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Measurement of Nucleate Pool Boiling Heat Transfer Limit using Fuel Cladding Material

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1. Introduction

Nucleate pool boiling is known to be an 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. However, the nucleate boiling regime is limited by a certain heat flux condition, the so-called CHF (Critical Heat Flux). After the CHF point, the heated surface is covered with a vapor blanket, and the surrounding liquid can't reach the heater surface. 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.

Zircaloy has been widely used as a fuel cladding material of light water reactor for more than three decades because it has a lower neutron absorption cross-section and cracking rate. Recently, HANA-6 has been developed in KAERI (Korea Atomic Energy Research Institute) as the advanced fuel cladding for high burn-up fuel [1]. Generally, under the normal and accident operating conditions of a nuclear reactor, the nuclear fuel cladding of zirconium based alloys undergoes the surface change, and the oxide layer can be formed. In such a case, the previous CHF correlations should be assessed and examined using the experimental results for not a fresh zircaloy surface but an oxidized one, to predict and examine the thermal margin and safety of a nuclear reactor core. Therefore, the experimental data using the oxidized zircaloy surface need to be provided quantitatively.

In this paper, the CHF in saturated water pool boiling is measured and discussed using the specimens of zircaloy-4, HANA-6, and oxidized zircaloy-4 in high temperature air environment.

2. Test preparation

Figure 1 shows a schematic diagram of the experimental set-up for pool boiling. The experimental facility and the test assembly for testing were described in detail in Ref. [2]. The test specimen was prepared to be 85 mm (L)×3 mm (W)×0.48 mm (H) in size. Both ends of test specimen were connected to the copper electrodes to apply DC (Direct Current) power, and 51 mm (L)×3 mm (W) of the surface was exposed for boiling.

Three kinds of test specimens were tested. The zircaloy-4 and HANA-6 specimens were mechanically polished with sandpaper of 2000-grit. The compositions of zircaloy-4 and HANA-6 specimens are shown in Table. 1 [1]. For oxidized specimen, a plain zircaloy-4 specimen was put into the furnace (NITTO KAGAKU, BMINI-1) set to be 300 °C. The temperature increase rate was about 2–2.5 °C/sec. The furnace maintained at the given temperature condition for 10 min, and then naturally and slowly cooled down.

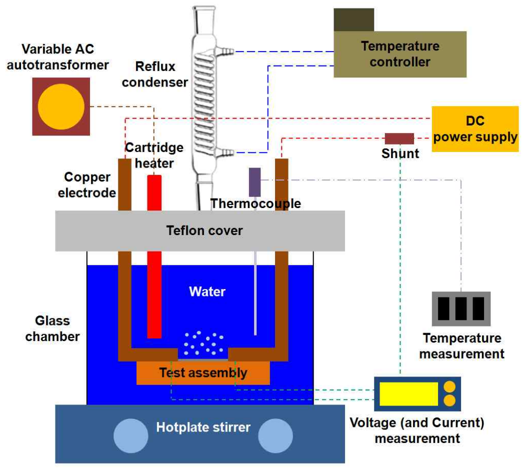

Fig. 1 Pool boiling test facility [2].

Table 1 Composition of test specimens [1].

Specimen	Zircaloy-4	HANA-6
Nb	-	1.1
Sn	1.5	-
Fe	0.2	-
Cr	0.1	-
Cu	-	0.05
O	0.12	0.12
Zr	Bal.	Bal.

3. Results

Figure 2 displays the CHF measurement data. The zircaloy-4 specimen was a similar CHF value to HANA-4 specimen, as considering the measurement uncertainty and reproducibility of tests. This is because both specimens mostly consist of zirconium. However, the oxidized zircaloy-4 specimen achieved the higher CHF, compared with the others. The enhancement of CHF by oxidation was about 40 %, which can be caused by the change in surface condition.

