Comparison of Debris Dispersal Correlations for HPME/DCH Modeling

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1. Introduction

When the reactor vessel fails, if the reactor coolant system (RCS) is at high pressure, the molten core in the lower head would be ejected forcefully, fragmentized into small particles and dispersed into the containment atmosphere. The dispersed molten core would be exothermically reacted and the generated energy would rapidly be transferred to containment atmosphere, which increases the pressure and the temperature of the containment. This is called High Pressure Melt Ejection (HPME) and Direct Containment Heating (DCH). DCH can cause the early containment failure and no mitigation feature would be applicable due to its rapid progression. Therefore, it should be properly considered in the design and the accident mitigation strategy. For that, the proper modeling and estimation tools would be essential.

As shown **Figure 1**, DCH can roughly be characterized into four phases: 1) blowdown of the molten core and the gas mixtures into the reactor cavity, 2) entrain and disperse of molten core debris out of the reactor cavity, 3) transport of molten core debris and gases to containment atmosphere, 4) chemical reactions. The entrainment of molten core debris and disperse out of the reactor cavity would be the most important factor because it determines the amount of energy generated by chemical reactions and transferred to containment atmosphere. In order to estimate the dispersed molten debris, many experimental studies have been conducted and analytical models have been proposed.

The purpose of this paper is to investigate the applicability of the disperse correlations to different types of cavity. First, the previous experimental and analytical studies related to debris dispersal phenomena are reviewed. Second, the correlations for dispersal fraction are collected and applied to different cavity shapes. The estimated dispersal fractions are compared to the experimental data. The applicability of each correlation for each cavity type is examined.

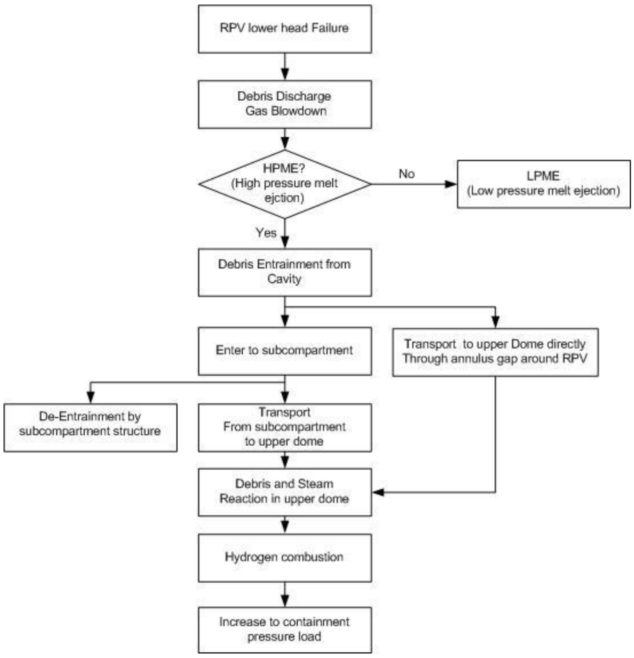

Figure 1. DCH process

2. Disperse Correlation

2.1 Ishii-Kataoka model [1-3]

Ishii-Kataoka model assumes that the gas and the melt eject as two-phase flow. When reactor pressure vessel fails, the molten core would escape the cavity in a form of film flow. Entrainment rate from the surface of the film is given as follows.

$$\varepsilon = 6.6\times10^{-7}(Re_f We)^{0.925}\left[\frac{\mu_g}{\mu_d}\right]^{0.26}\frac{\mu_d}{D_c}$$

$$We = \frac{\rho_g j_g^2 D_c}{\sigma}\left[\frac{\Delta\rho}{\rho_g}\right]^{1/3} \qquad \text{Weber number}$$

$$Re_f = \frac{\rho_d j_f D_c}{\mu_d} \qquad \text{Reynolds number}$$

Total disperse time is determined by a sum of film transport time and corium entrainment time.

