

Heat Transfer Surface Morphology and Oxidation Effect on the CHF under Vertical Flow Boiling Considering the RPV Manufacturing and Operating Condition

Jun Yeong Jung, Min Suk Lee, Yong Hoon Jeong *

Department of Nuclear Quantum Engr. KAIST, 291 Daehak-ro, Yuseong-gu, Daejeong

*Corresponding author: jeongyh@kaist.ac.kr

1. Introduction

Before installing the reactor pressure vessel (RPV) in the nuclear power plant, non-destructive inspection must be conducted to check the quality of the overall PRV structure and also welding parts. For smooth non-destructive testing, the RPV surface is polished with a stainless-steel wire brush, and it makes scratches on the RPV surface. After the RPV is installed in the plant, the RPV is exposed to the plant normal operations for decades. Under the normal operation of the APR1400, the average temperature and pressure of the primary side coolant are 310 °C and 155 bar, and the RPV is surrounded by thermal insulation structure to minimize heat loss. From this, the RPV outer wall surface temperature is almost 310 °C, and the air around the wall is also at a similar temperature and will be very dry. Since the RPV is made of carbon steel (SA508) which is easier to oxidize than other metals, under these conditions, an oxidation layer is formed on the RPV outer surface.

In the case of IVR-ERVC (In-Vessel Retention – External Reactor Vessel Cooling) strategy, in which the coolant is injected into the reactor cavity to remove the decay heat by flooding the reactor, the success of ERVC is usually determined using the CHF (Critical Heat Flux). The surface state of the RPV outer wall is one of the main factors affecting the CHF. This is because the CHF is highly affected by the surface condition of the heat transfer surface.

In this study, the effect of the heat transfer surface state on the CHF experimentally was evaluated, and two factors were selected as experimental variables. The first was the surface morphology of the specimen, and the morphology was adjusted using sandpaper. The second was surface oxidation of the specimen, and the oxidation time was adjusted using the furnace.

2. Specimen Pre-treatment

This part describes how to control the surface morphology and oxidation of the specimen. The effective heating surface of the specimen has a width and length of 30 mm, and the thickness of the SUS 304 and SA508 specimen are 1.9 mm and 1.2 mm, respectively.

2.1 Surface Morphology Control

During the fabrication of reactor vessel, the RPV surface was polished with the wire brush made whose

bristles were made of numerous stainless-steel wires. So, after polishing, it had a lot of shallow scratches on the RPV surface. This RPV surface polishing was done manually by the worker during the manufacturing process. As shown in Fig. 1, the specimen was polished under the same polishing conditions of position, loading pressure and so on, using auto-polisher and the jig. The polishing RPM and time were 60 rpm and 3 minutes × 3 times at least. For each polishing operation, sandpaper was used for one-time use and the specimen was polished at least three times.

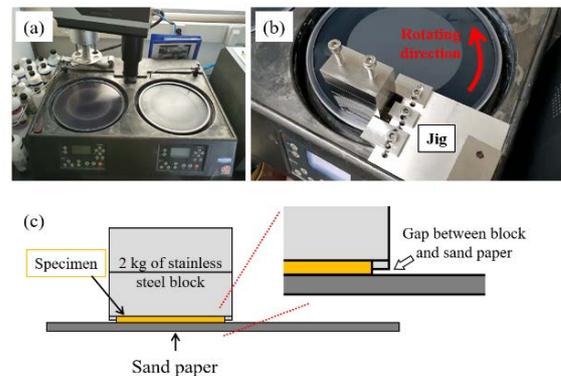


Fig. 1. (a) Auto polisher, (b) Picture of polishing process, (c) Concept diagram of polishing (side view)

As previously stated, surface treatment is done manually, so there is a limit to figure out the actual roughness of the PRV surface. Therefore, in this experiment, parametric studies have been performed by changing the roughness of the specimens. To make variation on the specimen roughness, they were polished using 120, 800 and 2000 grit number sand paper. At the same time, they were polished in two direction to demonstrate the effect of the scratch direction, respectively, called horizontal and vertical.

Fig. 2 shows the picture of the polished specimens for understanding polishing direction concept. To minimize other factors, the specimens was made of the stainless steel (SUS304). The average roughness of the surface was measured with a 3D profiler and the static contact angle was also measured.

