Heat Transfer Correlation Dependency on Thermal Load Response of a Melting Pool in a Lower Plenum during Severe Accident

Jae Ryong Lee[a*], Rae Joon Park[a], Seong Wan Hong[a]
[a]*Korea Atomic Energy Research Institute,1045 Daeduk-daero, Daejeon, Korea, 305-353*
[*]*Corresponding author: jrlee@kaeri.re.kr*

1. Introduction

A thermal load response from the molten pool to the outer RPV (Reactor Pressure Vessel) in a lower plenum during a severe accident is very important to evaluate reactor vessel failure mechanism and to determine the safety margin for an IVR-ERVC success. The Thermal load analysis is concentrated on heat flux distribution in consideration of a thermal barrier effect in the thin metallic layer. The melt pool configurations inside the lower plenum the RPV affect the initial thermal load to the outer RPV and play a key role in determining the integrity of the reactor vessel.

The main objective of the present study was to investigate a dependency of the heat transfer used in energy balance equation. The governing equations were solved using a non-linear Newton-Raphson method [1]. This model dependency has been performed by applying the lower plenum of the APR1400 reactor vessel.

2. Mathematical Model

Fig 1 shows a conceptual schematic of the two-layered melt pool configuration. The upper layer is assumed to be a light metallic layer and the lower is an oxidic layer. Since the metallic layer is assumed to be contain no uranium the heat generation is totally provided by lower oxidic layer.

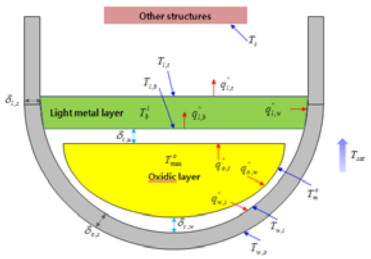


Fig 1 Schematic of the melt pool configuration in the lower head

2.1 Conservation of Energy

The conservation of energy equation in the lower oxidic layer and upper light metallic layer are as (1) and (2). Equation (3) and (4) is energy balance in the upper and downward crust region, respectively.

$$Q_l^{'''}V_l + q_{l,b}^{''}A_{l,b} = q_{l,t}^{''}A_{l,t} + q_{l,w}^{''}A_{l,w} \quad (1)$$

$$Q_o^{'''}V_o = q_{o,t}^{''}A_{o,t} + q_{o,w}^{''}A_{o,w} \quad (2)$$

$$q_{l,b}^{''}A_{l,b} = Q_c^{'''}V_{c,u} + q_{o,t}^{''}A_{o,t} \quad (3)$$

$$q_{w,i}^{''}A_{w,i} = q_{o,w}^{''}A_{o,w} + Q_c^{'''}V_{c,w} \quad (4)$$

2.2 Heat Transfer in Oxidic Layer

In the two-layer configuration shown in Fig 1, heat fluxes from the oxidic layer are distributed into upper light metal layer and the lower hemispheric vessel. First of all, the heat flux into the lower vessel wall is defined as (3).

$$q_{o,w}^{''} = h_{o,w}(T_{\max}^o - T_m^o) \quad (5)$$

Since the crust is treated to have same amount of heat generation, the heat flux at the inner and outer boundary of the sideward crust can be expressed as follows;

$$q_{w,i}^{''} = \frac{k_c}{\delta_{c,w}}\left(T_m^o - T_{w,i}\right) - \frac{Q_c^{'''}\delta_{c,w}}{2},\ q_{w,o}^{''} = \frac{k_c}{\delta_{c,w}}\left(T_m^o - T_{w,i}\right) - \frac{Q_c^{'''}\delta_{c,w}}{2} \quad (6)$$

The heat flux through the vessel wall is simply expressed as the temperature difference between the inner and outer wall. The heat flux from the vessel wall into the reactor cavity water, $q_{w,o}^{''}$, can be also expressed by the following nucleate boiling relations;

$$q_{w,i}^{''} = q_{w,o}^{''} = \frac{k_s}{\delta_{o,s}}\left(T_{w,i} - T_{w,o}\right) = C_{boil}(T_{w,o} - T_{sat})^3 \quad (7)$$

The other heat flux from the heat generation of the oxidic layer is transferred onto the upper light metallic layer;

$$q_{o,t}^{''} = h_{o,t}(T_{\max}^o - T_m^o) \quad (8)$$

And the heat flux through the upper crust region is defined as the following form which is similar with (6) and (7).

$$q_{o,t}^{''} = \frac{k_c}{\delta_{c,u}}\left(T_m^o - T_b^l\right) - \frac{Q_c^{'''}\delta_{c,u}}{2},\ q_{l,b}^{''} = \frac{k_c}{\delta_{c,u}}\left(T_m^o - T_b^l\right) - \frac{Q_c^{'''}\delta_{c,u}}{2} \quad (10)$$

2.3 Heat Transfer in Light Metallic Layer

A thermal load from the light metallic layer is originally from the upward heat flux of the oxidic layer since the light metallic layer does not have any heat generation. The heat transfer from the light metallic layer to other structure in the RPV is also assumed to be accomplished by radiation as follows;

$$q''_{l,t} = h_{l,t}(T_b^l - T_{l,t}) = \frac{\sigma\left[T_{l,t}^4 - T_s^4\right]}{\left[\frac{1}{\varepsilon_t} + \frac{1-\varepsilon_s}{\varepsilon_s}\frac{A_{l,t}}{A_s}\right]} \quad (11)$$

