Evaluation of heat flux on the external reactor vessel wall under a severe accident

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1. Introduction

Different system designs are adopted in nuclear power plants to ensure nuclear safety during severe accidents. In-vessel corium retention (IVR) through external reactor vessel cooling (ERVC) is one of strategies to manage severe accidents and is known to be an effective means to maintain the integrity of a reactor vessel [1]. It was adopted in the advanced power reactor (APR) 1400.

Under IVR-ERVC conditions, it is necessary to assure that the heat transfer from the reactor vessel wall is cooled sufficiently and to retain the molten corium inside the reactor vessel from preventing the ejection of the molten corium from the reactor vessel. Many studies have been performed to evaluate the IVR-ERVC to examine the feasibility of the IVR-ERVC strategy [2-4]. However, these studies do not reflect realistic severe accident conditions such as coolant additives, reactor vessel materials, and external reactor vessel wall heat flux, which should be considered. In particular, the external reactor vessel wall heat flux can be provided additionally with the thermal margin for the IVR-ERVC strategy.

To observe the difference between internal and external heat flux of the reactor vessel wall and to identify the parameters that control the external wall heat flux, numerical simulations were performed.

2. Model

2.1 Model description

During the IVR-ERVC conditions, the water from the in-containment refueling water storage tank is flooded into the reactor cavity passively, and the molten corium relocates into the lower plenum as shown in Fig. 1 which is a conceptual schematic of the steady-state two layered melt pool configuration [5]. The upper layer is assumed to be a light metallic layer of Fe, Zr and the lower to be an oxide layer of UO_2, ZrO_2. In this study, other configurations, such as three layer system, are not considered.

The heat generation rate of molten corium is dependent on the molten core formation. In this case, the SBO scenario was applied, the upper internal reactor vessel wall was heated up by radiation heat sources, and the external reactor vessel cooled by water.

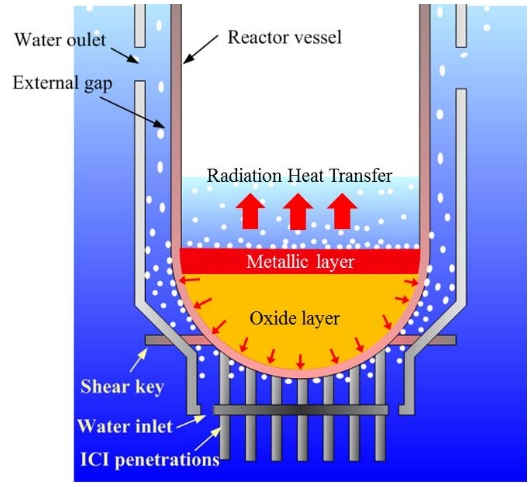

Fig. 1. Conceptual schematic of the two layered configuration

2.2 Numerical Formulation

The heat transfer from the molten corium to external wall is by conduction and is governed by the equation for energy conservation,

$$\frac{\partial T}{\partial t} - \frac{k}{\rho c}\nabla^2 T = 0 \qquad (1)$$

where ρ, c, and k are the density, specific heat, conductivity and temperature of the vessel medium which is SA508, Gr.3, Cl.1.

The computational domain is as shown in Fig. 2 because the reactor vessel is symmetric. The dimensions of the computational domain are summarized in Table. 1.

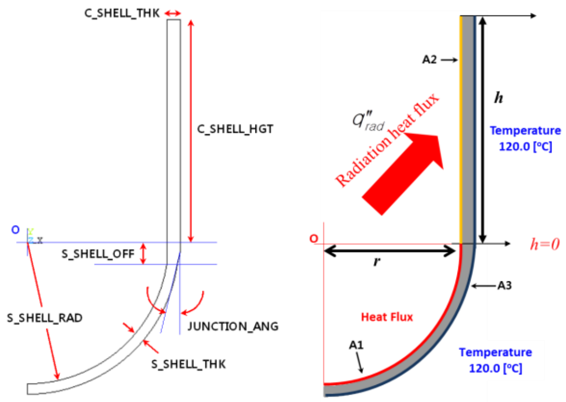

Fig. 2. Computational domain

Table 1. Computational domain dimension

Parameter	Dimension(m)
S_SHELL_RAD	2.3711
S_SHELL_THK	0.175
S_SHELL_OFF	0.368554
C_SHELL_HGT	3.768725
C_SHELL_THK	0.231648