$$\tau_{disp} = \tau_e$$

$$\tau_e = \frac{\delta_f \rho_f}{\varepsilon} \qquad \text{Corium entrainment time}$$

$$\tau_b = \frac{V_{pr}}{0.6\pi D_J^2 U_{go} / 4} \qquad \text{Blowdown time}$$

Dispersed fraction is given by

$$F_d = 1 - e^{-K_c \tau_b / \tau_{disp}}$$

2.2 Levy model [4]

Levy model is based on Ishii-Kataoka model. By introducing the standard value which is a function of failure size, gas constant, temperature, the correlation can be applied to different shapes of cavity. Total dispersed fraction by Levy is calculated as follows.

$$F_d = 1 - \frac{\delta}{\delta_0}$$

The film thickness (i.e., δ) is calculated by solving the following equation.

$$K_c f_1 f_2 \frac{0.36 V_v}{A_h \sqrt{RT_0}} Eu^{2.3} \left[\frac{2P_0}{\sigma}\right] \sqrt{\frac{2P_0}{\rho_d}} \left[\frac{\mu_g}{\mu_d}\right]^{0.26}$$

$$= \ln\left[\frac{\sqrt{1+300\frac{\delta_0}{D_c}}-1}{\sqrt{1+300\frac{\delta}{D_c}}-1} \frac{\sqrt{1+300\frac{\delta}{D_c}}+1}{\sqrt{1+300\frac{\delta}{D_c}}-1}\right]$$

$$f_1 = \left(\frac{d_s}{d}\right)^2$$

$$f_2 = \sqrt{\frac{R_s T_s}{RT}}$$

2.3 Henry model [5]

Dispersed mass of molten core by Henry model and dispersed fraction are given as follows,

$$m_D = 0.19 A_v \left[P_v L_p L \rho_D \left(\frac{A_s}{A_v}\right)\left(\frac{M_W}{RT}\right)\left(\frac{\rho_D}{\rho_g}\right)^{0.5}\right]^{0.5}$$

$$F_d = \frac{m_D}{m_0}$$

2.4 Kim model [6-8]

In Kim model, the geometry effect is considered by introducing non-dimensionless quantities. The dispersed fraction by Kim is given by

$$F_d = 40\left(1 + \tanh(3.79 \log\left(\frac{t^*}{15}\right))\right)$$

where

$$t^* = \frac{(\rho_{H_2O} / \rho_d)^{0.5}}{L_p (1-\gamma)} \frac{1}{\rho_g A_c} \left(\frac{P_0 V_0}{RT_0}\right)\left(1 + \frac{U_{gc}}{U_{g0}}\right)\left\{1 - \left(\frac{U_{gc}}{U_{g0}}\right)^{\frac{1-\gamma}{(1+\gamma)}}\right\}$$

3. Cavity Geometry

Molten core dispersal process has the dependency on the cavity geometry. The cavity geometry can be characterized by flow area, exit height, inclination angle, flight path length, etc. Depending on the cavity shape, the melt dispersal fraction would be varied significantly. In order to investigate the effect of the cavity geometry on dispersal and the applicability of the correlations to specific cavity type, the representative cavity shapes and experimental data are collected. The schematics of the selected cavity geometries are presented in **Figure 1 ~ 4**. Corresponding experiments are summarized in **Table I**.

