Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18-19, 2017

Tube Ejection Experiment for an APR1400 ICI Penetration Tube under ERVC Condition

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1. Introduction

KAERI has conducted a series of penetration tube failure experiments such as tube ejection and rupture for an APR1400 ICI (in-core instrumentation) tube [1-3] and ICM-GT (in-core monitoring guide tube) of Fukushima Daiichi NPP (nuclear power plant) [4]. They were performed under the condition which the RV (reactor vessel) bottom is cooled by natural convection of air. However, external reactor vessel cooling (ERVC) by water pool is adopted for ARP1400 as a primary severe accident management strategy for IVR (in-vessel retention) of corium. Therefore it is necessary to investigate the penetration tube failure under the ERVC condition, and compare the results with the previous experiments without ERVC. This paper describes the recent experimental investigations on the effect of ERVC on the tube and RV temperature distributions and resulting tube ejection failure for the APR1400 ICI penetration tube.

2. Experimental Methods

2.1 Experimental Setup

APR1400 ICI penetration tube ejection experiment under ERVC condition was performed in a VESTA facility [1-4], where the penetration tube specimen is heated at the same time during melt generation by induction heating. Figure 1 shows an assembly of an APR1400 ICI penetration tube specimen, specimen support, interaction crucible, induction coil, and ERVC channel at the RV bottom. The inside of the ICI tube is empty to allow melt flow after melt pool generation and tube failure, but blocked at the tube end to create a pressure boundary. That is, the inside of the specimen support is maintained at ambient pressure, while the outside is pressurized by compressed air. Thus the pressure and gravitational forces (ejecting forces) act on the ICI tube, which can lead to tube ejection if the tube weld failure occurs and the binding shear force between the RV hole and tube dose not overcome the ejecting forces [5]. There four separate coolant paths through an interaction crucible, induction coil, fix ring and ERVC channel. During melt generation and specimen heat-up, both the RV bottom and tube end are cooled by ERVC coolant.

A charging pattern of a mixture UO_2 and ZrO_2, and the TC (thermocouple) locations for measuring the tube and RV temperature distributions are represented in Fig. 1. 'RV2-RV11' indicate RV temperatures, 'PW1-PW4' ICI tube weld temperatures, 'RVH5-RVH11' RV temperatures near the RV hole, 'P1-P11' ICI tube temperatures. 'K1' is exposed just above the RV surface to represent the RV surface temperature. The numbers labeled with all the TC symbols imply the measuring locations from the RV surface.

2.2 Experimental Conditions

A mixture of UO_2 (70 kg) and ZrO_2 (33 kg) was used as a prototypic corium melt, and a Zr metal ring (0.28 kg) was used as an initiator for induction heating. The materials were charged as shown in Fig. 1. Two holes were made for gas venting during the melt generation. The melt temperature was measured using an optical pyrometer by adjusting a focus on the inside of the ICI tube. In addition, as the tube weld temperature increases rapidly, the supplying and exhausting gas flow rates were controlled to pressurize the tube to induce tube ejection.

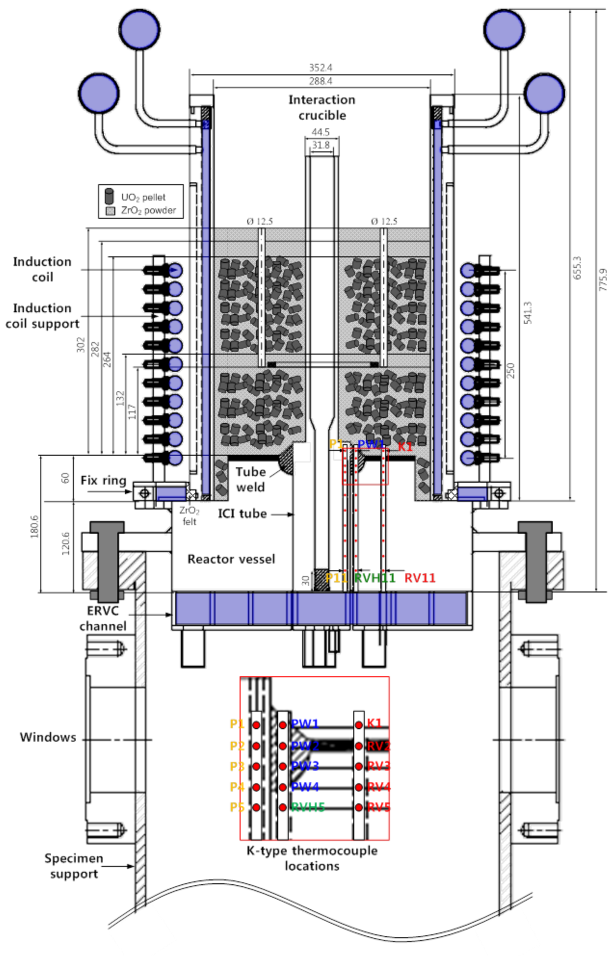

Fig. 1. Experimental setup.

