Evaluation of Tube Ejection Failure for APR1400 ICI Penetration at Various Experimental Conditions

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1. Introduction

The penetration tubes at the reactor lower head are considered a weak part during a severe accident because they could be damaged seriously by high temperature of melt and high RCS (Reactor Cooling System) pressure [1]. We have been interested in the penetration tube failure phenomena, specifically in the tube ejection failure mode and its criteria for the APR1400 ICI (In-Core Instrumentation) penetration tube. Several experiments have been performed in the VESTA (Verification of Ex-vessel corium STAbilization) facility using a prototypic melt and APR1400 ICI penetration test specimens [2, 3]. In the previous experiments, zirconia melt about 2500℃ was generated in a cold crucible by induction heating and interacted with the test specimen at high pressure condition to simulate the severe accident environment in a reactor vessel. However, the tube ejection phenomena have not been observed in previous experiments. Thus, in order to find the tube ejection criteria, we need to check the experimental conditions and find proper boundary conditions to induce tube ejection in the test facility.

The contact or non-contact status at the gap between the penetration tube and the reactor vessel hole is key information to estimate the tube ejection failure because the tube ejection occurs when the ejecting force exerted by the RCS pressure overcomes the binding shear force at the gap interface induced by differential thermal expansion of the tube and vessel materials. The objective of the present paper is to investigate the gap change (i.e., to identify the contact or non-contact status) between the tube and the reactor vessel hole, and to estimate the tube ejection for the APR1400 ICI penetrations according to various boundary conditions such as the constraint to fix the test specimen, external reactor vessel cooling, and melt penetration inside the tube.

2. Methods and Results

The gap change between the ICI penetration tube and the reactor vessel hole was studied using transient thermal and structural analysis of ANSYS 15.0.

2.1 Model Description

Figure 1 shows the installation configuration of the APR1400 ICI penetration test specimen to perform the failure experiment. The test specimen is installed on a support structure, and connected with a water-cooled cold crucible.

The detail model of the test specimen is given in Fig. 2. The material of the reactor vessel is SA508, Grade-3, Class-1, and its thickness is 180.6 mm. The top surface of the specimen is covered with 5.6 mm stainless steel cladding. The ICI penetration tube (ϕ 76.20 mm) material is Inconel-690, which is installed by boring a vertical hole (ϕ 76.30 mm) into the reactor vessel, inserting the tube through the hole, and welding the tube to the vessel inner surface. Thus, there exists a small gap (50 μm) between the tube and the reactor vessel hole. The weld materials are Inconel Welding Electrode 152 (ENiCrFe-7) and Inconel Filler Metal 52 (ERNiCrFe-7), which are generally used in nuclear power plants as the Inconel-690 welding materials [4-6]. A vertical length of the weld is 43 mm. There is a hole (ϕ 19.05 mm) inside the tube for the insertion of ICI assembly; however, it is blocked in the test specimen to create a pressure boundary and prevent melt discharge through the hole.