Table I. Summary of DCH Experiments

Research Institute	SNL	BNL	KAIST	KAIST
Reactor Cavity	Zion	Surry	Kori 1&2 (WH)	YGN 3&4 (CE)
Scale	1/10	1/42	1/20	1/30
Melt Simulant	Thermite	Water	Water	Water
Vessel Pressure [MPa]	5.9 ~7.1	0.3 ~5.27	0.4 ~2.0	0.5 ~2.8
Flow Area [m^2]	0.0524	0.00716	0.0162	0.01427
RPV failure area [m^2]	9.62E-4	1.78E-5 7.13E-5	7.85E-5 1.76E-4 3.14E-4	7.85E-5 1.76E-4 3.14E-4
Flight path length [m^2]	0.4283	3.6	0.563	0.845

Figure 1 shows the scaled cavity model of Kori 1,2 plant (Westinghouse type) [16]. Cavity floor and flow area shape are simplified as symmetric circular and rectangular form. Instrument tunnel is perpendicular to cavity floor. **Figure 2** shows the scaled cavity model YGN 3,4 plant [6]. This cavity floor shape is

asymmetrical form unlike other three plants. Because the flow path is not straight, the melt would be impact the wall and deposited more on cavity walls. Figure 3 shows the scaled cavity of Zion plant [5,14,15]. Angle between cavity and instrument tunnel is inclined at 26 degrees. Cavity Floor area shape is symmetric. This shape compose rectangle, trapezoid, circle. Floor area is getting narrower from RPV vessel to cavity exit area.

Figure 4 shows the scaled cavity of Surry [12,13] which is similar to Kori 1, 2. However, the instrument tunnel does not exist and the cavity is connected to exit directly. Thus, flight path length is shorter than the other cavities.

