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Experimental Study of Pool Quenching with Zircaloy and CrAl-Coated Claddings

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1. Introduction

The accident in Fukushima nuclear power plant (NPP) showed hydrogen explosion resulting from the metal(fuel cladding) and water reaction. The zircaloy cladding generates large amount of hydrogen and reaction heat at high temperature in the event of NPP accidents. The zircaloy cladding is widely used in commercial NPPs. Hence, the Korea Atomic Energy Research Institute (KAERI) has developed a CrAl-coated cladding for accident tolerant fuel (ATF) candidate in order to suppress the hydrogen generation [1]. It is therefore necessary to verify the cooling performance of CrAl-coated cladding in accident condition.

We conducted a pool quenching experiment to simulate a high temperature situation in postulated accidents of NPP using zircaloy-4 and CrAl-coated claddings. This paper presents quenching curves and visualization for zircaloy-4 and CrAl-coated claddings at low and high subcooling conditions.

2. Experimental Setup and Method

2.1 Experimental Setup

The experimental setup, as shown in Fig. 1, consisted of a radiant furnace, air slide, quenchant pool, testing cladding tube, hot plate, data acquisition system(DATA TRANSLATION DT9839), video camera(Canon VIXIA HFR62), surface roughness tester(Mitutoyo SJ-201) and personal computer. The testing cladding tube was heated in the furnace to a specified temperature. The air slide transported the heated cladding tube into the quenchant pool. The video camera recorded the quenching process and data acquisition system recorded the signals from the thermocouples.

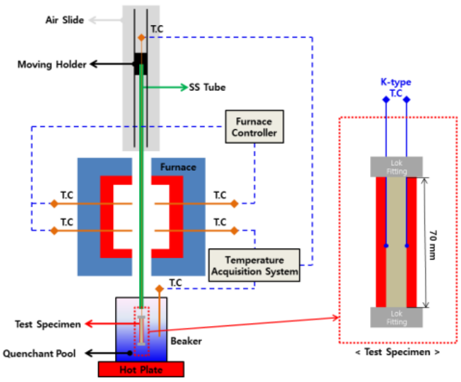


Fig. 1. Experimental Setup

2.2 Method

We prepared two kinds of specimens, e.g., Zircaloy-4 and ATF. The DI(de-ionized) water is used as coolants (50 and 100℃). The specimens were heated up to the 600 ℃ in the furnace and then dropped into the quenchant pool and then wait until the specimen reaches the temperature of the coolant. We repeated these steps three times. Temperature change throughout the quenching process was measured by K-type thermocouples attached between tube and ceramic, i.e., inner surface of tube specimen and recorded via a data acquisition system. Also, the surface roughness of specimens was measured before and after the experiment.

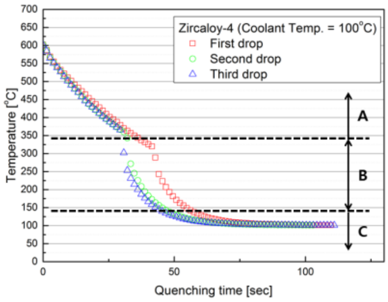
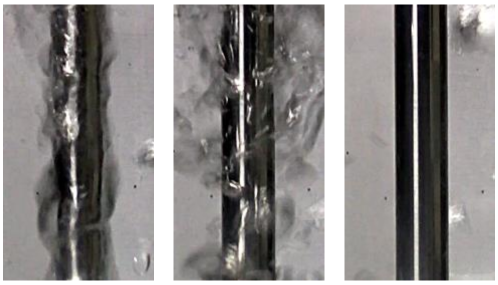


Fig. 2. Quenching curve of Zircaloy-4 tube
(Coolant temperature : 100℃)



(a) (b) (c)

Fig. 3. Quenching visualization under the saturated water condition (i.e., subcooling ~ 0℃)

