Evaluation of Gap Size Formed by Interaction between Melt and Water in RPV Lower Head

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1. Introduction

The existing gap cooling studies have shown that the gap between the melt and the vessel cools down and effectively mitigates the failure of the reactor vessel. However, the reliable mechanism for gap formation has not clearly identified. The reason why the mechanism has not been clear is that some of the gap formation experiments did not show a gap.

The existing studies for gap cooling modeling calculate the gap thickness from thermal deformations of the vessel and the melt as follows;

$$\delta = \delta_0 + \left(l_0 \beta \Delta T\right)_{vessel} + \left(l_0 \beta \Delta T\right)_{melt} \qquad (1)$$

However, the exiting approach overestimates the value of the gap thickness value than the experimental ones as seen in Table I.

Table I. Comparison between experimental data and predictions by the existing model [1]

	l_0 (mm)	β (10^{-6} K^{-1})	Existing Model: Eq. (1)	Exp. Data
LAVA-6, 10	250	7.00~11.0	3.24 ~ 5.10 mm	1 ~ 3.5 mm
LMP200-1, 2	400	7.00~11.0	5.16 ~ 8.11 mm	1 ~ 4.5 mm
TMI-2	2370	9.50 (UO_2), 7.50 (Zr)	51.8 mm (for UO_2) 40.9 mm (for Zr)	Several millimeters

Moreover, one of the gap formation experiments, EC-FOREVER, allowed the thermal deformations of the melt and vessel on the post-flooded condition, which is the water was ejected after the interaction between the melt and the vessel [2]. However, the gap did not appear due to the absence of the water in the vessel, although the thermal expansion and crust formation occurred. It means that the interaction between the melt and the water plays important role for the gap formation.

This study developed the model for estimation of the gap thickness for gap cooling analysis with consideration of the interaction between the melt and the water.

2. Interaction between Accumulated Melt and Water

To estimate the gap thickness between the melt and the vessel, this study considered three phenomena, thermal deformations of the crust and the vessel, thermal fracture of the crust, and Inverse-Leidenfrost effect as follows (Eq. (2) and Fig. 1);

$$\delta_{gap}{}^{i} = \delta_{Inv\_Leidenfrost} + \delta_{th\_contraction}{}^{i} - \delta_{th\_fracture}{}^{i} \qquad (2)$$

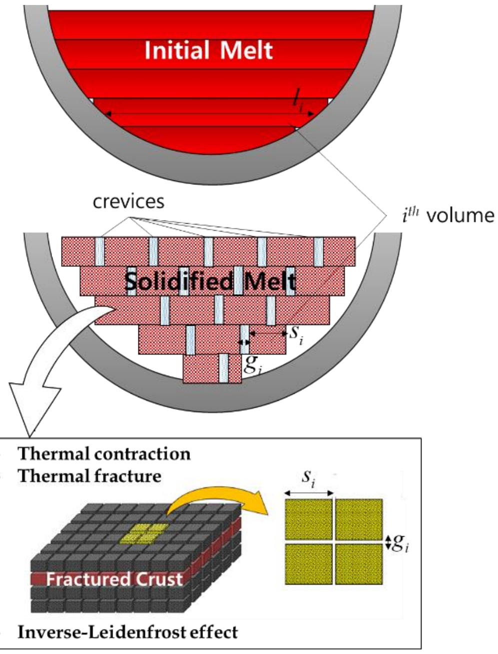

Fig. 1. Initial melt and modeling of solidified melt for calculation of the gap thickness

The melt was divided into one-dimension along to the direction of perpendicular to the melt top surface. The ways to obtain each term in Eq. (2) were introduced in following sections.

2.1 Inverse-Leidenfrost Effect

The Inverse Leidenfrost effect is that a significantly hot particle levitates on a plate because of the vapor layer generated by heat transfer from the hot particle to the liquid pool [3]. The vapor layer produced by heat transfer from the melt was considered an initial gap thickness, $\delta_{Inv\_Leidenfrost}$. The vapor layer thickness was obtained balancing the gravitational force of the melt against the pressure gradient due to the vapor flow.