Because the auto-polisher polished the specimen as it rotated, the specimen was scratched in a curved form. So, the method of the specimen installation on the test section determined the relationship between the surface scratch curve and the direction of the working fluid flow. In this study, if the convexity of the scratch curve coincides with the flow direction, as presented in Fig. 2,

this is called horizontal-up and the other is called horizontal-down like Fig. 2 presented.

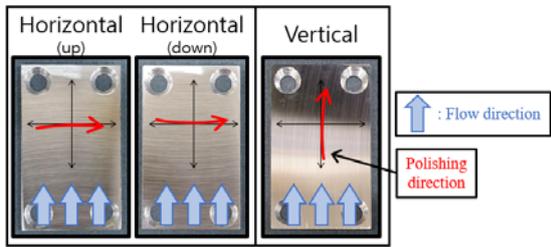


Fig. 2. Picture of polished specimen

2.2 Surface Oxidation Control

During the normal operation of the nuclear power plant, the outer wall of the RPV was oxidized in the hot and dry air, and the RPV was made of carbon steel (SA508 Class 3). Therefore, in this study, to simulate the RPV surface oxidation condition, the SA508 specimens were oxidized by an electrical furnace at 310 °C of dry air condition. Oxidation time was an experimental variable, and experiments were conducted with specimens oxidized for 3, 4, 6, and 10 days. Fig. 4 shows the picture of the specimen. The definite increase in the oxygen proportion on the surface after oxidation was confirmed by EDS analysis.

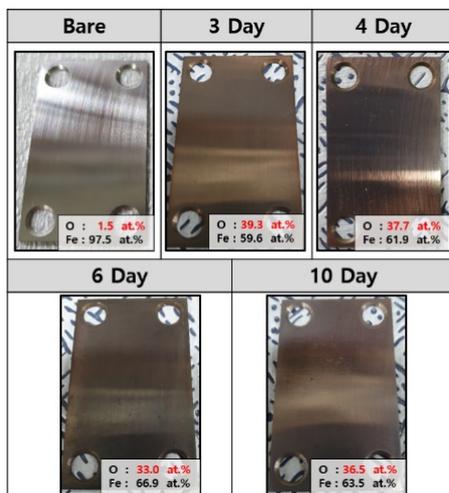


Fig. 3. Specimens picture with EDS results

3. Experimental Facility and Conditions

In this study, flow boiling CHF experiment facility was used to evaluate the specimen surface effect. This part describes the facility and experiment method.

3.1 Flow Boiling CHF Facility

Fig. 4 shows the schematic diagram of flow facility. All components were connected by SUS304 pipe. The working fluid was DI water basically. By using the boiler, the working fluid was heated to 98 °C of experiment condition. The flow meter and pump measured and controlled the working fluid mass flux. The flow channel consisted of a test section and plenums, and each part was gently connected by square curve channel with a radius of 0.5 m. This flow channel simulated the RPV outer wall condition. Two k-type thermocouples measured the working fluid temperature. The heat exchanger condensed the vapor which was generated at the test section.

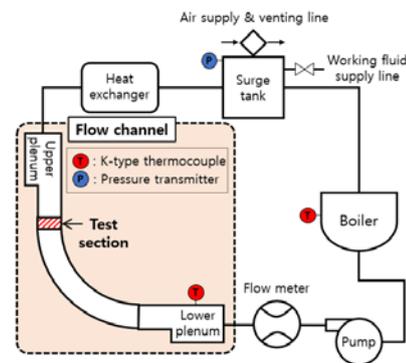


Fig. 4. Schematic diagram of flow facility

The specimen was connected with two copper electrodes (Fig. 5) and heated by direct joule heating. For this, DC power supplier was used, and the supplied current was measured from the power supplier. At the same time, copper rods for voltage measurement were installed at the back of the specimen to measure the voltage drop between the two ends of the effective heating area. Therefore, the surface heat flux was calculated based on the measured current and voltage drop, as like Eq. 1. The test section was composed of the specimen and flow structures to make downward-facing heat transfer flow channel, and the area around the specimen and electrodes were sealed with Teflon pieces to make electrical insulation and to prevent water leakage from the flow channel.

$$q'' = \frac{\text{Voltage drop} \times \text{Current}}{\text{Heat transfer area}} \quad \text{Eq. 1}$$

