Effects of chromium-based accident tolerant fuel coating on rewetting temperature under reflood condition

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1. Introduction

The idea to add an accident tolerant fuel (ATF) coating on conventional cladding system has been widely studied to enhance the oxidation resistance during postulated accidents [1]. Chromium, among many candidate materials, is considered most promising due to its strong oxidation resistance and stability at high temperature. As the surface modification by the ATF-coating inevitably affects the surface characteristics of heat transfer surface, it may alter some important safety parameters such as critical heat flux or rewetting temperature.

The rewetting temperature is an important safety parameter below which allowing the efficient cooling by direct liquid-solid contact. Many studies have investigated the rewetting temperature, or minimum film boiling temperature, of the ATF materials [2-4]. However, they could not elucidate how the rewetting temperature is affected under the presence of flow and simulated decay heat. Thus, the ATF coating effect on rewetting temperature has not been yet identified under realistic reflood condition.

The objective of this study is to experimentally investigate the how the rewetting temperature is affected by the Cr-coating under the presence of flow. Test specimen was designed with an internal heating element and a ceramic pellet to simulate the fuel rod. Changing the coolant subcooling and injection rate, the rewetting temperature of the bare and Cr-coated surfaces was analyzed.

2. Experiment

2.1 Experiment facility and test specimen

The experiment facility and the test specimen utilized in this study are shown in Fig. 1. The facility consists of a reflood chamber, a centrifugal pump, a preheater, and a coolant tank. The test specimen was designed to simulate the nuclear fuel rod consisting of Inconel 600, Al_2O_3 pellet, and a stainless-steel grade 316L tube as a cladding. The heat generation was carried out by applying DC power to the heating element. The cladding was electrically isolated to prevent any heat generation from the cladding itself. Three thermocouples (TCs) with sheath diameter of 0.5 mm were installed at the grooved lines in Al_2O_3 pellet to measure the temperature right below the cladding surface. The axial location of the TCs were 25, 50, and 75 mm from the bottom of effective heated length.

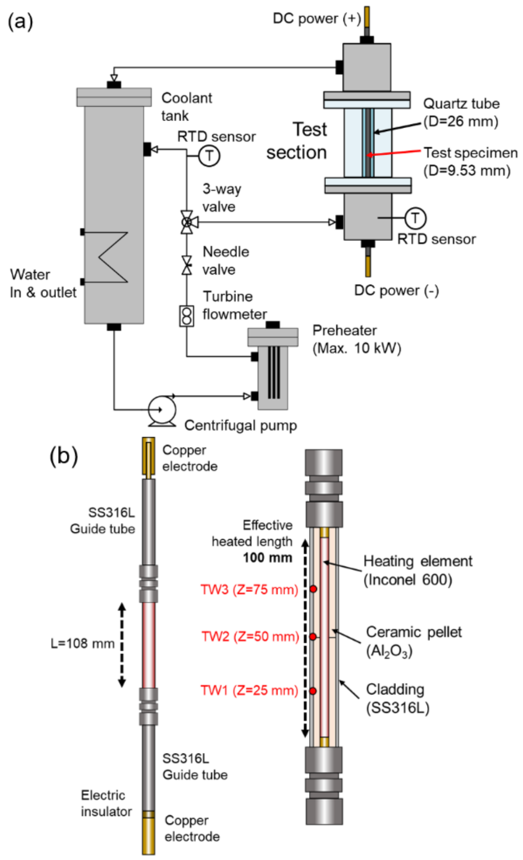


Fig. 1. Schematics of (a) the experiment facility and (b) the test specimen. Red circles indicate the position of the TCs.

2.2 Surface modification

To secure similar baseline surface roughness profile for the bare and Cr-coated specimens, the surface was initially grounded by a sandpaper with a grit number of 800. The Cr-coating on the cladding was carried out utilizing DC magnetron sputtering technique. As shown in Fig. 2, ionized argon (Ar+) particles are drawn to the Cr target assembled with a magnet. The sputtered Cr atoms are deposited onto the slowly rotating cladding surface below. Densely packed Cr layer without any porous structures was observed in scanning electron microscope (SEM) images as shown in Fig. 3. Detailed sputtering conditions is presented in study of Son et al. [5]. Due to particulate Cr clusters formed in nanoscale, the Cr-coated surface shows superhydrophilic characteristics with zero contact angle.

