Particle Size Distribution by Low Melting Point Alloy FCI Tests and Impact of Distribution Constant on Debris Bed DHF

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1. Introduction

Regarding the severe accident of nuclear power plants with mitigation strategy by cavity flooding, the prediction of the ex-vessel debris bed coolability is highly important to assess the integrity of containment. The coolability of the debris bed is commonly assessed by DHF (dryout heat flux), which has close relation with the debris size governing the pressure drop inside the debris bed. The debris size is determined by the FCI (fuel-coolant interaction) preceding the debris bed formation. Thus, some of previous research works about the debris bed coolability referred to the particle size distribution results from FCI (fuel-coolant interaction) experiments, such as FARO [1,2]. Moriyama et al. [3] reported that the Rosin-Rammler distribution well models the particle size distribution obtained by FCI experiments. They also suggested the characteristic constants of the Rosin-Rammler distribution to roughly approximate the existing experimental data for high temperature oxide melts.

This work presents the particle size distribution obtained by FCI experiments with a low melting point alloy and discusses the influence of the debris size distribution characteristics on debris bed coolability.

2. Size Distribution of Debris by MATE Experiement

2.1 MATE experiment

MATE (Melt jet breakup Analysis with Thermal Effect) facility was constructed and FCI tests were conducted [4, 5]. The schematic figure of MATE facility is shown in Fig. 1. The simulant metal (Bi-Sn alloy : 58:42 wt%; Density : 8750 kg/m^3) is used to produce the melt jet. The melt jet breakup behavior was captured by high-speed camera for the measurement of the jet breakup length. The particulate debris bed settled on the debris catcher was collected and sieved into 19 classes to obtain the particle size distribution. The agglomerated or very large diameter debris (than the jet diameter) were excluded.

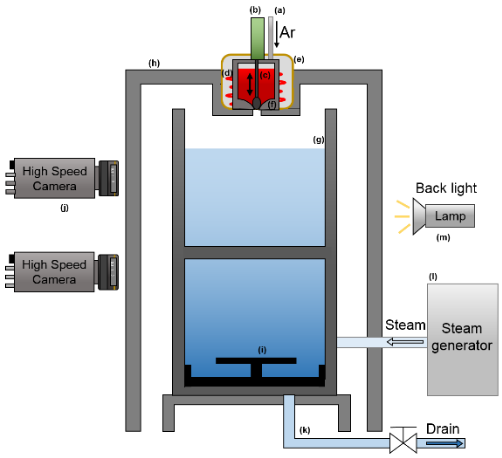

Fig. 1. Schematic figure of MATE facility; (a) Ar line, (b) air cylinder, (c) plug, (d) conduction heater, (e) insulator, (f) crucible, (g) pool, (h) support, (i) debris catcher, (j) high speed camera, (k) drain, (l) steam generator, (m) light

2.2 Rosin-Rammler Distribution

It was reported that the Rosin-Rammler distribution show a good agreement with the particle size distribution by the FCI [3]. The Rosin-Rammler distribution was proposed originally for the particle size distribution of fractured coal [6]. It is used to describe the size distribution of particles produced by break up of bigger particles. The Rosin-Rammler distribution is described by

$$\mathrm{F} = 1 - \exp\left[-\left(\frac{D_p}{D_e}\right)^n\right] \qquad (1)$$

where, F is mass fraction of particles smaller than D_p, D_e is the 'absolute size constant' and n is the 'distribution constant'.

Eq. (1) can be modified to Eq. (2) that appears as a linear function on modified coordinates.

$$\log\left\{log\left(\frac{1}{1-F}\right)\right\} = \mathrm{n}(\log D_p - log D_e) \qquad (2)$$

Here, D_e can be converted to the mass median diameter (MMD), D_{MM}, by Eq. (3).

$$D_{MM} = D_e(log2)^{1/n} \qquad (3)$$

The Rosin-Rammler distribution is characterized by absolute size constant (D_e) and distribution constant (n). Moriyama et al. [3] developed a correlation for the mass median diameter and suggested the distribution constant n=1.5 for FCI experiments with high temperature materials.

2.3 MATE Results

The particle size distribution obtained by MATE experiment also well fitted by the Rosin-Rammler formula and the characteristic constants for each case are shown in Table I. The determination coefficient R^2, for the fit were over 0.98. No clear tendency of the absolute size constant on experimental conditions were observed (Detailed test conditions are described in the Ref. [4]). The distribution constant is in the range 1.71 ~ 2.39 with the average 1.97. The present size distribution were compared with available existing data in Fig. 2. The experimental conditions are described follow: the water temperature was saturated condition, the melt temperature was 300 C^0, the ambient pressure was 1 bar, the jet diameter varies from 14 mm to 35 mm.

Table I. Results of MATE experiments analysis for the Rosin-Rammler distribution

	n	D_e	R^2	MMD [mm]	$\frac{D_{MM}}{\left({\sigma_m}/{g\rho_m}\right)^{0.5}}$
MATE00	2.39	5.3	0.99	4.0	1.9
MATE00-2	2.21	4.1	0.99	3.1	1.4
MATE01	2.01	3.8	0.99	5.7	1.3
MATE02	1.76	4.7	0.99	3.9	1.8
MATE04	1.76	3.7	0.98	2.6	1.2
MATE05	1.71	4.1	0.99	3.0	1.4
MATE06	2	3.7	0.98	2.6	1.2
MATE07	1.92	3.7	0.98	2.6	1.2