The boundary condition on A1 is according to the SBO scenario sketched in Fig. 3 [6]. Normalized heat fluxes were obtained by the heat flux normalized by averaged internal heat flux. On A2, the boundary condition is given by

$$q''_{rad} = \sigma \varepsilon T_m^4 F_d \qquad (2)$$

where σ, ε, T_m , and F_d are the Stefan-Boltzmann constant, an emissivity, a molten core temperature and configuration factor. The configuration factor is given by

$$F_d = \frac{1}{2}\left(1 - \frac{1+H^2-R^2}{\sqrt{Z^2-4R^2}}\right) \qquad (3)$$

$$H = \frac{h}{a} = \frac{h}{r},\ R = \frac{r}{a} = \frac{r}{r} = 1,\ Z = 1+H^2+R^2 \qquad (4)$$

where h and r are the height and radius of the reactor vessel, respectively. For simplicity, we assumed that the outer wall temperature is 120°C, and the effects of convection, phase change are assumed negligible at the outer wall.

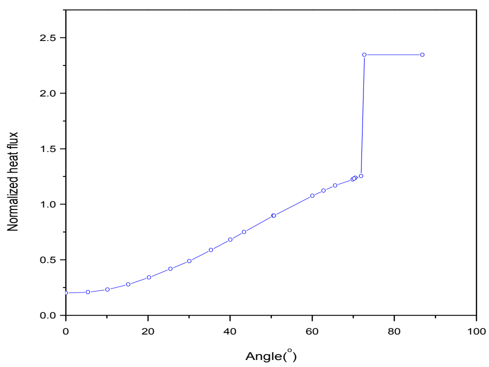

Fig. 3. Input heat flux on the A1

ANSYS Mechanics 14.5 was used to solve the conduction equation. In order to increase the numerical accuracy, the mesh size was decreased until the reactor vessel temperature is not affected with the mesh size. In present numerical simulations, a 4 mm mesh size was applied.

The numerical simulations in the computational domain (Fig. 2) were used to determine the vessel thickness and the heat flux distribution of external reactor vessel. The work proceeded in these steps:

(1) Solve the Eq. (1), find temperature profile of the reactor vessel.
(2) If each node temperature exceeds melting temperature of vessel material, the conductivity and specific heat of node replace with infinity and 0, respectively.
(3) Repeat steps (1) and (2) until temperature profile doesn't change.

3. Results and Discussion

3.1 Results

Figure 4 shows temperature distributions of the reactor vessel. The thickness of the reactor vessel is shown in Fig. 5 as a function of angle from the reactor vessel bottom. The reactor vessel thickness is 0.175 m at lower plenum. At the oxide layer, it is melted at less than 30% from the initial thickness. However, at the light molten metallic layer above the oxide layer, it is melted at up to 80% due to a focusing effect. This effect of the metallic layer is dominantly determined by the molten pool configuration in the lower plenum of the reactor vessel. This result indicates that the melt pool configuration plays a key role in determining the integrity of the reactor vessel.