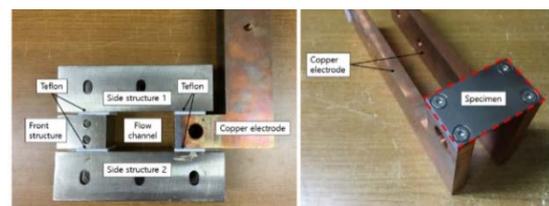


Fig. 5. Assembled test section (left) and the specimen with copper electrodes (right)

All data (temperature, mass flux, current, voltage and pressure) were collected via DAQ (Data Acquisition System, Agilent, 34980A) at 0.5 s intervals. In general, the resistivity of metals increases, as temperature rise. The specimen resistance can be monitored using the voltage and current being measured, and the occurrence of the CHF can be detected as a resistance change by utilizing the point which the specimen temperature rises sharply when the CHF occurs.

3.2 Experimental Conditions

In this study, it was experimentally evaluated that the effect of surface polishing conditions and surface oxidation on the CHF. First, to exclude other effects other than polishing, the SUS304 specimen was polished using grit number 120, 800, and 2000 sandpaper in the same polishing method. The SUS304 is one of very stable material and has excellent chemical resistance and is commonly used in experiments and also in industry.

Second, to evaluate the surface oxidation effect, experiments were conducted by the oxidized SA508 specimen. Before oxidation, the bare SA508 specimen was polished with 800 grit sand paper in order to remove foreign substance on the surface and make specimens consistent. The SA508 specimens were oxidized in the furnace under dry air condition. It produced 3, 4, 6 and 10 days of oxidized SA508 specimens. As shown in Fig. 3, the specimen surface after oxidation turned dark-blue and the EDS analysis confirmed that oxygen was present on the surface.

Table 1. Experiment and flow channel conditions

Overall experiment condition	
Pressure (bar)	1
Inlet subcooling (K)	2
Mass flux (kg/m ² s)	100
Surface polishing experiment	
Material	SUS304
Sand paper	120, 800 and 2000
Working fluid	DI water
Surface oxidation experiment	
Material	SA508
Oxidation time (day)	3, 4, 6 and 10
Working fluid	DI water and 2.5 wt.% Boric acid water
Boiling time (minute)	30, 90 and 180
Flow channel geometry	
Gap (m)	0.06
Width (m)	0.03
Radius curvature (m)	0.5

Both SUS304 and SA508 specimens performed the CHF experiments using the same flow boiling experimental facility. The working fluid was DI water, and experiments were conducted with the working fluid 98 °C under atmospheric conditions. Mass flux of the working fluid was 100 kg/m²s. For the SA508 specimens,

experiments were also conducted under boric acid water conditions to perform some evaluations of the CHF values in IVR-ERVC situations. This is because, during the ERVC, it was used a coolant from IRWST (In-containment Refueling Water Storage Tank) containing 2.5 wt% boric acid water. In addition, boiling time effect was also evaluated under boric acid water. The experimental conditions and flow channel information are as shown in Table1.

4. Result

In this part, the result of the specimen surface analysis and the CHF experiment result were described. For all graphs in this part, symbol is the mean value and error bar is the standard deviation.

4.1 Surface Analysis Result

Fig. 6 shows the SEM image of polished SUS304 surface. It was observed that the softer the sandpaper, the smoother the surface was formed. From a microscopic view, the valleys formed on the surface by sandpaper could serve as micro channels that provide coolant to the specimen during the boiling. To observe the surface characteristics, the average surface roughness was measured by a 3D profiler, and the static contact angle was measured to determine the hydrophilicity of the specimen according to the sandpaper number.

