oxidation periods. Local pitting corrosion was observed on the heating surface in 5 days of short-term oxidation but a fully oxidized surface with somewhat uniform thickness, 1 μ m, was formed in 25 days of long-term oxidation. Pool boiling heat transfer tests with the bare and oxidized heaters were conducted and major findings are summarized as follows:

- (1) Wettability in terms of the receding angle of the oxidized surface is enhanced regardless of the oxidation period.
- (2) Average roughness between the oxidized surfaces is almost the same in the range of nano-scale.
- (3) Effect of wettability and surface roughness on the CHF was negligible in the locally oxidized surface, which may be attributed to the presence of the disconnected porous channel. Unlike the local oxidation, fully oxidized surface shows the continuous oxide layer, which likely includes connected porous channel. This results in the higher CHF enhancement.
- (4) Consequently, the oxide layer formation on the outer surface of the RPV lower head under the condition of natural corrosion can enhance thermal safety margin if oxide has been fully deposited at the surface.

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