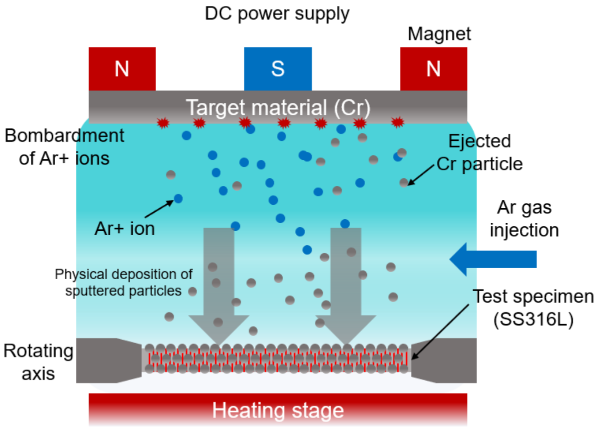


Fig. 2. Schematic of DC magnetron sputtering technique.

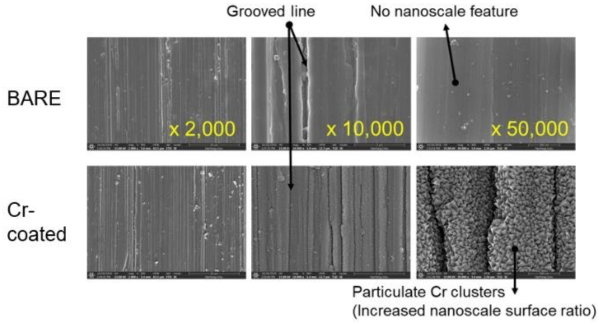


Fig. 3. SEM images of the bare and Cr-coated surfaces.

2.3 Experimental conditions and procedure

The experiments were carried out varying the injection rate and the subcooling of coolant. From the reflood condition of PWR summarized in Cho et al. [6], the experiment conditions were determined as shown in Table I. Linear heat generation rate was chosen to simulate the decay heat of typical PWR (6~8% of normal operation). Pressure was maintained at atmospheric pressure.

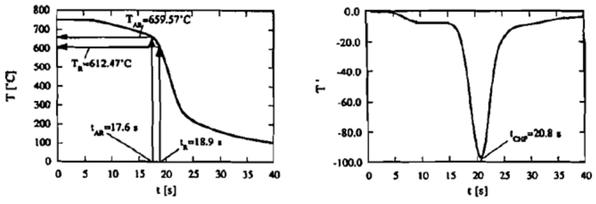
Table I. Test matrix for the experiments.

Parameter [Unit]	Value
Linear heat generation rate [kW/m]	1.55 (Constant)
Coolant subcooling, ΔT_{sub} [°C]	0 / 20 / 40
Coolant injection rate, U [mm/s]	25 / 35 / 45

The experiment procedure is as follows. First, the coolant was degassed at saturation temperature while circulating the by-pass loop for 2 hrs. Then, the coolant flow rate and subcooling was set to experiment condition. When the coolant reached the condition, the DC power was applied to copper electrodes. The reflood of coolant was initiated when the temperature measured by the TC at the center reaches 740°C. The coolant injection and heat generation were maintained until all the temperature measurement recordings reach steady state. Each condition was investigated at least 3 times to check the repeatability.

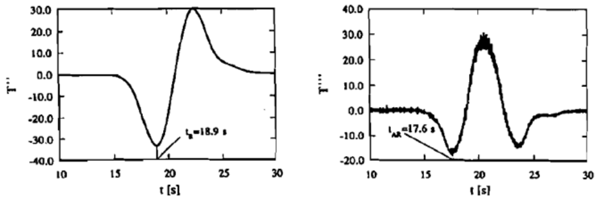
2.4 Data reduction

The rewetting temperature was determined from the temperature history of TC at the center. As shown in Fig. 4, Filipovic et al. [7] suggested method to determine rewetting temperature from the quench curve by obtaining 1st, 2nd, and 3rd derivatives of temperature measurement. The first minimum values of each derivative correspond to the temperature when maximum heat flux appears, when the gas-liquid-solid triple interface is formed, and when onset of rapid cooling occurs, respectively. In this study, the temperature for 3rd derivative was chosen as the rewetting temperature.



Quenching curve

1st derivative



2nd derivative

3rd derivative

Fig. 4. Methodology to determine rewetting temperature from the temperature history [7].

3. Results and discussions

3.1 Effects of coolant subcooling and injection rate on quench curve

Figure 5 shows the quench curves for the bare and the Cr-coated surface with varying coolant subcooling and injection rate of 25 mm/s. It is noted that there is no noticeable difference in quench performance between the bare and Cr-coated surfaces despite the superhydrophilic characteristic of the Cr-coated surface. For both surfaces, the film boiling heat transfer rate and the rewetting temperature were significantly enhanced with the increase in cooling subcooling. From these results, we concluded that there is no difference between the bare and Cr-coated surfaces for the given experimental range. Thus, the effect of injection rate on the rewetting temperature was investigated for the bare surface only.