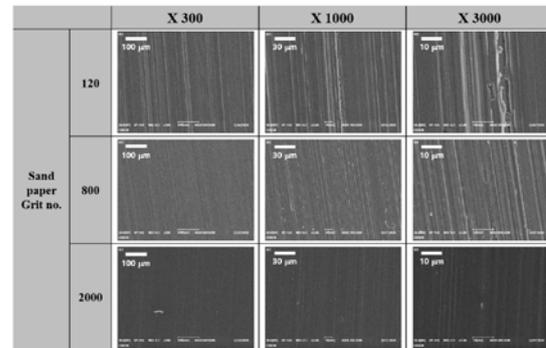


Fig. 6. SEM image of SUS304 surface

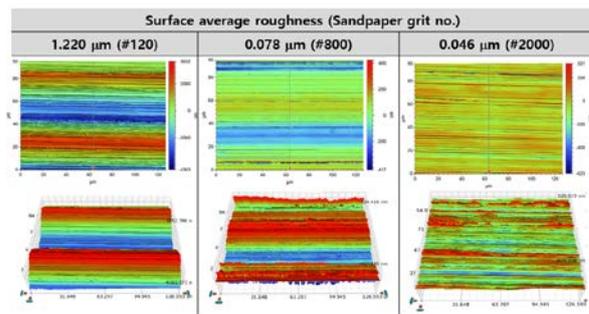


Fig. 7. Surface roughness result

Fig. 7 show the surface roughness results. The roughness is measured at least five times at different locations and the average value is shown in Figure 7. Depending on the roughness of the sandpaper, the surface roughness measured from 0.046 to 1.22 μm .

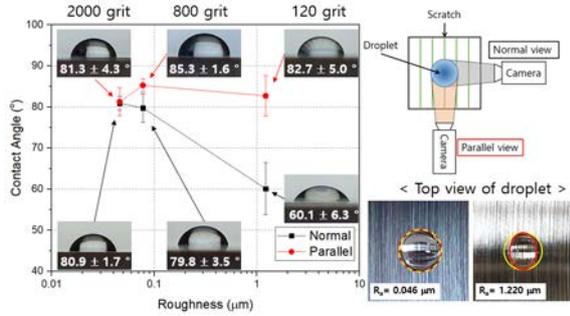


Fig. 8. Contact angle result of the polished SUS304 specimens

The contact angle results are shown in Fig. 8, and it is measured in two directions: parallel and perpendicular to the direction of surface scratch. It was observed that the scratch acted like a microchannel and the drop spread in the direction of the scratch by the capillary effect. At the same time, the pinning effect of the scratch prevented the drop spreading [1][2]. The rougher the surface, the stronger this phenomenon occurred. Consequently, when observing the drop in the top view, on the rough surface it was oval in shape. Depending on the surface roughness strength and the scratch direction, it was observed that hydrophilicity was measured differently, and it suggested that it could affect the CHF.

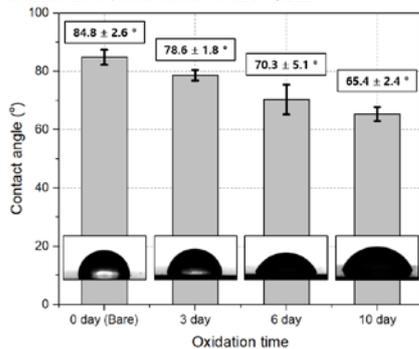


Fig. 9. Contact angle results of the oxidized SA508 specimens

The oxidized SA508 also measured the contact angle and the results were in Fig. 9. It was confirmed that the longer the oxidation time, the less contact angle and the more hydrophilic it was. The bare specimen contact angle was affected by the surface treatment as well as the material properties of the SA508. In this experiment, all SA508 specimens were oxidized after polishing with 800 grit sandpaper. By oxidation, the magnetite layer formed

on the SA508, and this oxide layer increased the hydrophilicity of the surface[3], suggesting that it could contribute to the CHF enhancement[4][5].

4.2 The CHF Result

The surface polishing effect on the CHF is present in Fig. 10, and legends of the Fig. 10 corresponds to Fig. 2. Basically, at all polishing conditions, the CHF improves with the roughness increasing. This CHF trend was also observed at pool boiling condition[1]. As the roughness increases, the water supply becomes smooth due to the surface scratch's capillary effect, which results in an increase in CHF. In case of the horizontal conditions, the direction in which the convex part of the scratch was oriented had no meaningful effect on the CHF.

The CHF of the horizontal conditions was measured higher than the vertical conditions for all roughness conditions. These results are assumed to be influenced by the relationship between the surface scratch direction and the working fluid flow direction. In the case of the vertical polishing conditions, the coolant supply to the specimen is already sufficient from the viewpoint of the flow direction, because the scratch and flow direction are the same. However, it is weakened in the left and right directions by the pinning effect.