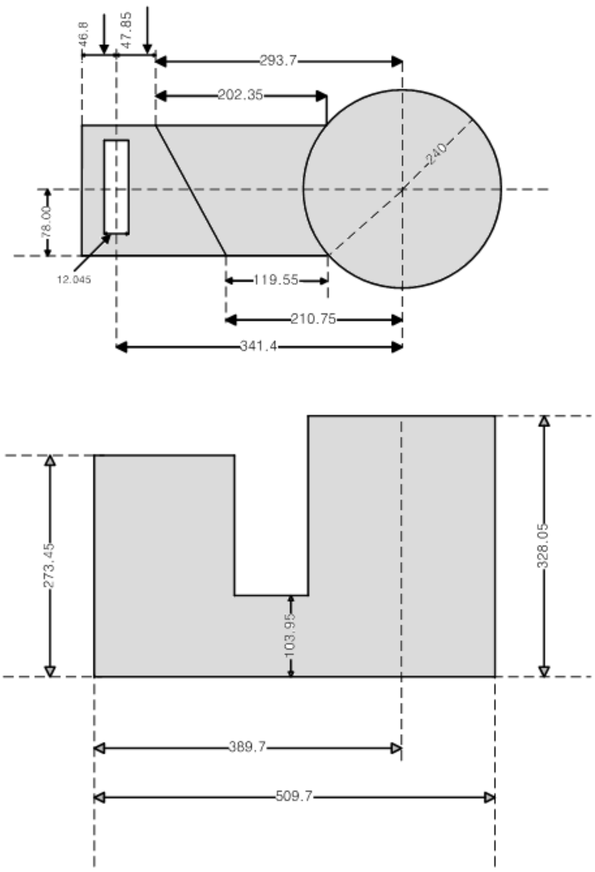

Figure 1. Kori1&2 1/20 cavity model

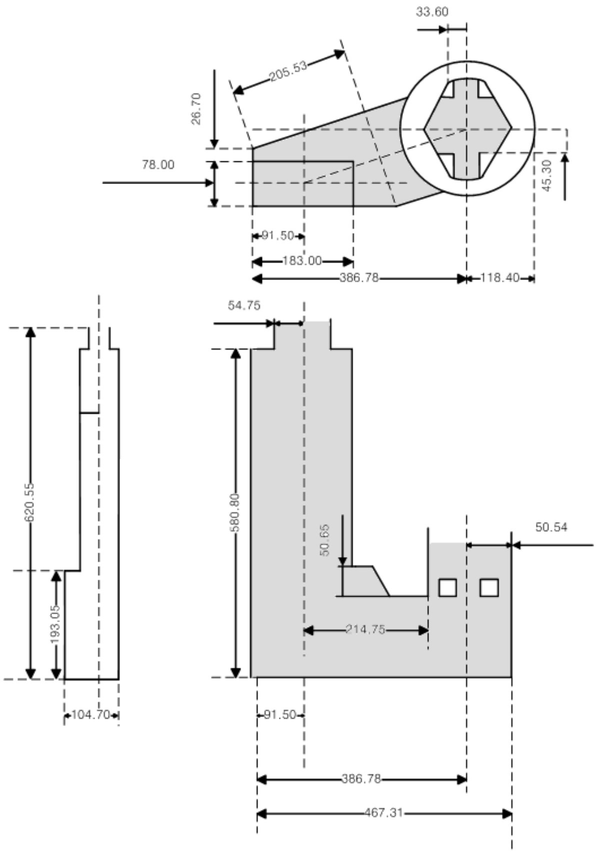

Figure 2. YGN3&4 1/30 cavity model

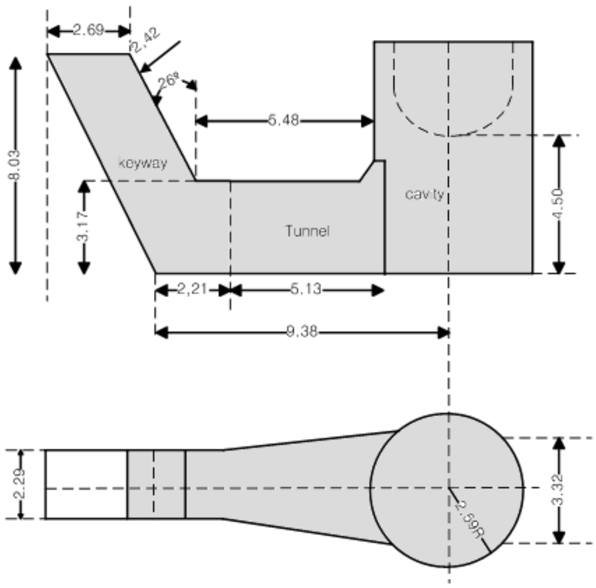

Figure 3. Zion 1/10 cavity model

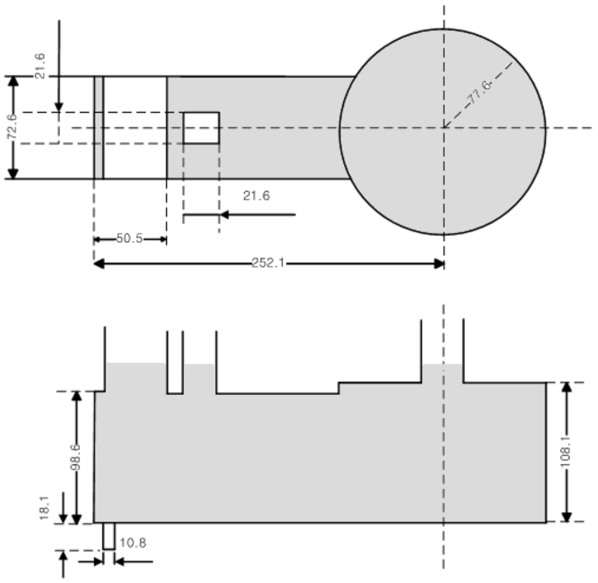

Figure 4. Surry 1/42 cavity model

4. Numerical Test

The amounts of dispersed molten core measured experimentally are compared to estimates by four correlations [3]. The standard error between measured data and the correlational estimates is calculated as

$$\sigma_{est} = \sqrt{\frac{\sum_{i=1}^{N_d} (Y_i - X_i)^2}{N_d}}$$

Y_i Measured Dispersal Fraction [%]

X_i Correlational Estimation [%]

N_d Number of Data Point

The lower σ_{est} means the better accuracy of the correlation.

