A Study of Transient Cooling Heat Transfer for CrAl-Coated Accident Tolerant Fuel Claddings

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1. Introduction

The severe accident at Fukushima nuclear power plants consequently demanded intensive reviews on the safety systems and technologies of nuclear power plants. As a result, Accident Tolerant Fuel (ATF) concepts were presented as a solution to eliminate potential danger, or at least extend accident tolerance hydrogen explosion significantly.

The KAERI has developed and currently been testing a CrAl-coated type ATF for a next-generation fuel cladding [1]. Both inertness and robustness of the alloy layer increases stability in extremely severe environments. However, more studies and thorough tests are still required to ensure design compatibility.

We conducted a small set of quenching experiment to simulate a Loss-of-Coolant Accident (LOCA) with both ordinary zircaloy-4 and CrAl-coated claddings.

2. Experimental Setup and Method

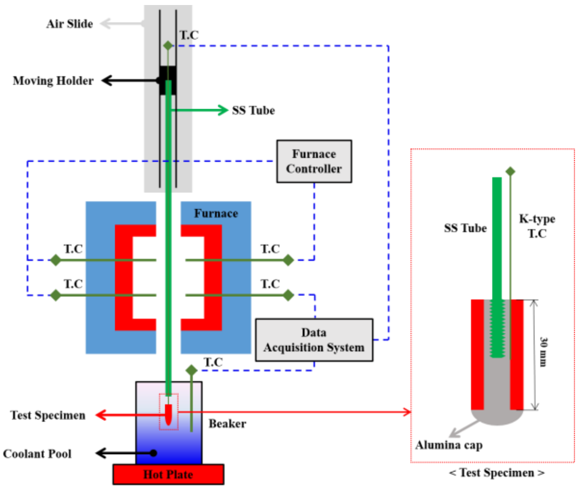

Fig. 1. Experiment setup

An experimental setup was prepared as illustrated in the Fig 1. Specimens were heated up to the 600 ℃ in the furnace and then dropped into the coolant pool. Temperature change throughout the quenching process was measured by a K-type thermocouple attached inside the specimen and recorded via a data acquisition system.

Type of claddings and temperature of coolant were set as control parameters. Ordinary zircaloy-4 and CrAl-coated claddings were cut to 3 cm in length as specimens. Saturated and room-temperature (100 ℃ and 20 ℃) deionized (DI) waters were prepared as coolants. The experiments were repeated for ten times for each condition to ensure repeatability.

Surface roughness of specimens was measured by a surface roughness tester, Mitutoyo SJ-210 in ISO 1997 method.

3. Results and Discussion

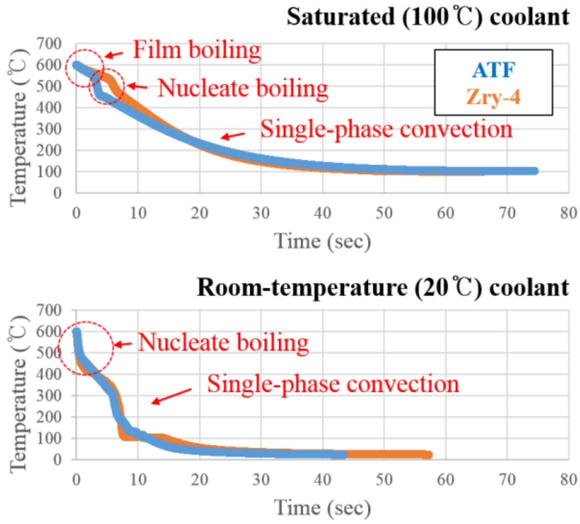

Fig. 2. Temperature change during the quenching process for saturated coolant (top) and room-temperature coolant (bottom)

Temperature change during the experiments is shown in the Fig. 2. Each curve represents average of 10 repeated experiments.

Generally, quenching curve represents a reverse process of the boiling curve; The specimen undergo film boiling, transition boiling, nucleate boiling and single-phase convection stage in sequence.

In a macroscopic view, cooling to the equilibrium state took similar time in both types of specimen, ~ 50 seconds for saturated coolant and ~ 30 seconds for room-temperature coolant.

However, cooling rate of ATF in both film boiling stage (~17.2 ℃ / sec) and nucleate boiling stage (~75 ℃ / sec) were significantly faster than zircaloy-4 (~ 14.3 ℃ / sec and ~ 45 ℃ / sec for each stage) in saturated coolant.