On the other hand, in the case of the horizontal polishing conditions, the coolant supply to the specimen by the flow will be stronger than the pinning effect inhibiting the coolant supply. At the same time, by the capillary effect, the coolant supply in the left-right direction of the specimen is relatively accelerated. Overall, it is believed that the coolant supply of the horizontal polishing conditions is smoother than the vertical conditions, resulting in a higher CHF value.

In addition, a little liquid located in the non-heating zone on the side of the specimen may be supplied to the specimen by a horizontal polishing scratch to enhance the CHF. However, near the CHF, the heat flux is sufficiently high to produce the vapor actively, making it difficult to assume that liquid may exist in non-heated area.

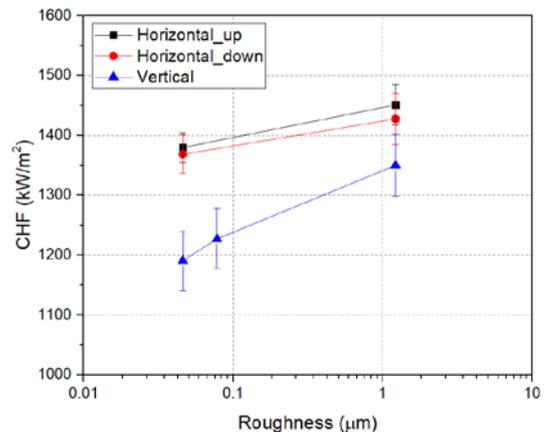


Fig. 10. The CHF result of polishing effect

Next, let's figure out the effect of specimen oxidation on the CHF. First, experiments were conducted under DI water condition to determine the effect of oxidation time on the CHF. The CHF value slightly rise at 3day oxidation condition and then became constant after decreasing. In addition, because the oxidation specimen has an oxide layer and it prevents reckless surface oxidation by the coolant, so the CHF deviation is relatively small.

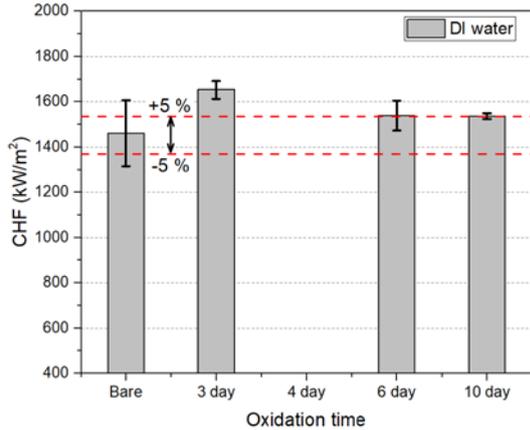


Fig. 11. Oxidized SA508 CHF result under DI water

Second, Fig. 12 is the result of the SA508 CHF under the boric acid water reflecting accident conditions. When comparing to the CHF value of DI water, the CHF increases by about 10% at the bare specimen, but the CHF values are about the same at the oxidation specimens. For the bare specimen, under boric acid water condition, extreme surface oxidation occurs, and it enhances the CHF[4][5]. However, for the oxidized specimens, the CHF values are similar regardless of the working fluid, as the oxide layer inhibits additional oxidation of the specimen.

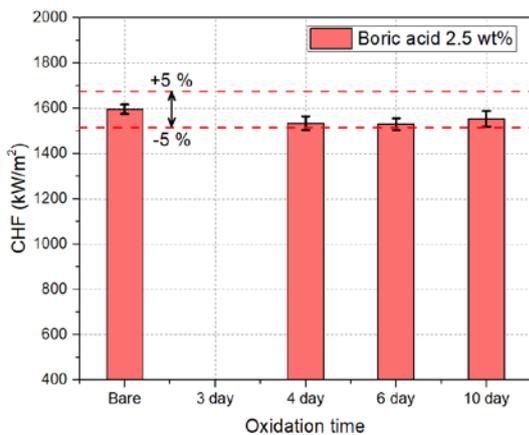


Fig. 12. Oxidized SA508 CHF result under boric acid water

Finally, from the viewpoint of the CHF, the oxide layer of the specimen was determined to be effective

even in long boiling time. Under the boric acid water condition, the boiling time effect experiment was conducted. Its result is shown in Fig. 13. For the bare specimens, the CHF decreased slightly (though within the data deviation range) in the 180-minute boiling condition, and for the oxidation specimens, the CHF remained similar in all boiling conditions.