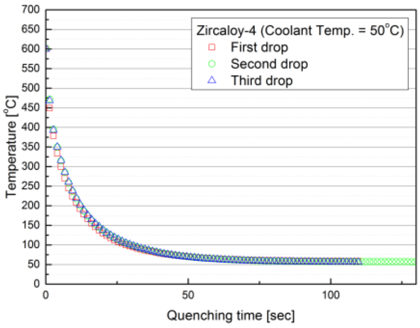
3. Results and Discussion

Quenching curve of zircaloy-4 tube in 100 ℃ coolant (low subcooling) is shown in the Fig. 2. Generally, the quenching curve represents a reverse process of the boiling curve. At region A, the temperature of cladding tube is so high that DI water is vaporized at the surface of the cladding tube and a thin vapor film surrounds the hot cladding tube. Cooling occurs by conduction and radiation through the vapor film, the cooling rate is relatively slow through this film boiling stage (Fig. 3(a)). At region B, this stage starts when the cladding tube has cooled to a temperature at which the vapor film is no longer stable. Wetting of the metal surface by the coolant and violent boiling occurs. Heat is removed from the cladding tube very rapidly. This is the fastest stage of cooling, i.e., transition to nucleate boiling (Fig. 3(b)). At region C, this stage starts when the surface temperature of the cladding tube reaches the boiling point of the coolant. Vapor no longer forms, so cooling is by free convection through the coolant. The rate of cooling is slowest in this stage (Fig. 3(c)).

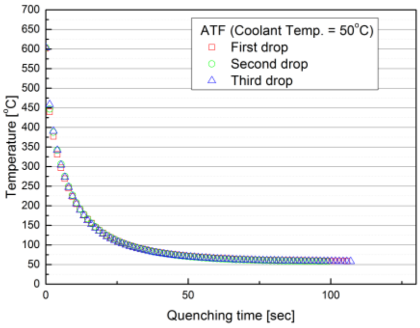
As the quenching progresses (Fresh - two - three times), the cooling speed increases and the oxidized layer grew. Generally, when the oxide layer is formed, the surface wettability is increased and then the heat transfer will be improved but this effect becomes insignificant after three times(Fig. 2) [2].

Quenching curve of the ATF cladding in 100 ℃ coolant is shown in the Fig. 4. In ATF case, as the quenching progresses (Fresh - two - three times), the cooling speed is almost same unlike the zircaloy-4 case. Because the ATF cladding suppresses oxidized layer formation the wettability appears to be constant during quenching progress therefore the heat transfer effect by the oxidized layer does not appear.

When the coolant temperature is 50 ^{o}C (high subcooling), the film boiling appeared for about 0.2 seconds and changed to nucleate boiling and natural convection in sequence as shown in Fig. 5. Because increasing degree of subcooling reduces the quenching time rapidly [3].



(Zircaloy-4)



(ATF)

Fig. 5. Quenching curve (Coolant temperature : 50 ℃)

Fig. 6 compares the quenching curves for the Zircaloy-4 and ATF claddings at low subcooling condition (coolant temperature of 100 ^{o}C). The ATF cladding appears to slightly increase quenching time with respect to the Zircaloy-4 cladding. It should be noted that the surface roughness of ATF cladding specimen is smaller than the Zircloy-4 specimen. Hence, the Zircloy-4 cladding with bigger roughness will increase the surface wettability which eventually reduces the quenching time by improving heat transfer

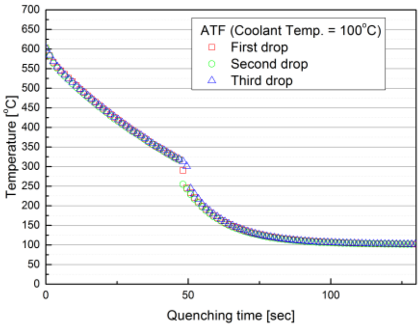


Fig. 4. Quenching curve of ATF cladding
(Coolant temperature : 100 ℃)

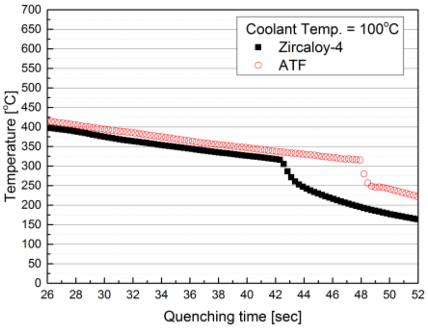


Fig.6. Comparison between Zircaloy-4 and ATF quenching curve of fresh specimen
(Coolant temperature : 100℃, 26 ~ 52 second)

on hot cladding surface. In the near future, the effect of surface roughness will be investigated.

3. Conclusions

The cooling performance of Zircaloy-4 and ATF claddings was examined by quenching experiment which simulates reactor accident condition. The pool quenching experiment was conducted at low and high subcooling conditions for the cladding surface temperature of 600 ^{o}C. The vapor film occurs at low subcooling condition but disappears at high subcooling. The ATF cladding showed an insignificant effect of surface oxidation on quenching heat transfer. The bigger surface roughness of cladding appears to reduce the quenching time by enhancing the boiling heat transfer. It is necessary to investigate the effect of surface roughness on the quenching performance and the heat transfer mechanism in the future.

ACKNOWLEDGMENTS

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