ABSTRACT

In this work, the CHF (Critical Heat Flux) of oxidized zircaloy surface and its enhancement were examined in saturated water pool boiling at atmospheric pressure condition. Three kinds of zircaloy specimens oxidized at three different temperature conditions (i.e., 300, 450 and 600 °C) were prepared, and tested together with a non-treated (i.e., fresh) surface. Oxidized specimens increased the CHF. This could be because the oxidized surface improves the surface wettability (i.e., decreases the water contact angle), which leads to a thicker macrolayer and promotion of the rewetting process on the heated surface with hot and dry spots. The CHF enhancement of the oxidized specimens was about 40 %, and interestingly, it was a comparable value with the specially treated zircaloy surfaces of a previous report, having a similar water contact angle to the present oxidized surface. This implies that the oxidation process may be a simple, convenient, and cost-effective way to improve the CHF of a zircaloy surface. Among the previous correlations tested, Kandlikar’s correlation was in good agreement with the present experimental data within a reasonable degree of accuracy.

1 INTRODUCTION

Nucleate pool boiling is known to be a very effective mechanism of a phase change heat transfer to achieve a higher heat transfer coefficient than a single phase at a given temperature difference condition. In the nucleate boiling regime, a number of bubbles are produced from the surface, and the heat is rapidly transferred by their latent heat transport and local convection enhancement. However, the nucleate boiling regime is limited by a certain heat flux condition, the so-called CHF (Critical Heat Flux). The CHF is the maximum heat flux value sustaining the nucleate boiling regime. After the CHF point, the heated surface is covered with a vapor blanket, and the surrounding liquid is not able to touch the heated surface. In other words, the heat transfer mode changes from nucleate boiling to film boiling. Such a case leads to a dramatic decrease in the heat transfer performance and a sudden increase in the surface temperature, and consequently results in a failure of the heater surface. Hence, the CHF enhancement is a key issue for maximizing the efficiency and safety of an industrial thermal energy system such as a nuclear power plant.
For the large safety margin and high performance of a nuclear reactor core, investigations on the enhancement of CHF using the nanofluids [1-3] and surface modification [4-6] have been performed and reported extensively.

Nanofluids, a dispersion of nanoparticles in water, have been reported to increase the CHF value [1-3]. During the boiling, nanoparticles are deposited on the heated surface, which change the surface conditions (e.g., the morphology and wettability). In other words, the surface change caused by the deposition of nanoparticles results in increasing the CHF. The use of nanofluids is an easy way to enhance the CHF, but it may have a limit in being acceptable to a nuclear core application, since the nanoparticles can contaminate the water coolant flow.

For enhancement of the CHF through the surface modification, various techniques [4-6] were adapted to uniquely modify and fabricate the heater surfaces of various materials. However, the available researches on CHF enhancement using the surface treatment of nuclear fuel cladding materials (e.g., zircaloy and zirconium) are insufficient and limited. Ahn et al. [7] investigated the effect of zircaloy surface modification using the anodizing technique on the CHF in the saturated water pool boiling under atmospheric pressure. They mentioned that the good liquid spreading of anodized zircaloy surfaces having a much smaller contact angle (e.g., below 10°) can significantly contribute to enhancing the CHF. Stange et al. [8] carried out water pool boiling CHF tests using a zirconium wire under atmospheric pressure. The wire was coated with the nanoparticles of YSZ (Yttria-Stabilized Zirconia), titania, and titanium through the EPD (ElectroPhoretic Deposition) technique. Two oxide coated surfaces (i.e., YSZ and titania) appeared to have a higher CHF enhancement than a titanium-coated surface, which may be due to the improved surface wettability of the oxide layer. Based on both studies, the formation of the oxide layer on the nuclear fuel cladding surface of zircaloy may result in increasing the CHF. However, considering a practical approach to a nuclear reactor application, the techniques previously introduced may not be easy to be applicable to the nuclear fuel cladding owing to their complexity and high cost. Hence, more convenient and cost-effective processes for the CHF enhanced surfaces need to be developed.

In general, the normal and accident operating conditions of a nuclear reactor are under high temperature. In such a case, the nuclear fuel cladding undergoes the surface change, and the oxide layer can be formed. For the prediction and analysis of thermal-hydraulic performance in a nuclear reactor core, the previous correlations are used. In such a case, the oxidation effect on nuclear fuel cladding should be considered. In other words, the previous CHF correlations should be assessed and examined using the experimental results of not a fresh zircaloy surface but an oxidized one, to ensure the thermal margin and safety of a nuclear reactor core. Therefore, the experimental data using the oxidized zircaloy surfaces need to be provided quantitatively.