$$\delta = 0.464C \frac{k_{g,eff}^{\ 3/8} \Delta T^{3/8} \mu_g^{\ 1/24}}{(mg)^{5/24} \rho_g^{\ 5/24} h_{fg}^{\ 3/8}} R$$

where

$$k_{g,eff} = \frac{\delta}{D_h} k_g Nu + \varepsilon\sigma\left(T_d^{\ 2} + T_w^{\ 2}\right)\left(T_d + T_w\right)\delta \tag{3}$$

$$C = \left(\int_0^{\theta_0} \sin\theta \left(\int_0^{\theta} \left(\frac{1-\cos\theta'}{\sin\theta'} \right)^{9/5} d\theta' \right) d\theta \right)^{5/24}$$

2.2 Thermal Fracture of the Crust

To calculate the thermal fracture of a melt, this study adopted Yeo and NO's study [4] which evaluated the thermal fracture of the crust being cooled down under the flooded condition. The relation between the released strain energy and the toughness was utilized.

$$\frac{E_c \beta_c \left[T_{sol} - T_{crust\_front} \right]}{1 - \nu_c} > \sigma_{TS} \tag{4}$$

$$\frac{E_c s^2}{1-\nu_c} \int_0^{d_c} \beta_c^{\ 2} \left(T_{sol} - T_{crust}(x) \right)^2 dx \geq 2 G_c s d_c \tag{5}$$

From Eq. (4) and (*5), the spacing length s can be obtained. The $\delta_{th\_fracture}{}^{i}$ in Eq. (2) can be calculated as follows;

$$g_i = s_i \beta_c \left[T(0) - T_{sat} \right] \tag{6}$$

$$\delta_{th\_fracture}{}^{i} = \left(\frac{l_i}{s_i} - 1 \right) g_i \tag{7}$$

2.3 Thermal Deformations of Crust and Vessel

As the temperatures of the crust and the vessel are changes, the thermal deformations take place. After the thermal interaction between melt and water, the melt temperature significantly decreases while the vessel temperature becomes same as its initial temperature. Thus, the $\delta_{th\_contraction}{}^{i}$ was calculated from Eq. (1), however the reference length, l_0, is the width of the i-th volume in Fig. 1.

3. Results and Comparison with Experimental Data

Table II shows the experimental data of the gap formation studies. R and θ in Table II are shown in Figure 3. Figure 2 shows the calculation results of gap thickness depending on angle predicted by the proposed model for the LAVA-6 test. There are four lines which represent each term in Eq. (2). The thermal contraction term and the crust fracture term depend on the thermal expansion coefficient as can be seen. For the Inverse Leidenfrost term, it is not dependent on the thermal expansion coefficient.

Table II. Experimental Data for Validation

	Simulants	Pressure/ Temperature (Simulants/ Water)	Geometric Condition
KAIST test (debris particle)	3.5 g of Cu	1 bar /1050℃ /80℃	R = 10.05 mm
LAVA-6 (hemispherical)	40 kg of Al_2O_3+Fe	17.6 bar/ 2050℃ /154℃	R = 250 mm θ = 60°
LAVA-10 (hemispherical)	30 kg of Al_2O_3	16.2 bar/ 2050℃ /197℃	R = 250 mm θ = 60°
LMP200-1 (hemispherical)	360 kg of Al_2O_3+Fe	14.2 bar/ 2050℃ /150.7℃	R = 400 mm θ = 78°
LMP200-2 (hemispherical)	200 kg of Al_2O_3	14.2 bar/ 2050℃ /50.7℃	R = 400 mm θ = 71.3°
ALPHA [5] (hemispherical)	30 kg of Al_2O_3	13.0 bar/ 2427℃ /172℃	R = 250 mm θ = 60°