3. Results and Discussion

3.1 Melt Generation and Specimen Heat-up

Figure 2 shows the melt temperature by an optical pyrometer and RV surface temperature ('K1') according to the electrical power supply for induction heating. The power was increased gradually up to about 316 kW for stable melt generation. A Q-factor, a measure for the coupling of melt and induction heating, decreased as the amount of melt increased [6]. As the melt temperature increased above 2600℃, 'K1' increased higher than the maximum measurement limit of K-type TC (~ 1250℃) and then showed arbitrary signal due to TC failure.

As shown in Figs. 3 and 4, the ICI tube temperatures near the RV surface (P1-P5) and its weld (PW1-PW4) showed a sudden increase after 3000 s, and some of them failed after reaching the maximum limit. Therefore, it was estimated that the part near the center of the RV surface was melted and the weld failure occurred. Except near the RV surface, the RV and RV hole displayed generally low temperatures owing to ERVC at the RV bottom, even lower than the previous experiment without ERVC [1]. Based on the ERVC coolant flow rate (~ 2.5 m^3/hr), temperature difference between inlet and outlet temperatures and cooling area of the specimen, the maximum removal heat flux by ERVC was evaluated at about 466 kW/m^2. The pressure difference between inside and outside of the specimen support (i.e pressure acting on the tube) increased up to 2.9 bar. However, despite the weld failure and high ejecting pressure force, the tube ejection failure did not occur in the present experiment.

The temperature difference between the RV hole and ICI tube is shown in Fig. 5. After 3000 s, the RV hole temperatures were lower than the tube for the moment but became almost the same with the tube. That means the thermal expansions between them are not so different, thus the thermal binding shear force would be very low to resist the ejecting forces. A precise calculation of the binding shear force is necessary to estimate the tube ejection failure criteria, which is left as a future work using 'PENTAP plus' code [7].

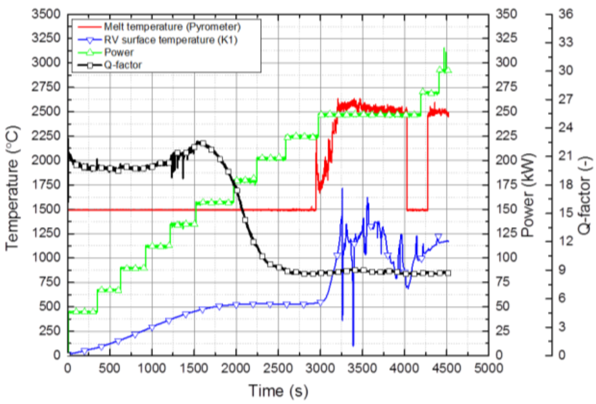

Fig. 2. Melt generation and penetration tube specimen heat-up history along with supplied power.

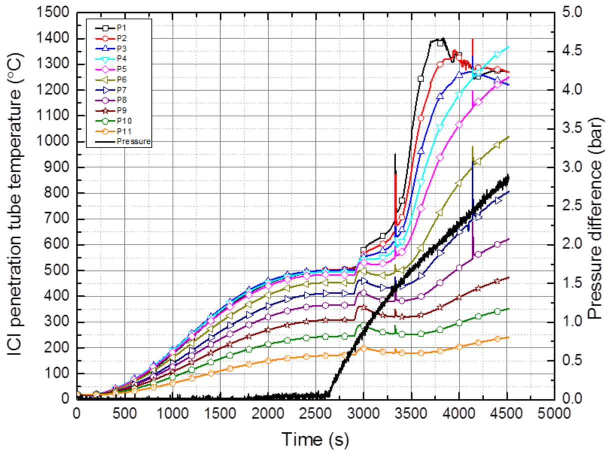

Fig. 3. ICI tube temperature distribution and pressure acting on the tube.