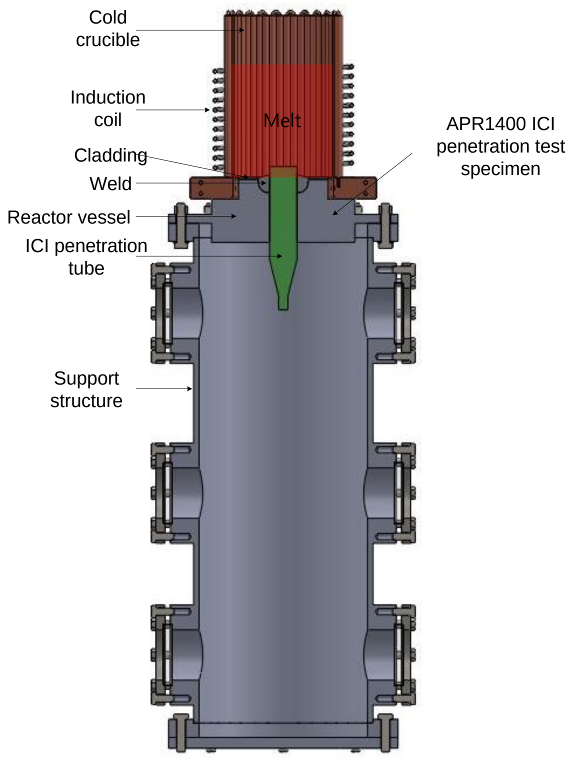


Fig. 1. Installation configuration of the APR1400 ICI penetration test specimen

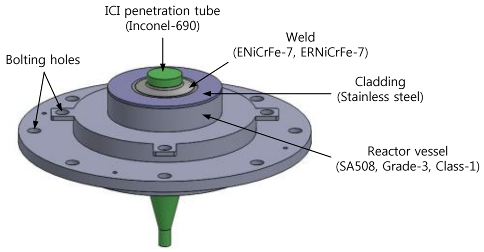


Fig. 2. APR1400 ICI penetration test specimen

The computational domain and mesh configuration are shown in Figs. 3 and 4, respectively. The computational model assumed to be an axial symmetry. The mesh size is 2 μm and the grid consists of 33048 nodes and 10715 elements. Total analysis time is 10000 s and the time step is 1 s.

As shown in Fig. 3, the weld was assumed to be made of the same material with the penetration tube (Inconel-690). The initial conditions for the surface temperature at the top of the specimen being in contact with melt and the lateral surface temperature cooled by a cold crucible were set to be 2000℃ and 100℃, respectively. A natural convection boundary condition (20℃, 10 W/m^2℃) was applied to the surface exposed to the ambient. The alphabets from ‘A’ to ‘C’ indicate the regions for applying the boundary conditions. ‘A’ is the center line of a bolt hole to fix the specimen on the support structure. ‘B’ represents the center line of the hole inside the penetration tube (insulation boundary condition for no melt flow into the hole and 1200℃ for the melt flow case). ‘C’ is the outer surface of the specimen exposed to the ambient air (20℃, 10 W/m^2℃) or water (120℃ for the ERVC (external reactor vessel cooling) case). The boundary conditions applied to the regions from ‘A’ to ‘C’ are summarized in Table I.

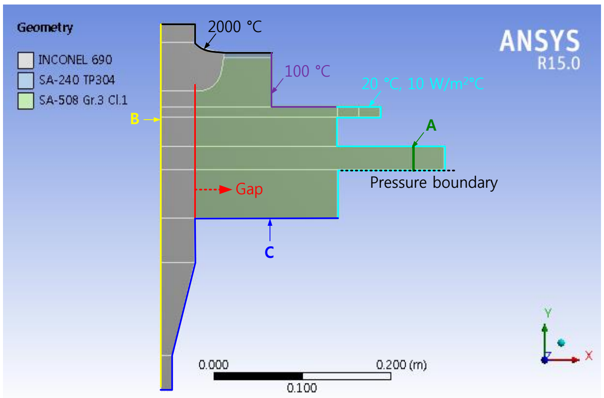


Fig. 3. Computational domain

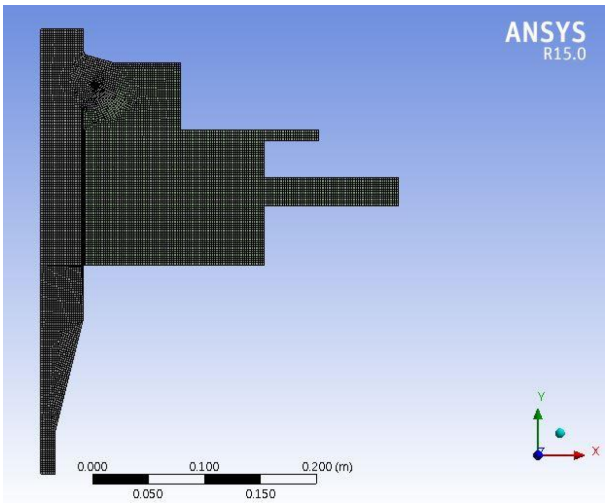


Fig. 4. Mesh configuration

Table I: Boundary conditions

Study case	A	B	C
1	Fixed	No melt flow	Natural convection
2	Not fixed	No melt flow	Natural convection
3	Fixed	Melt flow	Natural convection
4	Fixed	No melt flow	ERVC
5	Not Fixed	No melt flow	ERVC
6	Fixed	Melt flow	ERVC