The light metallic layer does not form the crust region at the contact area with sideward vessel wall. And also, the heat flux can be transferred through the vessel wall without any thermal loss since the vessel wall is considered to have no heat generation. Therefore, the heat flux through the vessel wall is provided as;

$$q''_{l,w} = h_{l,w}(T_b^l - T_m^v) = \frac{k_w}{\delta_{l,s}}(T_m^v - T_{w,o}) \quad (12)$$

2.4 Solution methodology

For the heat partition to the lower hemispheric vessel wall, the main physical variables we focused on are the heat flux to water, the inner/outer temperature and the crust thickness. Since the heat flux and the crust thickness as well as the vessel wall thickness are a function of the heat transfer coefficient, they are also expressed as the angular variation form. Since the governing equations are non-linear, they are solved by using a Newton-Raphson method.

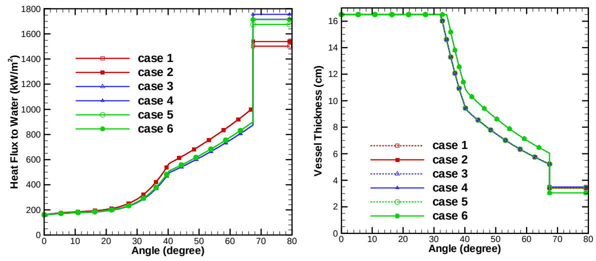
3. Result and Discussion

This study, of various severe accident scenarios, focused on the SBLOCA and LBLOCA without SI (Safety Injection) in the APR1400. The inner radius and thickness of the vessel are 2.37 m and 0.165 m, respectively.

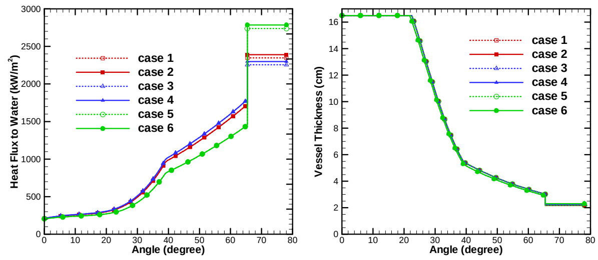
Table 1 Case of heat transfer coefficient for both layers

Case	Ceramic layer Top)			Metal layer (Top-Bottom)	
	ERI model	DOE model	INEEL model	Globe-Dropkin	Globe-Dropkin "specialized"
1	■			■	
2	■				■
3		■		■	
4		■			■
5			■	■	
6			■		■

Table 1 shows the case option of which heat transfer coefficients are applied [2]. In this calculation, Churchill-Chu correlation [3] was used for the sideward heat transfer coefficient for light metal layer for the conservative expectation of the heat flux to vessel wall. Fig 2 shows the heat flux to water and reactor vessel wall thickness as a function of the angle. The ERI model expected larger amount of the heat flux to water than those of other two in the oxidic layer region, whereas smallest amount in the metal layer regardless of which accident scenario it is. The DOE and INEEL model are observed almost same in the oxidic layer for heat flux to water as shown in the Fig 2(a). However, from the Fig 2(b), the vessel thickness profile said that ERI and INEEL model looked similar each other. For the SBLOCA, the reactor vessel thickness is remained with about 3 cm. On the other hand, the scenario of the LBLOCA has the maximum heat flux to water at about 2700 kW/m2 by using INEEL model in the ceramic layer. The reactor vessel, nevertheless, were still observed not to be failure.



(a) q''_{water} for SBLOCA (b) δ_{vessel} for SBLOCA



(a) q''_{water} for LBLOCA (b) δ_{vessel} for LBLOCA

Fig 2 heat flux to water and vessel thickness for SBLOCA

4. Conclusions

The thermal load response from the molten pool to the outer RPV (Reactor Pressure Vessel) in the lower plenum during a severe accident was analyzed with the conservation of energy equations by adopting Non-linear Newton-Raphson iteration method. The scenario of SBLOCA and LBLOCA in the APR1400 were considered. Since the heat partition toward light metallic layer is larger than one to lower vessel, one can observed the heat flux to water has a quite large value. Thus, Through both scenario, the reactor vessel was estimated and found that it did not happen to be failure.

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REFERENCES

[1] J.R. Lee, et al, Analysis on thermal load response in the lower plenum fo the reactor pressure vessel during a severe accident, proc of NTHAS7, Chuncheon, Korea, Nov. 14-17, 2010

[2] E. Esmaili, et al. Analysis of In-Vessel Retension and Ex-Vessel Fuel Coolant Interaction for AP1000, NUREC/CR-6849, Rockvill, MD, USA, 2004

[3] S.W. Churchill, and H.H.S. Chu, Correlating equations for laminar and turbulent free convection from a vertical plate, *Int. J. Heat & Mass Trans.* Vol.18, pp.1323, 1975