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Thermal-Structural Analysis of SMART Reactor Vessel Lower Head under IVR-ERVC and In-vessel Steam Explosion Conditions

Sang Mo An [a*], Dong Gun Son [a], Sang Ho Kim [a], Rae-Joon Park [a]
[a]*Korea Atomic Energy Research Institute (KAERI), 989-111 Daedeok-daero, Yuseong-gu, Daejeon, Korea*
[*]*Corresponding author: sangmoan@kaeri.re.kr*

1. Introduction

An IVR-ERVC (In-Vessel corium Retention through External Reactor Vessel Cooling) is known as an effective means for maintaining the RV (Reactor Vessel) integrity during a severe accident, especially for low- and medium-power reactors such as AP600 and AP1000. Despite a controversial issue due to not enough safety thermal margin, this strategy was adopted for high-power reactors of APR1400 and APR+.

The IVR-ERVC strategy is also applied to a small modular reactor SMART [1]. Compared to the thermal power and size of typical LWRs (Light Water Reactors), SMART RV is relatively large and thick because the main components of the steam generators, pressurizer, and reactor coolant pumps are integrated in the RV. There are no penetrations at the RV lower head, and the corium compositions and mass during a severe accident would be quite different. Because of these design features and inherent accident characteristics, the thermo-mechanical behavior of SMART RV during a severe accident should be different from the typical LWRs.

In our previous research [2], a preliminary coupled thermo-mechanical creep analysis of SMART RV was performed under the IVR-ERVC condition. Constant heat fluxes from the stratified oxdic and metallic melt pools to the RV inner wall were applied, which were obtained by SIMPLE (Severe In-vessel Melt Progression in Lower plenum Environment) [3] calculations. In the present paper, dynamic load from in-vessel steam explosion to the RV lower head was taken into account to investigate the RV integrity and also reflect the deformed geometry on the following thermal-structural analysis. The transient heat flux distributions obtained by SIMPLE calculations as well as ERVC boundary condition were applied. Finally, a structural analysis was performed using the deformed RV lower head geometry by thermal and mechanical loads to investigate the long-term creep rupture failure.

2. Analytical Approach

A commercial code ANSYS 18.0 APDL was used for the structural integrity analysis of SMART RV lower head. A simplified axisymmetric 2D model with the boundary conditions is shown in Fig. 1. The RV lower head is divided into 5 zones, where zone-1 to zone-4 are occupied with 37.1 tons of corium pool, and zone-5 is assumed to be exposed to saturated vapor at the RV internal pressure. We assumed that the RV internal pressure is reduced down to 10 bar, and the whole RV outer wall is maintained at 390 K by ERVC. Thermo-mechanical properties of the SMART RV (SA508, Grade 3, Class 1) were taken by ASME code and KAERI material database for high temperature range [4]. About ~ 6 mm stainless steel cladding at the RV inner wall was neglected.

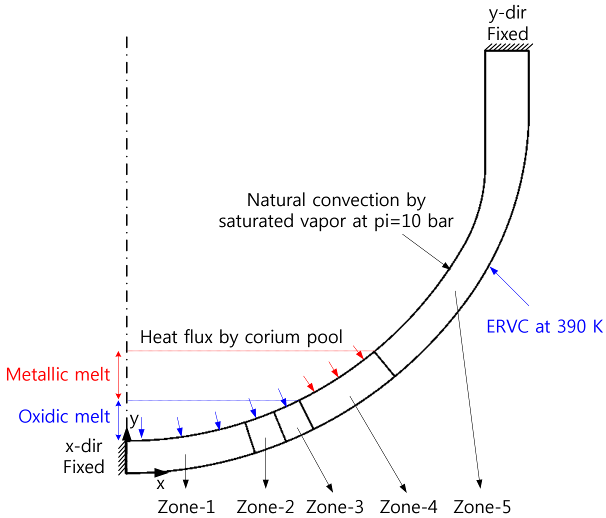

Fig. 1. 2D axisymmetric model and boundary conditions

The analysis method and procedure are summarized in Fig. 2. In-vessel steam explosion may occur at very early stage of melt relocation into the RV lower head, and its time duration is only a few ms. A very conservative and simplified dynamic pressure load by in-vessel steam explosion was applied, which is shown in Fig. 3. In-vessel steam explosion is set to occur at t=0 s, and a transient structural analysis was performed using a Plane183 element, which is a 2D 8-node structural solid. Here, the isotropic kinematic hardening model was used to investigate the permanent plastic deformation of RV lower head by steam explosion.