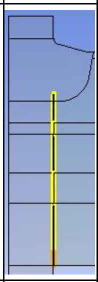
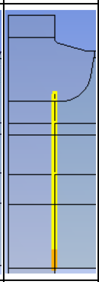
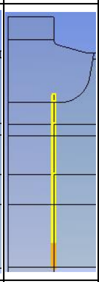
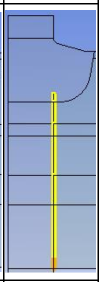
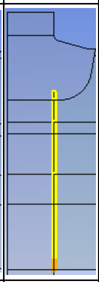
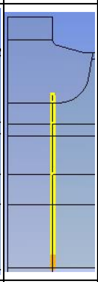
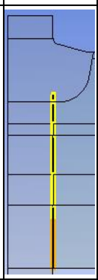
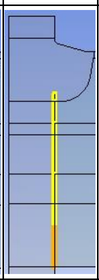
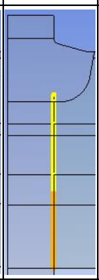
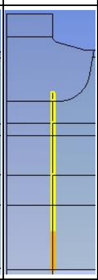
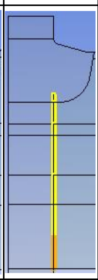
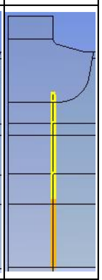
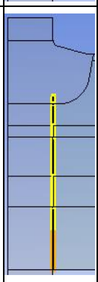
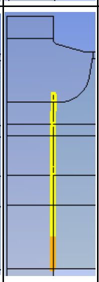
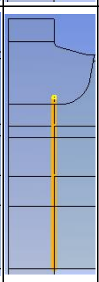
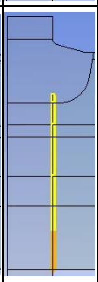
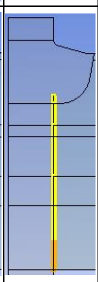
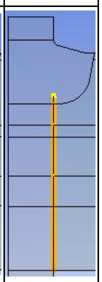
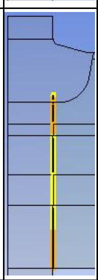
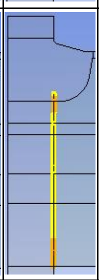
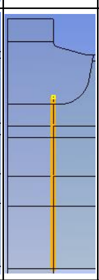
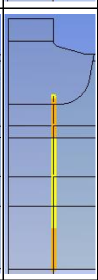
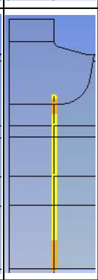
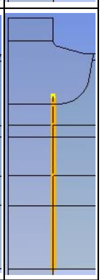
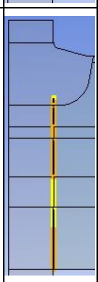
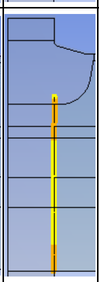
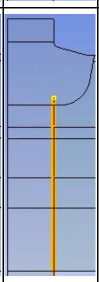
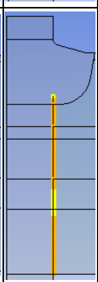
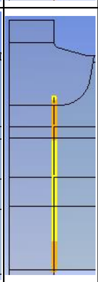
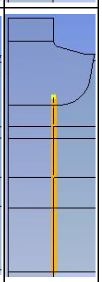
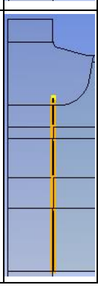
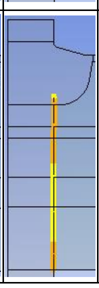
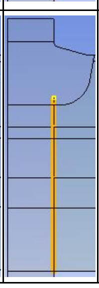
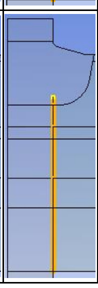
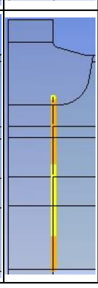
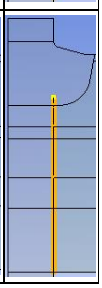
2.2 Results