The effect of coolant injection rate on the quench curve is shown in Fig. 6. The coolant injection rate showed negligible effect on film boiling and single-phase convection regimes. The rewetting temperature showed slight increase with increasing coolant injection rate.

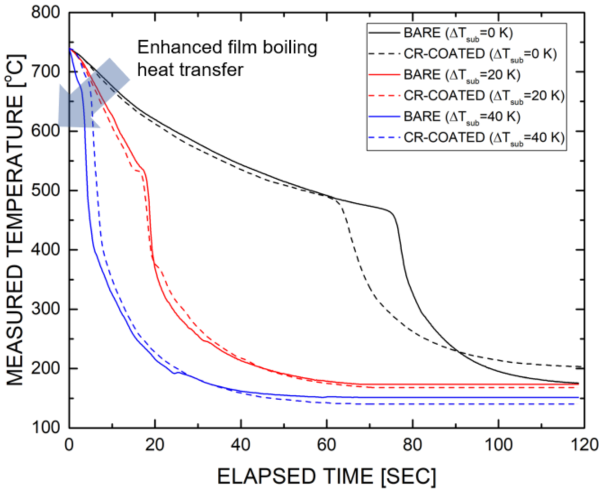


Fig. 5. Quench curves of the bare and Cr-coated surfaces with different coolant subcooling

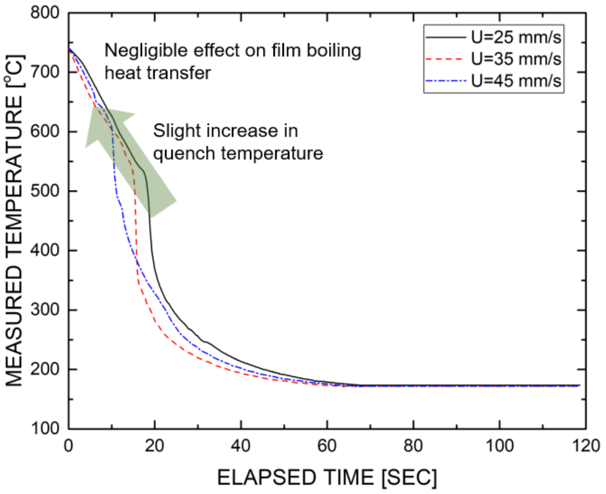


Fig. 6. Quench curves of bare surface with different coolant injection rate for coolant subcooling of 20°C.

3.2 The rewetting temperature

The rewetting temperature was analyzed using the methodology suggested in section 2.4. Figure 7 shows the comparison of rewetting temperature for the bare and Cr-coated surface under injection rate of 25 mm/s. It shows linear increase with increasing coolant subcooling. The rewetting temperature of the Cr-coated surface do not show noticeable change compared to the bare surface for the coolant subcooling of 0 and 20°C. For higher coolant subcooling, however, the Cr-coated surface shows higher rewetting temperature about 40°C than that of bare surface. As the thickness of the vapor film decreases with increasing subcooling, the intermittent liquid-solid contact occurs more frequently at higher subcooling. Due to superhydrophilic characteristic of Cr-coated surface, the liquid can maintain longer contact by means of capillary wicking through the micro/nanostructures.

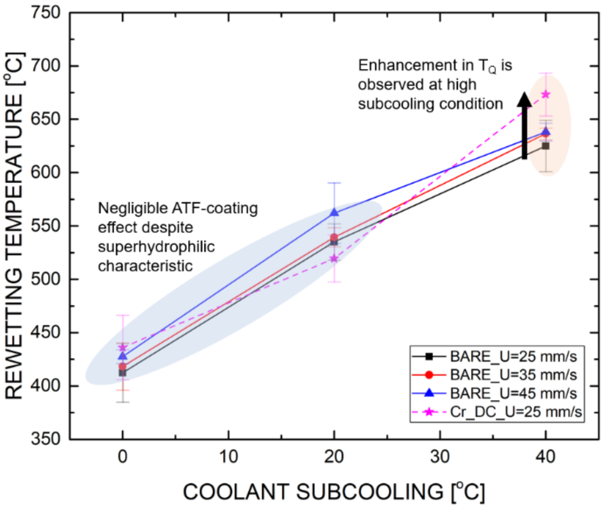


Fig. 7. Rewetting temperature of the bare and Cr-coated surfaces with different coolant subcooling and injection rate.