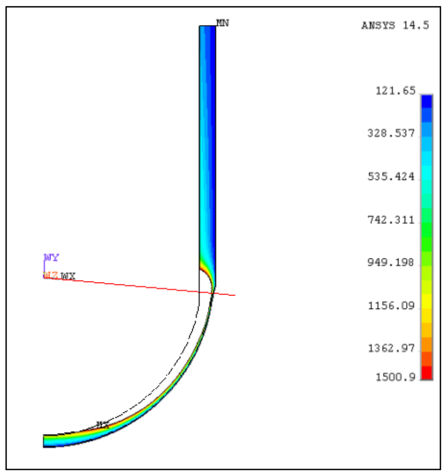

Fig. 4. Temperature distribution of the reactor vessel

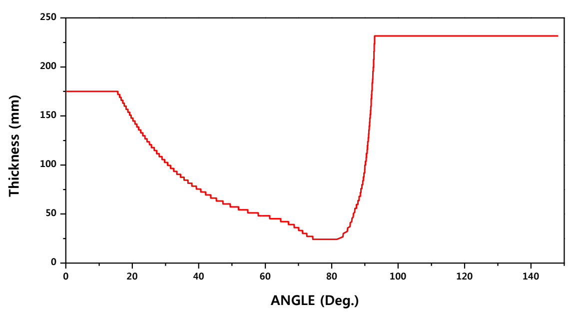

Fig. 5. Thickness of the reactor vessel

The external heat flux distributions were compared with the internal heat flux distributions, as shown in Fig. 6. The maximum heat flux at the outer reactor vessel was decreased compared to the maximum internal heat flux. One of the reasons is the different surface area. The external wall surface area is much larger than the internal wall surface area. Some researchers have not considered the effect of the external wall heat flux. However, this result suggests that the external heat transfer should be considered to analyze a thermal margin for the IVR-ERVC strategy.

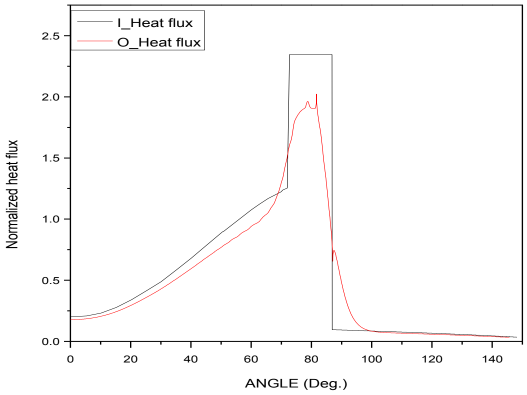

Figure 6. Heat flux distributions

3.2 Sensitive Analysis

Numerical simulations with various boundary conditions were computed to identify the parameters which control external wall heat flux. It was observed that the maximum heat flux and heat flux distributions of the external reactor vessel are similar. The partial insulation on A3 from the top was also applied to assume the decreasing water level. However, the heat flux distributions do not vary significantly.

This means that the boundary conditions of A2, A3 are not affected to determine the heat flux distributions of the external reactor vessel wall. Conversely, the oxide layer and the light molten metallic layer heat flux are key parameters that determine the reactor vessel wall heat flux.

4. Conclusions

A simulation using ANSYS can be useful for solving the heat conduction in a melting medium. The external reactor vessel heat fluxes have been calculated according to a severe accident which is a SBO scenario by using ANSYS. Since the maximum heat flux of external reactor vessel was reduced compared to the maximum internal reactor vessel heat flux, the external reactor vessel wall heat flux should be considered to analyze a thermal margin for the IVR-ERVC strategy.

Several numerical simulations with various boundary conditions revealed that the heat flux and reactor vessel thickness are affected most by the molt pool formation which determines the oxide layer and the light molten metallic layer heat flux. The external reactor vessel conditions are not significant. Since there are many uncertainties (e.g., the material properties with temperature and melt pool formation in the lower plenum of the reactor vessel), a more detailed sensitivity analysis is necessary to evaluate the internal and external heat flux of reactor vessel for a reliable reactor vessel.

ACKNOWLEDGMENTS

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REFERENCES

[1] Rempe, J.L., Suh, K.Y., Cheung, F.B., Kim, S.B., 2008. In-vessel retention of moltencorium-lessons learned and outstanding issues. Nucl. Technol. 161 (210).

[2] Dinh, T.N., Tu, J.P., Salmassi, T., Theofanous, T.G., 2003. Limits of Coolability in the AP1000-Related ULPU-2400 Configuration V Facility. CRSS-03006. Center for Risk Studies and Safety, University of California, Santa Barbara.

[3] Jeong, Y.H., Chang, S.H., 2004. Critical heat flux experiments on the reactor vessel wall using 2-d slice test section. Nuclear Technology 152, 162–169.

[4] Theofanous, T.G., Liu, C., Additon, S., Angelini, S., Kymalanen, O., Salmassi, T., 1997. Invessel coolability and retention of a core melt. Nuc. Eng. Des.169.

[5] Park, R.J., Lee, J.R, Ha, K.S, Kim, H.Y, 2013, Evaluation of in-vessel corium retention through external reactor cooling for small integral reactor, Nucl. Eng. Des. 262, 571-578.

[6] Kim. S.B. el al., DEvelopment of Optimal Severe Accident Management Strategy&Engineered Safety Features Development, KAERI/RR-2528/2004.