In this paper, the CHF of oxidized zircaloy surfaces in saturated water pool boiling is investigated. Three kinds of oxidized zircaloy surfaces are prepared together with a non-treated (i.e., fresh) surface, and their water contact angle, the key factor in determining the CHF, is provided. CHF performances are tested and discussed, and then, the previous correlations are assessed and compared, based on the experimental data.

### 2 DESCRIPTION OF EXPERIMENT

In Fig. 1, a schematic diagram of the experimental set-up for pool boiling is shown. A glass chamber of 160 mm (L)×50 mm (W)×150 mm (H) was prepared with a Teflon cover, which was placed on a hotplate stirrer (WiseStir, MSH-20A). In the Teflon cover, an auxiliary heater, copper electrodes, a reflux condenser, and thermocouples were installed. To provide
additional heating, an auxiliary cartridge heater of 200 W and 9.525 mm (3/8 inch) in diameter was used, and amount of power was supplied to it by the variable AC (Alternating Current) autotransformer. The hotplate stirrer and the auxiliary cartridge heater were operated to heat up and maintain the saturated temperature of the water. The water temperature was measured using a T-type thermocouple 3.175 mm (1/8 inch) in diameter, and a reflux glass condenser and temperature controller (JeioTech, RW-1040G) were used to condense the vapor generated from the boiling chamber. The copper electrodes connected to the DC (Direct Current) power supply (Agilent, N8754A, 20V×250A) were mounted on the Teflon cover to support the test assembly. To measure the current accurately through the test specimen, shunt (250 V and 50 mV) was installed. All voltage and current were collected by a data acquisition system (Agilent, 34972A and VEE software). The temperature was monitored using another data acquisition system (Omega, OM-USB-TC).

![Figure 1: Schematic diagram of pool boiling set-up.](image)

For a test assembly, an insulation bed of 110 mm (L)×40 mm (W)×15 mm (H), made of Teflon, was prepared, and a silt of 85 mm (L)×3 mm (W)×0.45 mm (H) was machined along its center. The test specimen, 85 mm (L)×3 mm (W)×0.48 mm (H) in size, was placed on the slit. Both ends of test specimen were made to be connected to the copper electrodes to apply DC power. 51 mm (L)×3 mm (W) of the surface was exposed for boiling, where the voltage drop was measured to calculate the heat flux. The remaining part of the test specimen was insulated using transparent two-tone epoxy.

Four kinds of test specimens were tested. As a non-treated specimen, the zircaloy surface was mechanically polished using an ultra fine sandpaper of 2000-grit, and then cleaned thoroughly with methanol and pure water. For oxidized specimens, non-treated surface specimens were put into the furnace (NITTO KAGAKU, BMINI-1) set to be the
target temperatures of 300, 450, and 600 °C, respectively, and gradually heated up. The temperature increase rate was about 2–2.5 °C/sec. The furnace maintained at the given temperature condition for 10 min, and then slowly cooled down. Finally, three kinds of oxidized surfaces were simply obtained. In this paper, an acronym is used for the test specimens: NS and OS stand for the Non-treated Surface and Oxidized Surface, respectively. The number with OS indicates the setting temperature of the furnace for oxidation. In other words, OS-300, OS-450, and OS-600 are the surfaces oxidized in a furnace of 300, 450, and 600 °C, respectively.

Heat flux \( q'' \) was calculated by Eq. (1).

\[
q'' = \frac{VI}{LW}
\]  

where \( V \) and \( I \) are the voltage and current measured in the test specimen, respectively, and \( L \) and \( W \) are the length and width of the test specimen for boiling, respectively. Using Eq. (2) [9], the uncertainty of the CHF data was estimated to be within about ± 5%.

\[
\frac{U_{q_{\text{CHF}}}}{q_{\text{CHF}}} = \sqrt{\left(\frac{U_v}{V}\right)^2 + \left(\frac{U_l}{L}\right)^2 + \left(\frac{U_i}{I}\right)^2 + \left(\frac{U_w}{W}\right)^2}
\]  

where \( U \) is the uncertainty of each measurement parameter.

The CHF was determined by the visualization and current measurement. When the CHF occurs, the surface visually glows and the current of the test specimen drastically decreases. After CHF, the film boiling regime, where the vapor film covers the heated surface, was observed.

3 RESULTS AND DISCUSSION

It is known that a hydrophilic (i.e., a small water contact angle) surface can have the advantage of improving the CHF performance [10]. The water contact angles of all specimens were measured using a contact angle analyzer (S.E.O, Phoenix-300 Touch), as shown in Fig. 2. The water contact angles on each specimen were measured three times, and then averaged. The contact angle of the NS specimen appeared at about 58°. However, the OS specimens made the water contact angle smaller. Once the water droplet contacted such specimens, it spread out in an instant. The water contact angles on all OS specimens appeared almost the same as around 10°.