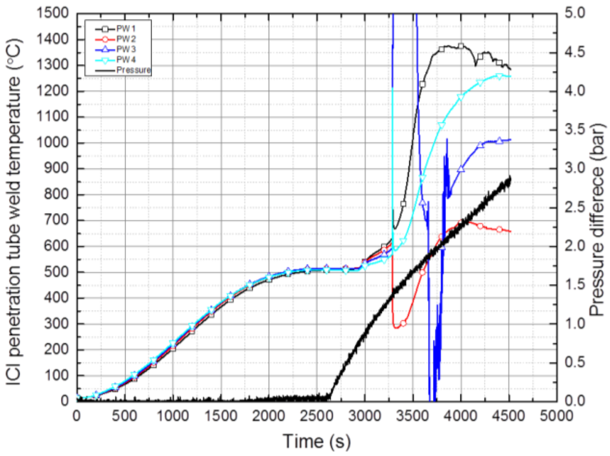

Fig. 4. ICI tube weld temperature distribution and pressure acting on the tube.

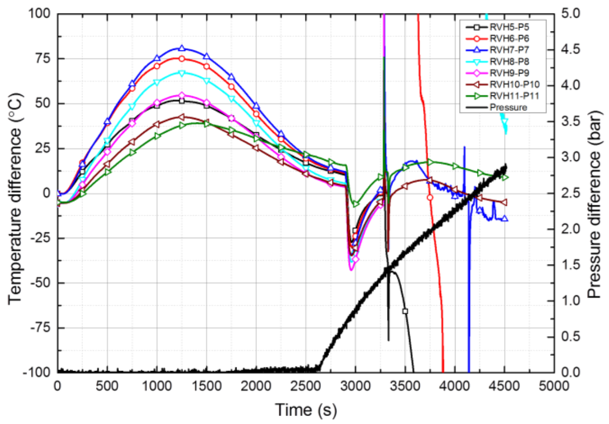

Fig. 5. Temperature difference between the RV hole and ICI tube, and pressure acting on the tube.

3.2 Observations

The configurations of melt ingot and APR1400 ICI penetration tube specimen were shown in Fig. 6. As estimated from Figs. 3 and 4, it was found that the ICI tube above the RV surface and its weld were melted or eroded severely, while the RV and tube below the RV surface remained unmelted owing to ERVC. In addition, it is believed that the melt did not flow inside the ICI tube because the temperature difference between the RV hole and tube was not so big (Fig. 5), and showed almost the same values with the previous experiment without melt penetration inside the tube [1]. Consequently, the ERVC effect on the binding shear force and resulting tube ejection failure might not be significant because the temperature difference between the RV hole and tube remained almost the same regardless of ERVC. This result was estimated in the previous numerical analysis [8]. Nevertheless, it is expected that ERVC could be very effective in preventing the RV failure and tube rupture out of the RV by maintaining low temperatures.

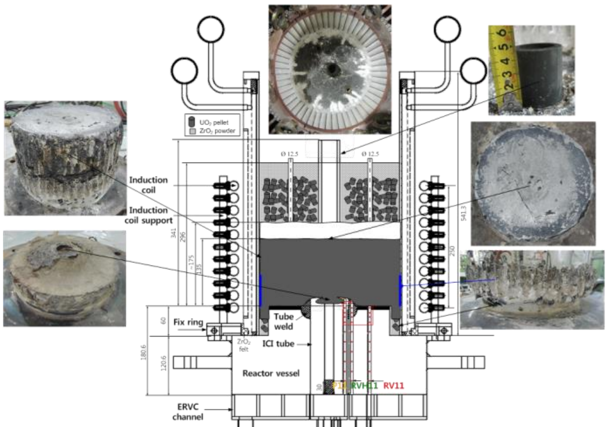

Fig. 6. Configurations of melt ingot and APR1400 ICI penetration tube specimen in the interaction crucible.

4. Conclusions

A tube ejection failure experiment under ERVC condition was performed for an APR1400 ICI penetration tube. About 100 kg of a mixture of UO_2 and ZrO_2 was generated by induction heating, and interacted with the APR1400 ICI penetration tube specimen. It was found that the ICI tube near the RV surface and tube weld were melted or eroded severely, while the lower part of the specimen below the RV surface maintained low temperatures owing to ERVC. Even though a binding shear force is estimated not to resist the ejecting pressure force effectively at the gap between the RV hole and tube because of low temperature differences between them and the tube was also pressurized up to 2.9 bar, the tube ejection failure did not take place in the end. Consequently, the ERVC effect would be very effective in preventing the RV failure and tube rupture out of the RV by maintaining low temperatures rather than in preventing the tube ejection failure.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2017M2A8A4015274).

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