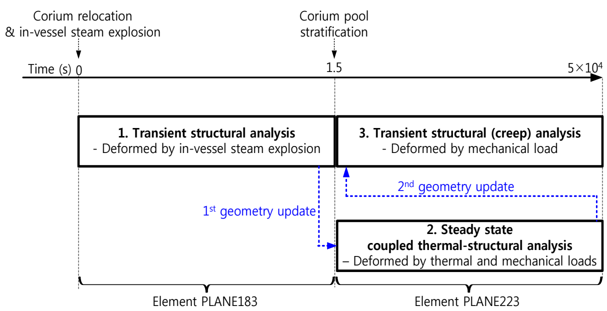

Fig. 2. Analysis method and procedure

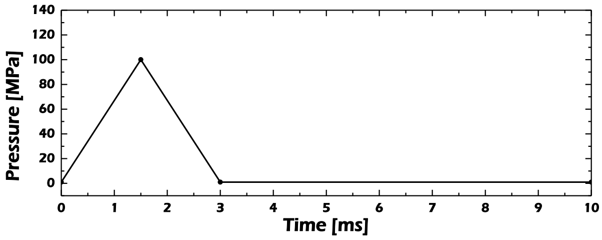

Fig. 3. Dynamic pressure load by in-vessel steam explosion

Then, for the steady state coupled thermal-structural analysis, the deformed RV geometry is updated using Plane223 element, which is a 2D 8-node coupled-field solid. Heat flux distributions (Fig. 4) from oxidic (from zone-1 to zone-3) and metallic (zone-4) melt pools are applied to the RV inner wall. An 'element-birth-and-death' technique [2] is implemented to investigate the erosion of RV lower head, which can be achieved by deactivating the elements higher than the vessel melting temperature (1501℃).

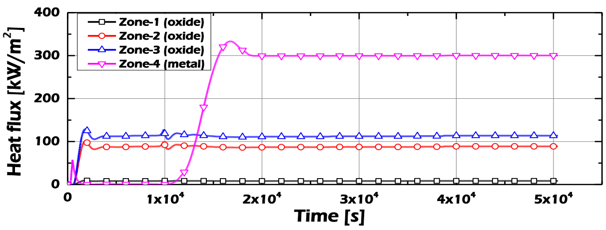

Fig. 4. Heat flux distribution by corium pool to the RV inner wall

Finally, the deformed RV geometry after the thermal-structural analysis is updated and a transient structural (creep) analysis is performed again to investigate the creep rupture failure by long-term mechanical loads of RV internal pressure, corium mass and RV structure weight. This approach provides very conservative results because the RV lower head geometry deformed by thermal and mechanical loads was used for the next structural (creep) analysis even though both analyses should be performed at the same time.

3. Results and Discussion

3.1 Structural Analysis (In-vessel Steam Explosion)

The change of y-dir displacement by in-vessel steam explosion at the bottom of RV lower head, at which it has a maximum, is shown in Fig. 5. The values oscillate in the early phase and then approaches -57 mm at 1.5 s, and the deformed shape is given in Fig. 6. The distribution of equivalent plastic strain at 0.01 s, at which it has a maximum, is displayed in Fig. 7. Despite the very conservative steam explosion assumption, the maximum equivalent plastic strain at the bottom of RV lower head is about 4.7%, which is even lower than the failure criteria 11% by Shockey et al. [5]. This means that the SMART RV lower head maintains its structural integrity under the severe steam explosion conditions.