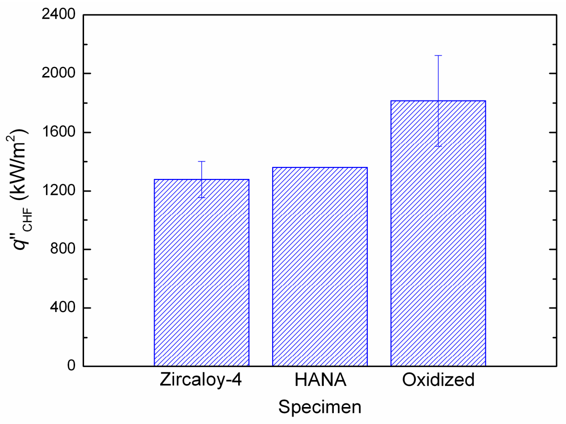

Fig. 2 CHF measurement data.

It is known that the water contact angle is an important parameter to determine the CHF [3]. In Fig. 3, the water contact angle measured on plain zircaloy-4 and HANA-6 specimens are shown, which were almost same as around 57–58°. On the other hands, oxidized specimen exhibited a smaller water contact angle of about 10° (but not shown in this paper). Once a water droplet touched on the surface, it spread out instantly.

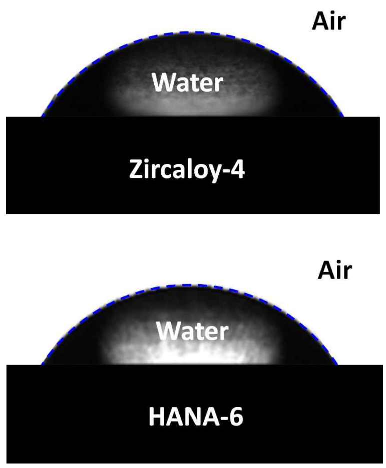

Fig. 3 Water contact angles of zircaloy-4 and HANA-6 specimens.

The water contact angle of specimen described well the trend of present experimental data: Zircaloy-4 and HANA-6 specimens appearing the similar water contact angles exhibited the similar CHF values. On the other hand, increase in CHF of oxidized specimen is caused by the small water contact angle. Hydrophilicity of oxidized surface may contribute the promoting the rewetting process with hot and dry spots on heater surface.

The well-known correlation considering the contact angle, Eq. (1), proposed by Kandlikar [4] compared with the present experimental data of the zircaloy-4, HANA-6, and oxidized specimens.

$$q''_{\mathrm{K}} = i_{\mathrm{fg}}\rho_{\mathrm{g}}^{1/2}\left(\frac{1+\cos\beta}{16}\right)\left[\frac{2}{\pi}+\frac{\pi}{4}(1+\cos\beta)\cos\phi\right]^{1/2} \times\left[\sigma g\left(\rho_{\mathrm{f}}-\rho_{\mathrm{g}}\right)\right]^{1/4} \quad (1)$$

where, where ρ_g, ρ_f, i_{fg}, σ, and g indicate the vapor density, liquid density, latent heat of vaporization, surface tension, and acceleration of gravity, respectively. In addition, β and ϕ are the receding contact angle and inclination angle, respectively. Kandlikar's [4] correlation predicted the CHF to be about 1100 kW/m^2 for zircaloy-4 and HANA-6 specimens, and about 1560 kW/m^2 for oxidized zircaloy-4 surface, which agreed with the present experimental data within a reasonable accuracy.

4. Conclusions

The CHF of zircaloy-4, HANA-6, and oxidized surface was tested. Zircaloy-4 and HANA-6 had a similar CHF performance. This is because both are the zirconium based alloys, and appear the almost same water contact angle. On the other hands, the oxidized specimen became to be higher CHF than plain zircaloy-4 and HANA-6 specimens, due to smaller water contact angle (i.e., good hydrophilicity of specimen). The Kandlikar's (2001) correlation reasonably predicted the present experimental data.

Acknowledgements

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