In the case of the bare specimens, surface oxidation is severe as shown in Fig. 14, and the transfer characteristics of the oxide layer are quite poor[3]. Therefore, it is believed that the CHF of the bare specimens slightly decreased. However, when we compare to the CHF of DI water condition, the CHF of boric acid condition is improved. These results are assumed to be: The bare specimens have increased CHF value due to surface hydrophilicity increasing by active surface oxidation in the boric acid water condition compared to the DI water condition. However, under the boric acid water condition, a longer boiling time leads to an excessive oxidation layer, which interferes with the heat removal of the specimen, resulting in a slight reduction in CHF at the long boiling time.

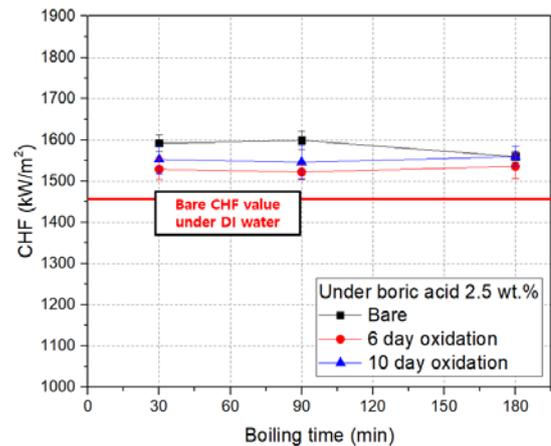


Fig. 13. Boiling time on the CHF under boric acid water

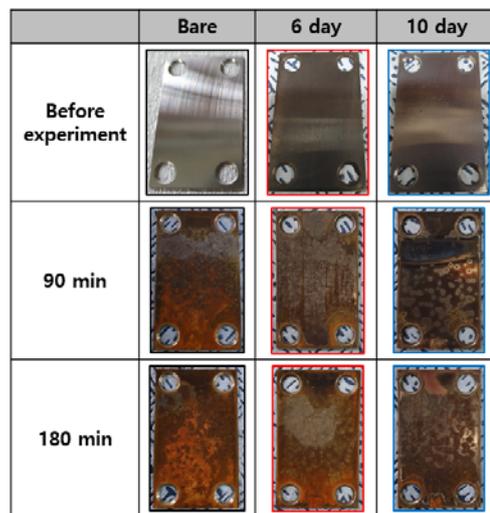


Fig. 14. Picture of the SA508 specimens

On the other hand, for oxidation specimens, the CHF values are almost constant under all boiling-time conditions because there is already stable oxide layer. From Fig. 14, the oxidized specimens are less oxidized by the boric acid water than the bare specimens. In other words, the CHF values of the oxidation specimens are constant regardless of the operating fluid (DI water or boric acid water), because the oxidation layer prevents the specimen from being oxidized by boric acid water.

3. Conclusions

In this study, it is experimentally evaluated that the effects of surface condition (roughness and direction) on the CHF by using SUS304 and the effects of specimen oxidation on the CHF by using SA508. From viewpoint of the CHF, these parameters can be considered as factors that affect the RPV outer surface during the manufacturing and normal operation.

It is confirmed that the direction of the scratch as well as the surface roughness can affect CHF, under flow boiling conditions. The CHF of the oxidized specimen is stable compared to that of the bare specimen, and the CHF values are almost constant after 3 days of oxidation.

Through this study, the heat transfer surface state of the specimen has an effect on CHF. Therefore, in other words, uniforming the initial conditions of the specimen surface will help to reduce the experimental deviation of CHF.

However, this experiment also has limitations. Experiments were conducted with SUS304 to verify the polishing effect only. Although SUS304 is a widely used steel for experimental specimens, it is not a material for making the RPV. Second, The SA508 had a maximum oxidation period of 10 days and a maximum boiling time of 3 hours under boric acid water. In reality, the RPV surface will be oxidized over decades, and the boiling time will be longer during the severe accident. Nevertheless, this study confirms that the initial conditions of the heating surface can affect the CHF and obtains fundamental data for further research.

Acknowledgments

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