The comparison graph of predicted and measured data for Kori 1&2 cavity, YGN 3&4, Surry and Zion are shown in **Figure 5** ~ **7**, **Figure 8** ~ **10**, **Figure 11** ~ **12** and **Figure 13**, respectively and standard errors are summarized in **Table II**. 4 plant cavity. For Kori 1& and YGN 3&4 cavities, all models except Henry model tend to over-predict the dispersed molten core than experimental data. Henry model shows poor estimation accuracy. On the other hands, for Surry type cavity, most models tend to under-predict the dispersal fraction. For Zion cavity, only Ishii model under-predicts the fraction.

Levy model shows the lowest standard error. This is because Levy model has general fluid characteristic. For experiment of Surry plant, Levy model shows very accurate estimate. However, it requires the standard value and cavity constant which is experimentally determined for each cavity type, which hinders the applicability of Levy model.

All models show poor estimations for cavity of Zion plant, which has asymmetric geometry. Due to its asymmetric geometry, it is expected that the dispersed molten core would impact the cavity walls more than other cavities, which result in the large error in estimation. Also the inclined angle of instrument tunnel may induce the error. The correlations have no consideration of the effects from the inclination.

Also, it can be seen that all models have large error for cavity of Surry plant, which has very short flight length. Because of short flight length, the melt may directly escape from the cavity by bouncing the cavity wall. This portion may not be properly captured by correlations and result in large uncertainty in estimation.

Table II. Comparison of Standard Error

	Kori1,2	YGN3,4	Zion	Surry
Henry	24.74	18.23	15.95	37.77
Kim	2.31	0.62	8.64	51.84
Ishii-Kataoka	10.48	5.25	7.47	29.26
Levy	3.10	2.00	7.03	19.76

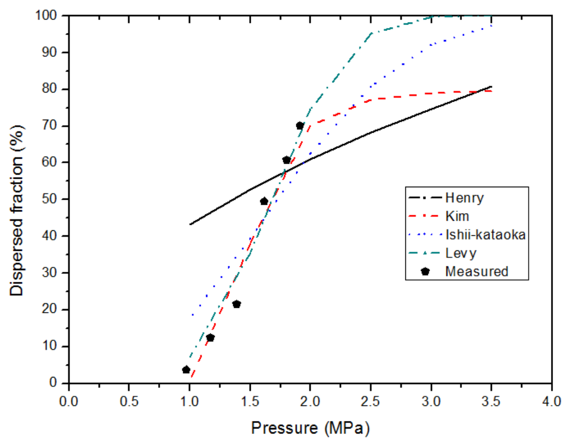

Figure 5. Comparison for Kori 1&2 Cavity (hole diameter = 10mm)

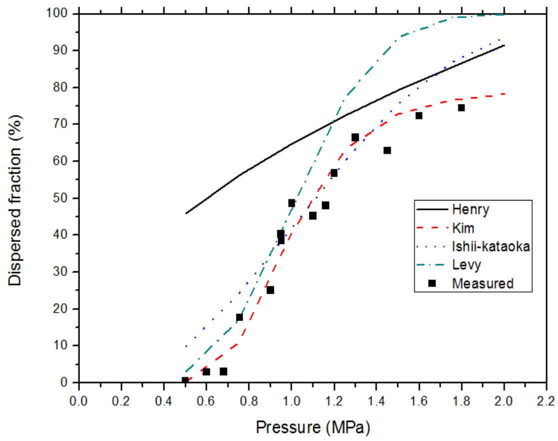

Figure 6. Comparison for Kori 1&2 Cavity (hole diameter = 15mm)