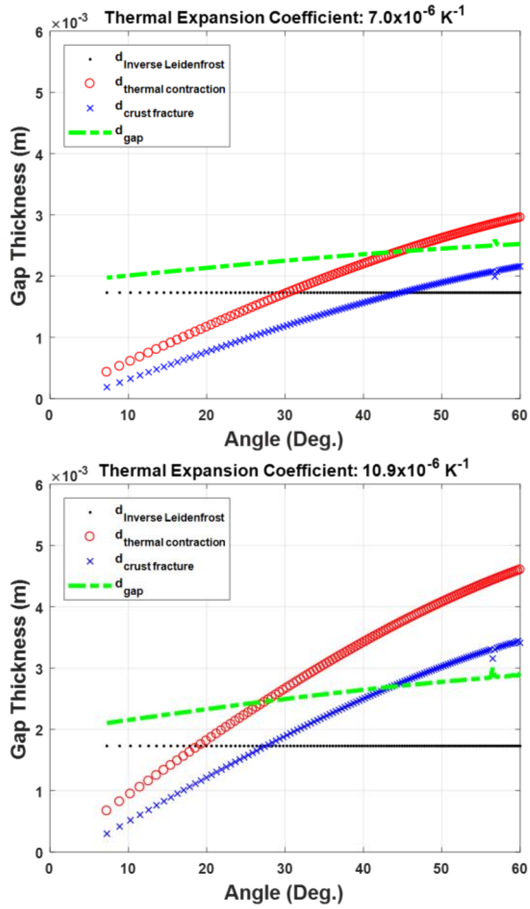

Fig. 2. Calculational gap thickness of Eq. (2) for LAVA-6

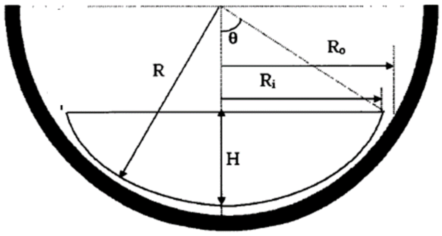

Fig. 3. Description of R and θ in Table II

The calculation results were compared with experimental data as shown in Fig. 4 and 5. As discussed previously, the linear thermal deformation model (red region in Fig. 4) overestimates the experimental data. The proposed model predicts better than the existing model as can be seen in Fig. 4 and 5. However, it still over-estimates the experimental data for the ones of LMP200-1 tests of which melt mass is 200 kg of oxide. The melt of the LMP200 test contains iron layer at its bottom. Because the superheat of the iron layer is much higher than the oxide layer, the stable crust may not be formed in LMP200 case. Thus, the stability analysis of the crust facing the inner vessel wall is required.

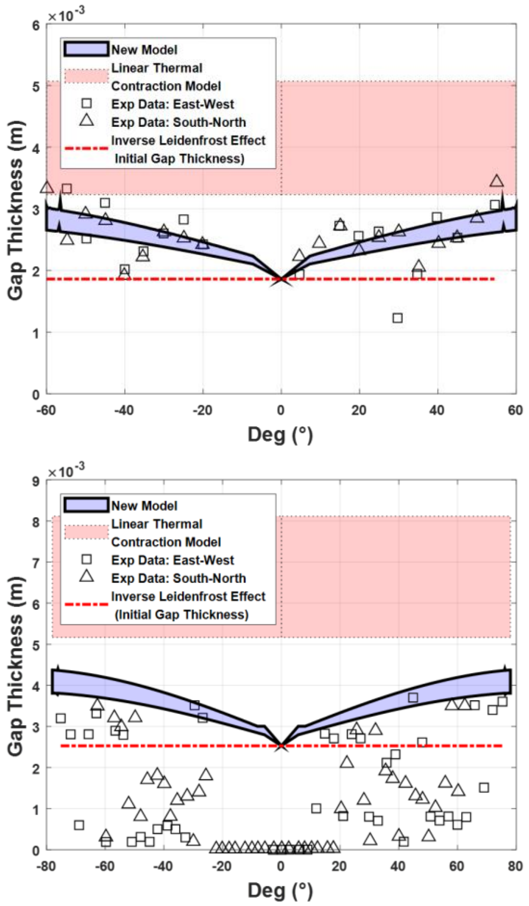

Fig 4. Comparison between experimental gap thickness and predictions according to gap position (top: LAVA-6, bottom: LMP200-1)

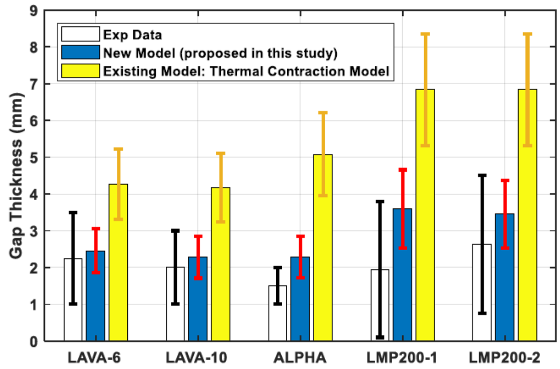

Fig. 5. Comparison between the experimental gap thickness and predictions

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