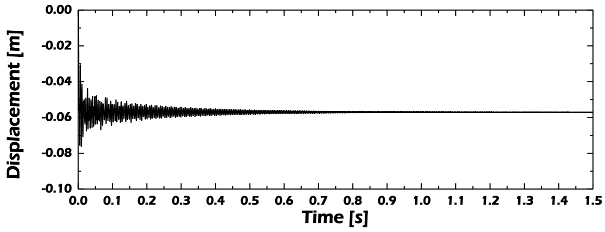

Fig. 5. y-dir displacement at the bottom of RV lower head by in-vessel steam explosion

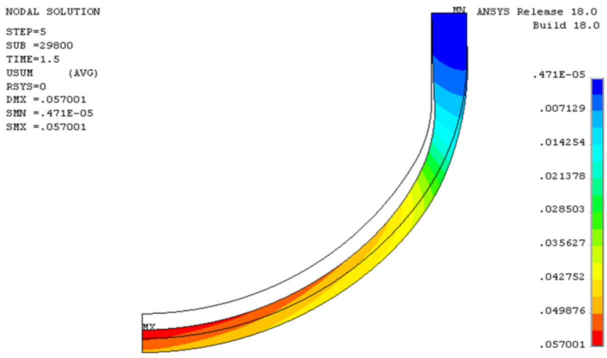

Fig. 6. Deformed geometry by in-vessel steam explosion

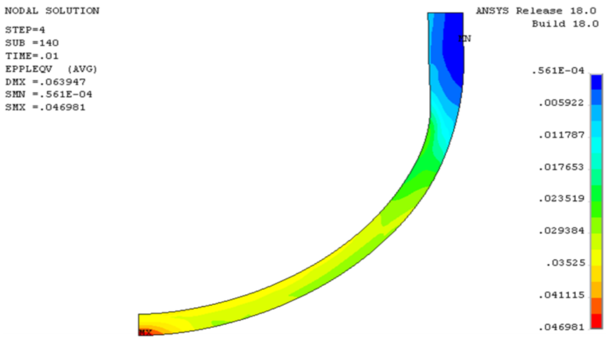

Fig. 7. Equivalent plastic strain

3.2 Coupled Thermal-Structural Analysis

The deformed geometry of RV lower head by steam explosion (Fig. 6) was used to perform the steady state coupled thermal-structural analysis. Figure 8 shows the temperature distribution of RV lower head. Despite partial erosion by high heat flux from the metallic pool, RV integrity is retained by ERVC. It was found that the maximum deformation (17.62 mm) occurs at the outer wall near the eroded part, as shown in Fig. 9.

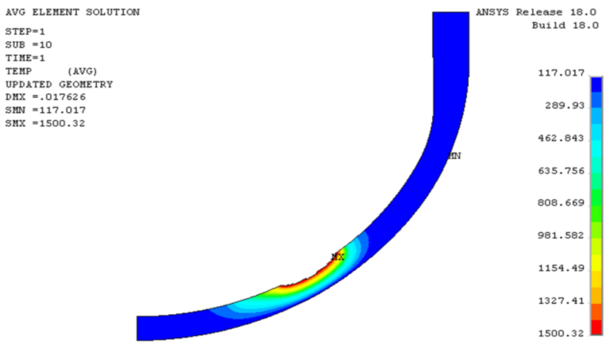

Fig. 8. Temperature distribution

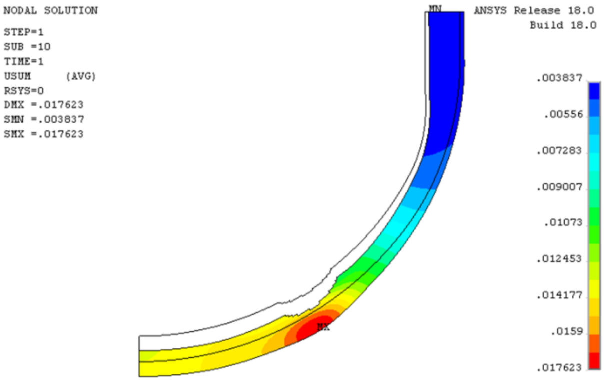

Fig. 9. Deformed geometry by thermal and mechanical loads

3.3 Structural (Creep) Analysis

In order to investigate the long-term RV creep rupture failure by mechanical loads, the deformed RV geometry after the coupled thermal-structural analysis (Fig. 9) was used and a transient structural analysis was performed until 5×10^4 s. The modified time hardening (primary) creep model was used, which is expressed as Eq. (1),

$$\varepsilon_{cr} = \frac{C_1 \sigma^{C_2} t^{C_3+1} e^{-\frac{C_4}{T}}}{C_3+1} \tag{1}$$

where ε_{cr} is equivalent creep strain, σ equivalent creep strain, t time, T temperature. C_1-C_4 are creep constants to be determined by creep test database, which were obtained by Walter et al. [6].