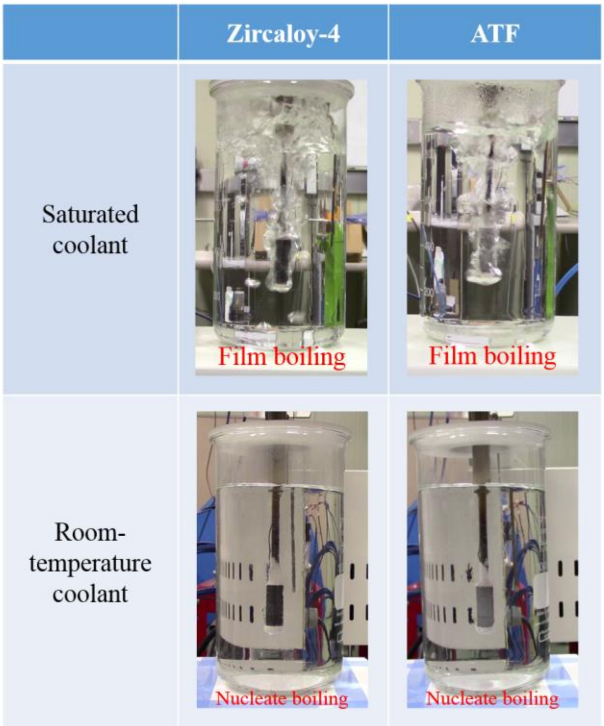

Fig. 3. Boiling stages at t = 0 for each experimental conditions

Quench behaviors at the start of cooling process for each specimens are shown in Fig. 3. No film boiling stage was observed in the room-temperature coolant because the specimen did not have enough heat to vaporize the coolant. However, ATF also showed higher cooling rate in the nucleate boiling (~ 171 ℃ / sec) than zircaloy-4 (~ 94.7 ℃ / sec). The results imply the vapor film on the ATF specimen were thinner and more unstable.

Material	Condition	Trial 1	Trial 2	Trial 3	Average
Zry-4	Bare	0.214	0.261	0.214	**0.230**
	100 ℃	0.251	0.249	0.261	**0.254**
	20 ℃	0.280	0.254	0.294	**0.276**
ATF	Bare	2.048	2.308	1.883	**2.080**
	100 ℃	2.033	1.810	2.103	**1.982**
	20 ℃	2.179	1.941	2.242	**2.121**

Units in μm

Table I. Surface roughness data of specimens

Surface roughness was measured and the data are shown in Table. I. Roughness of ATF specimen was about ten times higher than normal zircaloy-4. Repeated quenching process caused increase in the roughness, possibly because of microstructure evolution.

Former researches reported that rough surface enhances heat transfer rate in quenching in water and brine because of increased surface area [2]. In addition, the rough surface can capture more microbubbles and provide more activated nucleation sites [3], consequently enables significantly higher heat transfer rate than single-phase convection.

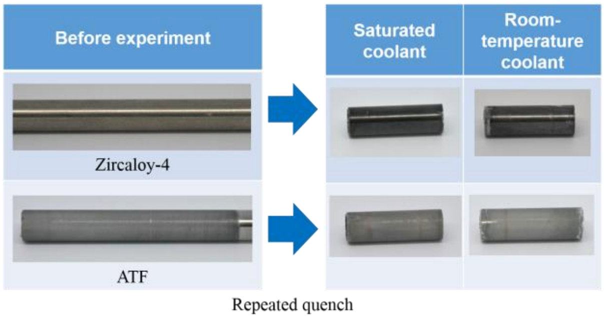

Fig. 4. Surface image of both specimens before (left) and after (right) the quenching experiments.

Macroscopic surface of specimens before and after the experiments are shown in Fig. 4. Repeated heating & cooling cycles caused black oxide layer on zircaloy-4. In contrast, no significant changes were observed in the ATF specimens, which show an excellent resistance against high-temperature oxidation.

In addition, ATF also showed no significant change in surface roughness in Table. I, while the zircaloy-4 cladding resulted in about 10 % increased surface roughness in saturated coolant and 20 % for room-temperature coolant.

This result proves superior inertness of ATF in repeated heating and cooling cycle, in high fuel temperature condition in postulated accidents.

4. Conclusion

Repeated quenching experiments were conducted for both ordinary zircaloy-4 and CrAl-coated ATF tubes. There was no notable difference in cooling time into equilibrium, but the ATF showed significantly enhanced thermal heat transfer rate in both film boiling and nucleate boiling. Measured data implies thinner and more unstable vapor film on the ATF at the transient processes. Also the ATF cladding resulted no notable deterioration in visual observation and surface roughness measurements, which proves superior inertness of the ATF in our experimental conditions simulating postulated accidents.

ACKNOWLEDGEMENTS

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

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