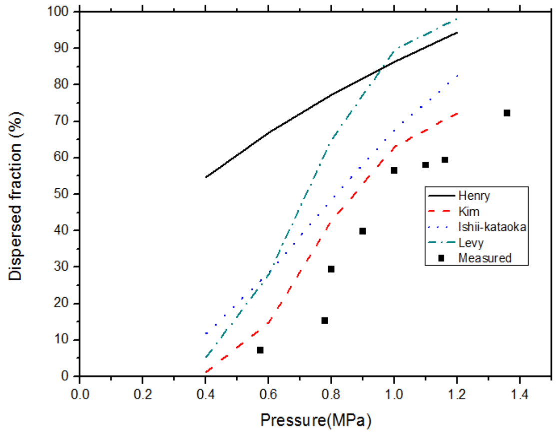

Figure 7. Comparison for Kori 1&2 Cavity (hole diameter = 20mm)

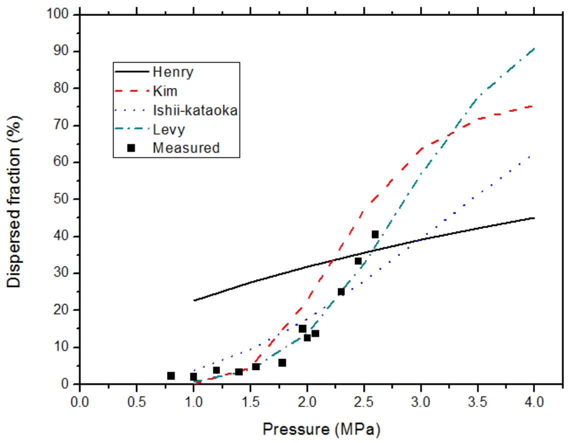

Figure 8. Comparison for YGN 3&4 Cavity (hole diameter = 10mm)

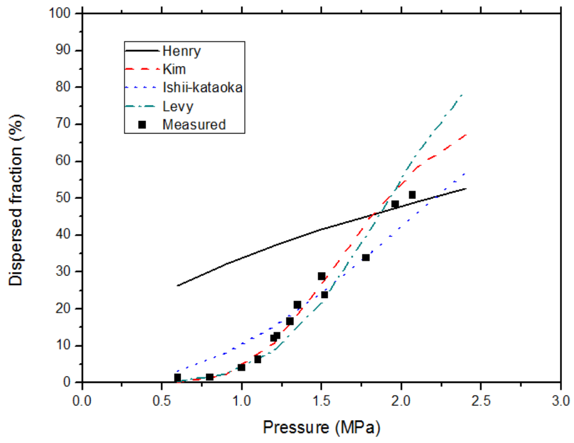

Figure 9. Comparison for YGN 3&4 Cavity (hole diameter = 15mm)

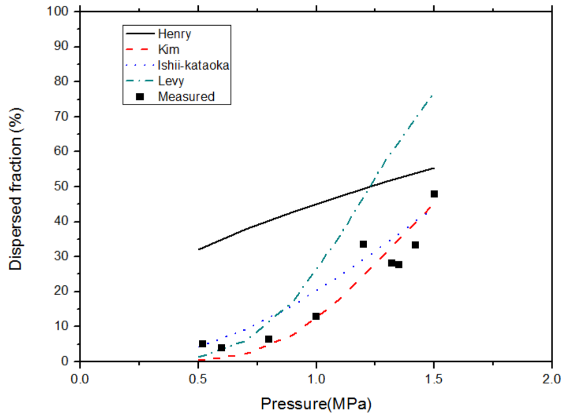

Figure 10. Comparison for YGN 3&4 Cavity (hole diameter = 20mm)

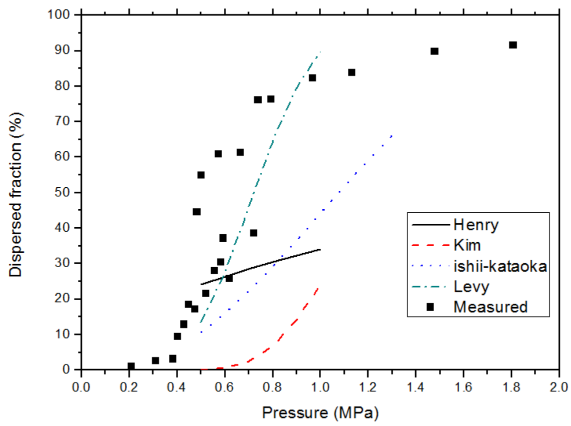

Figure 11. Comparison for Surry Cavity (hole diameter = 9.53mm)

