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Gap Formation Study for In-vessel Gap Cooling

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1. Introduction

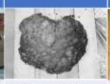
In this study, the mechanism for gap formation was proposed based on the several experimental observations. When the TMI reactor accident occurred, approximately 19 tons of molten corium were relocated from the reactor core to the lower head of the reactor vessel. Unlike the existing analysis of a severe accident, the reactor vessel did not failed. After the cleanup study, gaps between the solidified corium and the reactor vessel were observed. Through the gap formation study, the re-evaluation of the focusing effect, which is the most critical conditions for reactor vessel failure, can be established.

Therefore, several researchers have actively carried out the gap cooling studies for both experiments and modeling. It was successful to estimate the temperature changes of the simulants for a reactor vessel according to the quenching time. Based on numerous experiments, several models have been proposed, which are the hydraulics and boiling.

The one of the representative studies for gap cooling, LAVA [1], applied the gap distance as user-input to their quenching analysis. The verification study for ALPHA [2] experiments, the gap distance was calculated considering the thermal expansion of the reactor vessel and the contraction of the molten corium. The FOREVER [3] study showed that no gaps were formed from their experiments. Overall, it is not clear how the gaps form when the molten corium relocates from the reactor core to the reactor vessel.

2. Previous Experimental Studies and Pre-flooded Condition

Table 1. Experimental Studies for Gap Formation [1, 3, 4, 5]

	FARO L-19	LAVA	ALPHA	IC-FOREVER	KAIST- Cu Exp	
Picture						
Simulants	157kg of 80wt% UO2 +20wt% ZrO2	30~360kg of Al2O3 or AL2O3+Fe	30kg of Al2O3	121kg of 30wt% CaO +70wt% B2O3	2.9g of Cu	
Observations	- Wavy with a furrowed structure (several mm) - Void pockets	The gap thickness was measured by ultrasonic wave. (1~5mm)	1~2mm of gap was formed	No gap forming	Easy to detach	Hard to detach
Pre-flooded	Yes	Yes	Yes	No	Yes	No

The FARO study explained that gap formation is determined by the flooding condition of the reactor vessel. They found that there were gaps of several millimeters in the flooding case. In addition, the gaps were not observed unless flooding occurred prior to ejection of the melt.

The experimental studies for the measuring gaps between the high temperature melt and the reactor vessel are shown in Table 1. As a result, the pre-flooded condition was the most critical condition to determine whether the gaps form as shown in LAVA and ALPHA experiments. On the contrary, the IC-FOREVER experiment did not find the gaps because the water was poured after the ejecting melt to avoid the steam explosion.

KAIST performed the melt experiments with the Cu metal under conditions both pre-flooded and non-flooded. Under the non-flooded condition, detaching the melt was difficult. Conversely, the detaching was easily done under the pre-flooded condition. We concluded that the reason that the flooding condition affects the sticking is the gap formation. In conclusion, the pre-flooded condition is the critical condition for the formation of gaps according to the experimental studies.

3. Modeling: Inverse Leidenfrost Effect

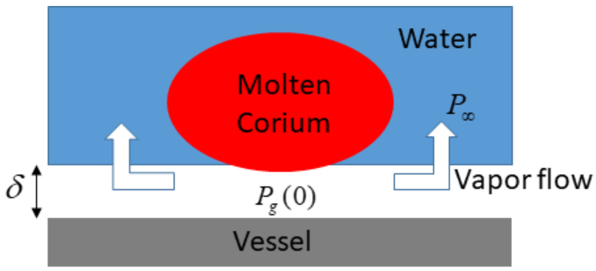


Fig. 1. Inverse Leidenfrost Effect under a Hot Melt

In this study, we suggested that the reason for the gap formation under the pre-flooded condition is the inverse Leidenfrost effect. As described in Figure 1, the vapor flow is generated between the hot melt and the wall of the vessel due to the heat transfer from the hot melt. The Leidenfrost effect is the phenomenon that a liquid drop floats when the wall temperature is much higher than the boiling temperature. In the inverse Leidenfrost case, the melt temperature is significantly higher than the boiling temperature instead of the wall.