In Fig. 3, the CHF measurement results are shown. For all specimens, the CHF data measured three times were averaged. The NS specimen appeared to have a CHF value of about 1280 kW/m². On the other hand, the OS specimens had larger CHF values of around 1800 kW/m², which achieved the averaged enhancement of about 40 %, as compared with the NS specimen.

The present experiment results were consistent with the previous reports [11-12] in that the oxide layer on the heater surface can improve the CHF. An increase in the CHF of OS specimens with small water contact angles can be explained by the macrolayer, and hot and dry spot theories. In other words, the OS specimens may have the thicker macrolayer and promote the rewetting process on the heated surface with hot and dry spots, and consequently, lead to increase the CHF.
Here, it is quite meaningful to compare the CHF enhancement of the present experimental data with the previous report using the specially treated zircaloy surface [7]. Interestingly, the OS surfaces appeared to have a comparable CHF enhancement. The zircaloy surface with a water contact angle of around 10°, which was specially fabricated by the anodizing technique and had a close water contact angle with the present OS specimens, appeared to have around 30–50 % enhancement [7]. This was a similar value to about 40 % obtained by the present OS specimens. In other words, the oxidation process may be a simple, convenient, and cost-effective way to increase the CHF for a practical approach.
The experimental data of the CHF were compared with the previous correlations. Eq. (3) is the well-known CHF correlation proposed by Zuber [13], based on the hydrodynamic theory. It postulates that the flow pattern on a heated surface is a square array of vapor jets leaving the heater surface with a pitch equal to the fastest growing Taylor instability wavelength.

\[ q''_z = \frac{\pi}{24} \rho_{fg}^{1/2} i_g \left[ g \left( \rho_i - \rho_g \right) \right]^{1/4} \]

where \( \rho, i, \sigma, \) and \( g \) indicate the density, enthalpy, surface tension, and acceleration of gravity, respectively. The subscripts \( g, f, \) and \( fg \) are the vapor, liquid, and latent heat of vaporization, respectively.

Moissis and Berenson [14] took account of the lateral interaction of the vapor columns and Taylor-Helmholtz instability at the interface between the vapor flow columns and liquid flow, and proposed the CHF correlation of Eq. (4).

\[ q''_{MB} = 0.18 \frac{\rho_{fg}^{1/2} \left( \frac{\rho_i + \rho_g}{\rho_i \rho_g} \right)^{1/2} \left[ \sigma_g \left( \rho_i - \rho_g \right) \right]^{1/4}}{1 + 2 \left( \rho_g / \rho_i \right)^{1/2} + \left( \rho_g / \rho_i \right)} \]

Kandlikar [15] modeled the CHF correlation considering the heated surface condition through adapting the contact angle as an important parameter. He developed the theoretical model of Eq. (5) using the balance of the recoil force and the surface tension on the heated surface. He mentioned that evaporation at the liquid-vapor interface of a bubble induces a parallel force to the heated surface, which is an essential factor to determine the CHF. When this force exceeds the retain forces (e.g., from gravity and surface tension), the vapor in the bubble spreads over the heated surface, and consequently, the CHF can be initiated.

\[ q''_K = i_g \rho_{fg}^{1/2} \left( \frac{1 + \cos \beta}{16} \right)^{1/2} \left[ \frac{2}{\pi} + \frac{\pi}{4} \left( \frac{1 + \cos \beta \cos \phi}{\left[ \sigma_g \left( \rho_i - \rho_g \right) \right]^{1/4}} \right) \right] \]

where \( \beta \) and \( \phi \) are the receding contact angle and inclination angle, respectively.

Another CHF correlation considering the effect of contact angle, proposed by Kirishenko and Cherniakov [16], is available as below.

\[ q''_{K&C} = 0.171 i_g \rho_{fg}^{1/2} \left[ \sigma_g \left( \rho_i - \rho_g \right) \right]^{1/4} \left( \frac{1 + 0.324 \times 10^{-3} \theta^2}{0.018 \theta} \right)^{1/4} \]

Figure 4 shows a comparison of the measured CHF data with previous correlations. The present CHF data decreased with an increase in the contact angle, and this trend was consistent with the previous correlations considering the contact angle, proposed by Kandlikar [15], and Kirishenko and Cherniakov [16]. However, the Kirishenko and Cherniakov [16] correlation over-predicted the experimental data. On the other hand, the Zuber [13] and Moissis and Berenson [14] correlations, developed by the hydrodynamic instability theory, predicted the CHF values of all specimens to be the same. This is because they do not take into account the heater surface condition (e.g., contact angle). Among the correlations tested, Kandlikar’s [15] correlation was in good agreement with the present measurement data of the OS specimens as well as the NS specimen within a reasonable degree of accuracy.
Figure 4: Comparison of measured CHF data with previous correlations.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation (NRF) funded by the Korean government (MSIP) (NRF-2012M2A8A5025824).

REFERENCES