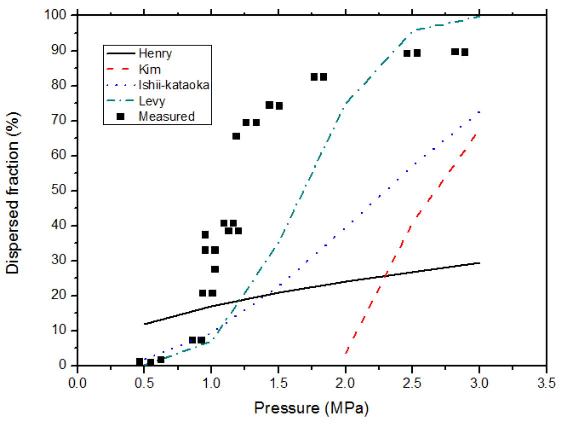

Figure 12. Comparison for Surry Cavity (hole diameter = 4.76mm)

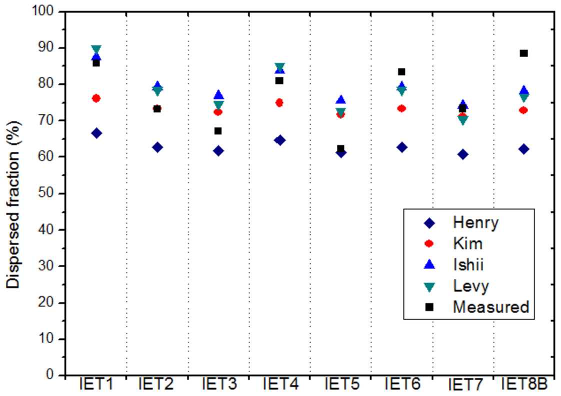

Figure 13. Comparison for Zion Cavity (hole diameter = 3.5mm)

5. Conclusion

In order to investigate the geometry effect on molten core dispersal and examine the applicability of correlations to specific cavity, HPME/DCH experiments are collected and the measured dispersal fractions are compared to estimates by correlations. It has been shown that Iif the geometry of cavity is complicated asymmetrically, melt dispersion is decreased as deposited at cavity structure wall. This complexity increases the error in the prediction. On the other hands, if the flight length for dispersed melt is too short, a large amount of melts could directly escape from the cavity without experiencing the entrainment, the correlation estimate would not be accurate. Therefore, special attention should be given for applying the correlations to those cases.

It can be concluded that for Kori 1&2 and Zion which have sufficient flight length and symmetrical flow area, all correlations except Henry model would be applicable with reasonable errors. The estimation would be conservative because the correlations are over-estimating.

NOMENCLATURE

A_v	Vessel failure area
M_W	Gas molecular weight
P_v	RPV pressure
A_s	Horizontal surface area of cavity and instrument tunnel
ρ_D	Debris density
ρ_g	Gas density
D_c	Hydraulic diameter
d_h	Failure diameter
μ_d	Debris viscosity
μ_g	Gas viscosity
σ	Debris surface tension
U_{g0}	Maximum gas velocity
U_{g0}	Minimum gas velocity
A_c	Cavity flow area
γ	Specific heat ratio
V_0	Primary system volume
δ	Film thickness
$\delta_0 = 0.25 d_h$	Initial film thickness
K_c	Cavity constant
L_p	Length of debris flow path
L	Effective cavity length
R	Gas constant
T	Gas temperature
m_o	Initial mass
v_f	Film velocity
d_s	Standard diameter
R_s	Standard gas constant
T_s	Standard gas temperature

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