The gap distance can be estimated by calculating the thickness of the vapor layer. Conservation laws for mass, momentum, and energy were applied to obtain the thickness of the vapor layer. Consequently, we obtained the pressure drop of the vapor flow for both laminar (Eq. (1)) and turbulent (Eq. (2)):

$$P_g(r) - P_\infty = \frac{k_{g,eff}\Delta T}{3\delta^4}\frac{\mu_g}{\rho_g h_{fg}}\left(r_d^{\,2} - r^2\right) \tag{1}$$

$$P_g(r) - P_\infty = 4.1\times10^{-3}\frac{k_{g,eff}^{\;9/5}\Delta T^{9/5}\mu_g^{\;1/5}}{\delta^{24/5}\rho_g h_{fg}^{\;9/5}}\left(r_d^{\,14/5} - r^{14/5}\right) \tag{2}$$

where

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

For the Nusselt number, the solution of the laminar flow or Dittus-Boelter correlation was applied. Applying the force balance for the gravity of melt and pressure drop due to vapor, Eq. (4), we have

$$\int_0^{r_d} 2\pi r\left(P_g(r) - P_\infty\right)dr = mg \tag{4}$$

$$\delta = \left(\frac{3\mu_g k_{g,eff}\Delta T}{2mg\rho_g h_{fg}}\pi\right)^{0.25} r_d \;\; \text{laminar} \tag{5}$$

$$\delta = 0.361\frac{k_{g,eff}^{\;3/8}\Delta T^{3/8}\mu_g^{\;1/24}}{(mg)^{5/24}\rho_g^{\;5/24}h_{fg}^{\;3/8}} r_d \;\; \text{turbulent} \tag{6}$$

A solution for the geometry of reactor vessel was obtained in the same manner as for the melt droplet:

$$\delta = 0.464C\frac{k_{g,eff}^{\;3/8}\Delta T^{3/8}\mu_g^{\;1/24}}{(mg)^{5/24}\rho_g^{\;5/24}h_{fg}^{\;3/8}} R \tag{7}$$

where

$$C = \left(\int_0^{\theta_0}\sin\theta\left(\int_0^{\theta}\left(\frac{1-\cos\theta'}{\sin\theta'}\right)^{9/5}d\theta'\right)d\theta\right)^{5/24} \tag{8}$$

4. Validation

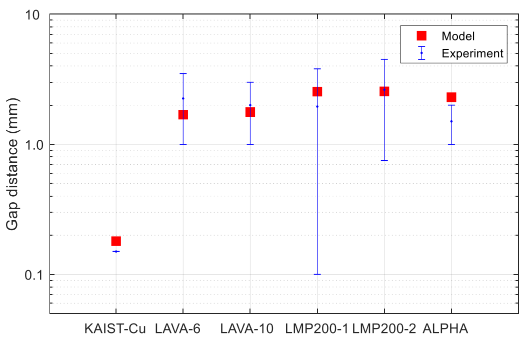


Fig. 2. Comparison between measured data and calculated vales [1, 4]

Table 2. Experimental Data for Validation

	Simulants	Pressure	Temperature (Simulants/Water)	Geometric condition
KAIST-Cu exp* (debris particle)	Cu, 2.9g	1bar	1050℃/80℃	R = 10.05mm
LAVA-6 (hemispherical)	Al2O3/Fe, 40kg	17.6bar	2050℃/154℃	R = 0.25m θ = 60°
LAVA-10 (hemispherical)	Al2O3, 30kg	16.2bar	2050℃/197℃	R = 0.25m θ = 60°
LMP200-1 (hemispherical)	Al2O3/Fe, 360kg	14.2bar	2050℃/150.7℃	R = 0.4m θ = 78°
LMP200-2 (hemispherical)	Al2O3/Fe, 220kg	14.2bar	2050℃/155.7℃	R = 0.4m θ = 71.3°
ALPHA (hemispherical)	Al2O3, 30kg	13.0bar	2427℃/172℃	R = 0.25m θ = 60°

*** Not directly measured, predicted by CFD**

Table 2 shows the experimental data utilized for validation. As can be seen in Figure 2, the model successfully predicted the measured data. Except KAIST data, Eq. (7) was utilized due to geometric conditions, which were hemispherical. The Eq. (5) was applied to validate the KAIST data because the melt and the condition of the vapor flow were particle-debris and laminar, respectively.

LAVA and LMP experiments qualitatively measured the gap thickness with ultrasonic wave. They provided the gap thickness values according to the positions of the gaps on the hemisphere surface. For this reason, the measured values were plotted as range data. In the LMP data, where the condition is a larger mass than other experiments, no gaps occurred in the region where the azimuth angle was within 20 degrees. A hot spot in which there were no gaps appeared in the TMI accident likewise. To explain this, the analysis of water penetration through combination of gap formation and quenching analysis is needed.

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