The simulation results on the gap change between the penetration tube and the reactor vessel hole are summarized in Table II. In the figures, the yellow and orange lines represent the non-contact and contact status, respectively. For all the study cases, the gap was found to maintain the contact status after about 700 s.

The effect of fixed constraint of the test specimen on the support structure can be found by comparing the case 1 to 2, and 4 to 5. If the test specimen is fixed with the support structure by a bolt connection, the penetration tube is expanded freely while the reactor vessel expansion in outward direction is suppressed, thus the tube can touch the vessel hole early. In the previous experiments, the specimen was fixed with the support structure to create the pressure boundary between inside and outside of the support structure. Therefore, the experimental conditions can be thought to be less conservative than the real accident situations in terms of tube ejection failure because the reactor vessel itself expands without any constraints during a severe accident (i.e., global vessel failure) [1]. Nevertheless, as mentioned above, the gap maintains the contact status after 700 s for all the cases, therefore the fixed constraint in the experiments does not affect the gap change seriously because the experiment duration time is much longer (~ 10000 s).

The effect of melt flow into the penetration tube hole can be confirmed by comparing the case 1 to 3. It was found that melt flow into the penetration tube hole have the greatest influence on the gap change. That is, the melt flow into the tube leads to large temperature difference between the tube and the reactor vessel, and

Table II: Results on the gap change between the ICI penetration tube and the reactor vessel hole

Time [s]	Study case					
	1	2	3	4	5	6
5						
50						
200						
300						
400						
500						

accordingly early contact between the tube and the reactor vessel hole due to the faster expansion of the tube. Therefore, even though the melt flow into the penetration tube hole might cause early tube rupture, it might be helpful to prevent the tube ejection failure unless the tube rupture takes place.

The effect of ERVC on the gap change can be confirmed by comparing the case of 1 to 4, 2 to 5, and 3 to 6. The ERVC have little effect on the gap change but the tube touches the vessel hole slowly for the ERVC case, which implies the tube ejection can occur faster. This could be because the temperature difference between the tube and the reactor vessel decreases due to ERVC and accordingly the tube and reactor vessel will expand with similar speed. Consequently, it can be thought that ERVC does a minor effect on the tube ejection but it will have a dominant effect on the tube rupture because the melt in the penetration tube will be cooled effectively by ERVC.

Finally, the combined effect of melt flow into the penetration tube hole and ERVC can be confirmed by comparing the case 1 to 6. The case of melt flow and ERVC condition (case 6) shows earlier contact at the gap. As explained before, this is because the melt flow effect is dominant upon the gap change while the ERVC effect is minor.

3. Conclusions

The gap change between the APR1400 ICI penetration tube and the reactor vessel hole was studied by numerical simulation to estimate the tube ejection possibility in the previous experiments and to investigate the effects of various boundary conditions.

It was found that the structural constraint of the reactor vessel hole not to expand outward and large temperature differences between the penetration tube and the reactor vessel reduces the tube ejection probability. That is, when the thermal expansion of the reactor vessel is suppressed and the temperature difference becomes large, the tube touches the reactor vessel hole early, and thus the tube ejection would not occur. Moreover, the melt flow inside the tube turned out have the greatest effect on the early gap contact because it leads to large temperature difference.

For the verification of the simulation results, the penetration failure experiments according to each boundary condition are necessary, which left as a future work.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2012M2A8A4025885).

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