The intermittent liquid-solid contact appearing in Cr-coated surface at high subcooling not only affects the rewetting temperature, but also the quench front propagation velocity. Figure 8 shows the high speed video images of Cr-coated surface at coolant subcooling of 40°C. While main quench front propagates from the bottom, there exists local quenched area ahead of main quench front. The local quenched area then expands radially accelerating the propagation speed of main quench front. Comparing to the bare surface at same condition, the Cr-coated surface shows 100% increase in quench front velocity.

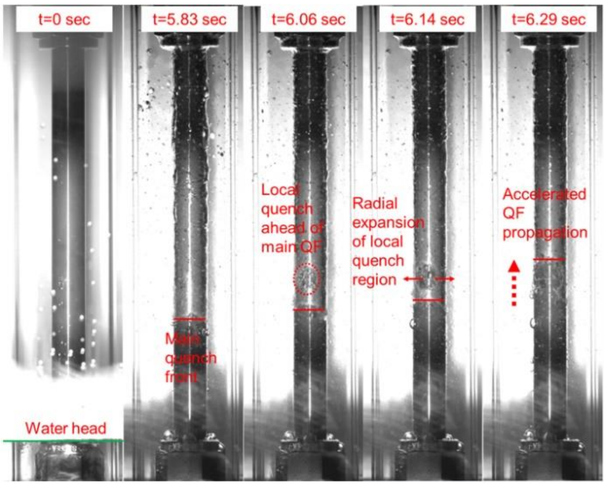


Fig. 8. High speed video of Cr-coated surface at high coolant subcooling of 40°C.

3.3 Comparison of rewetting temperature with previous models

Many researchers have proposed different models to predict the rewetting temperature. Among those models, models that include the effect of injection rate and surface condition were compared with the experiment data. Kim and Lee [8] utilized Buckingham's π-theorem to obtain empirical correlation for rewetting temperature from the over 400 experiment data sets. Carbajo [9] developed a new correlation from the review of each effect of variables including injection rate, subcooling, and surface condition. Detailed equations are not shown in here.

Figure 9 shows the comparison results of rewetting temperature with our experiment data. While the Carbajo's model significantly underpredicts the experiment data, the Kim and Lee' model slightly overpredicted the data. As Kim and Lee model is valid for the coolant subcooling range of 10 to 80°C and mass flux of 100 to 400 kg/m^2-sec (This study: 23~45 kg/m^2-sec), the overprediction and significant deviation at saturation condition is deemed reasonable.

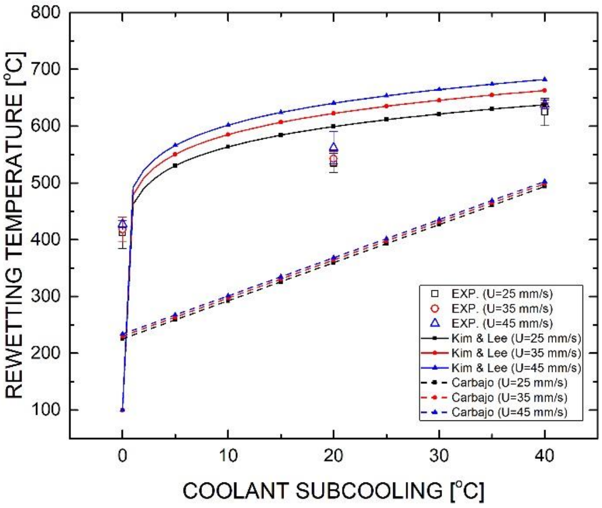


Fig. 9. Comparison of rewetting temperature with existing models.

4. Conclusions

In this study, the rewetting temperature of Cr-coated cladding surface under flow condition was investigated. Experiments were carried out using a specially designed heater design capable of simulating decay heat. The rewetting temperature was analyzed from the derivatives of the quench curve. Results showed that the Cr-coating on the cladding had negligible effect on the rewetting temperature except under higher subcooling condition. Due to the thin vapor film, the local intermittent liquid-solid contact was observed which enhanced the rewetting temperature. The contact also accelerated the quench front propagation velocity due to the local quench phenomenon ahead of main quench front. The existing models that include the effects of flow and surface condition did not show good agreement with the experiment data. As the models were not developed in the range of reflood condition in PWRs, some modification is inevitable to accurately evaluate the rewetting temperature for nuclear applications.

ACKNOWLEDGEMENT

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