The distribution of y-dir displacement at the bottom of RV lower head at 5×10^4 s and its variation during the entire time period are shown in Figs. 10 and 11, respectively. As shown in Fig. 10, the maximum deformation takes place at the bottom of the RV lower head. In addition, the bottom of RV lower head is deformed very rapidly in the very early stage (primary creep), and then linearly over the long period of time (secondary creep), as shown in 11. That means neither tertiary creep does nor RV lower head creep rupture failure takes place. The y-dir displacement at 5×10^4 s is about -1.2 mm, which is very small during a long time period.

The equivalent stress distribution is displayed in Fig. 12, which shows very low values over the entire region. This is due to the stress relaxation effect created by a constant mechanical load during a long time period. Based on ASME code [7], the minimum stress value leading to the creep rupture failure at 538℃ ranges from 400 MPa (1 hr) to 31 MPa (100,000 hr). As shown in Fig. 12, the maximum equivalent stress near the eroded part is 27.4 MPa, which is much lower than the failure criteria even though very conservative assumptions were applied in the present structural (creep) analysis. Therefore, it can be concluded that the creep rupture failure of SMART RV lower head is prevented very effectively by ERVC.

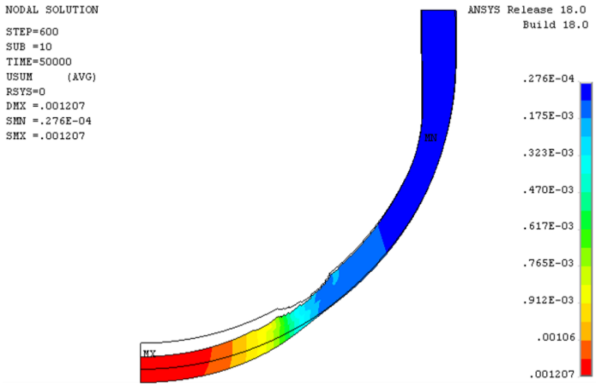

Fig. 10. Deformed geometry by long-term mechanical load

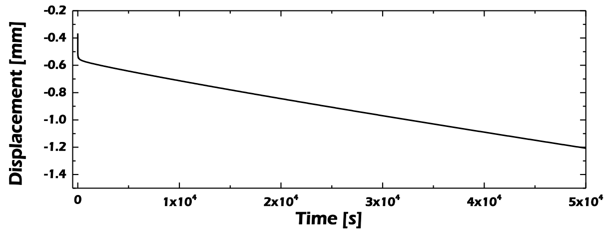

Fig. 11. y-dir displacement at the bottom of RV lower head by long-term mechanical load

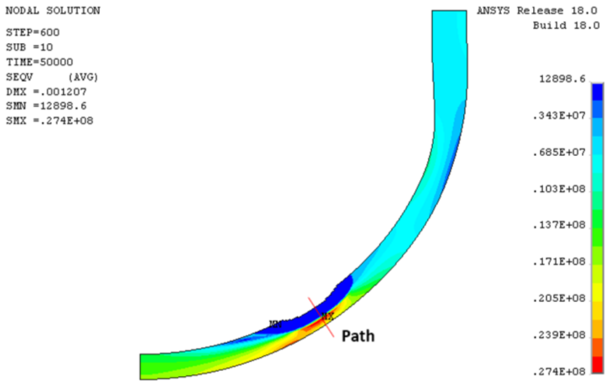

Fig. 12. Equivalent stress

4. Conclusions

A comprehensive thermal-structural analysis was performed to investigate SMART RV integrity during a severe accident. It was found that the plastic deformation of RV lower head by early in-vessel steam explosion is negligibly small. Also, in spite of high thermal and mechanical loads exerted by large amount of corium relocated into the lower head, a long-term creep rupture failure does not take place by means of ERVC. Consequently, the IVR-ERVC strategy turned out an effective means for maintaining the SMART RV integrity during a severe accident.

ACKNOWLEDGMENTS

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