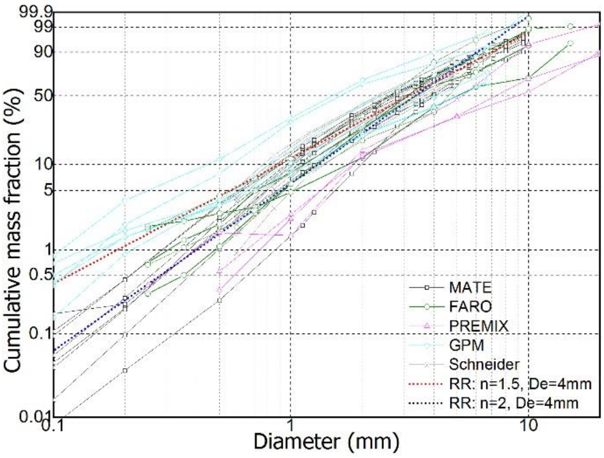

Fig. 2. Particle size distribution of MATE experiments and previous experiments with Rosin-Rammler distribution; MATE [4, 5], FARO [7], PREMIX [8], GPM [3], Schneider [9].

FARO results [7] show the range 1.17 ~ 2.06 with the average 1.57, PREMIX results [8] show the range 1.32 ~ 1.99 with the average 1.69, GPM results [3] show the range 1.36 ~ 1.76 with the average 1.54 and Schneider results [9] show the range 1.58 ~ 2.69 with the average 1.96. FARO, PREMIX and GPM used the high-melting point simulant and Schneider and the present work, MATE, used the low-melting point alloy simulant.

Therefore, the distribution constants for the cases with high-melting point simulant show the average value about 1.5 that for the cases with low-melting point alloy simulant show the average value about 2. The reason of the deviation of the distribution constant is not clear so far.

Dimensionless MMD values obtained by MATE experiment show similar range with previous experiments, as shown in Table I. However, the correlation for the MMD developed by Moriyama et al. [3] doesn't fit well with the results showing larger dimensionless diameter (factor of 2 ~ 3).

3. Effect of Distribution Constant on DHF

The observed deviation of distribution constants by the groups of materials is interesting from the view point of uncertainty in the actual debris bed characteristics in relation to the debris bed coolability, as well as the mechanism of particle generation. Thus, we studied the effect of distribution constant on DHF of debris bed using a 1-D top flooded debris bed model [10].

3.1 1-D Top Flooded debris bed pressure drop Model for DHF Calculation

Basic concept and the detailed calculation process is described in the reference [10]. DHF is calculated by solving the first order ordinary differential equation as follows:

$$\nabla p_g - \nabla p_l = \nabla p_c = \left(\rho_l - \rho_g\right)\vec{g} + \frac{\overrightarrow{F_{pl}}}{\varepsilon(1-\alpha)} - \frac{\overrightarrow{F_{pg}}}{\varepsilon\alpha} \tag{4}$$

$$-\nabla p_g = \rho_g\vec{g} + \frac{\overrightarrow{F_{pg}}}{\varepsilon\alpha} \tag{5}$$

$$-\nabla p_l = \rho_l\vec{g} + \frac{\overrightarrow{F_{pl}}}{\varepsilon(1-\alpha)} \tag{6}$$

$$P_c = P_g - P_l = \sigma cos\theta\sqrt{\frac{\varepsilon}{K}}J(s) \tag{7}$$

$$\overrightarrow{F_{pg}} = \varepsilon\alpha\left(\frac{\mu_g}{KK_{rg}}\overrightarrow{J_g} + \frac{\rho_g}{\eta\eta_{rg}}\left|\overrightarrow{J_g}\right|\overrightarrow{J_g}\right) \tag{8}$$

$$\overrightarrow{F_{pl}} = \varepsilon(1-\alpha)\left(\frac{\mu_l}{KK_{rl}}\overrightarrow{J_l} + \frac{\rho_l}{\eta\eta_{rl}}\left|\overrightarrow{J_l}\right|\overrightarrow{J_l}\right) \tag{9}$$

where $\boldsymbol{\varepsilon}$ is the porosity, $\boldsymbol{\alpha}$ is the void fraction, $\overrightarrow{\boldsymbol{F_{pl}}}$, $\overrightarrow{\boldsymbol{F_{pg}}}$ are drag forces between solid particles and fluid in porous media, K is the permeability, $\boldsymbol{\eta}$ is the passability, $\boldsymbol{K_{rg}}$ is the relative permeability, $\boldsymbol{\eta_{rg}}$ is the relative passability by the Reed model [11], $\boldsymbol{\mu}$ is the viscosity and $\mathbf{J}(\boldsymbol{s})$ is a function of saturation, suggested by Lipinski [12]. Through iterative calculations of Eq. (4) with increase of heat flux, DHF ids obtained when the dryout occurs in the bed.

3.2 Test Matrix

The postulated particle size distribution conditions are described on Table II. MMD is set as constant value varying from 2 mm to 6 mm. The value of distribution constant, n, varies from 1 to 2.7 in each MMD condition as seen in the FCI experimental data. The surface area mean diameter (d_a), as a representative harcteristic length for pressure drop in a debris bed with particle size distribution proposed by Park et al. [1], was calculated in each cases and applied in the DHF evaluation by Reed model [12].

Table II. Test matrix for DHF calculation

MMD [mm]	n	d_a [mm]	D_e [mm]	DHF [kW]
2	1	0.8	2.89	238
	1.5	1.16	2.55	373
	2	1.48	2.4	498
	2.5	1.67	2.32	566
	2.7	1.72	2.29	585
4	1	1.35	5.77	449
	1.5	2.26	5.11	748
	2	2.92	4.8	916
	2.5	3.32	4.63	1004
	2.7	3.43	4.58	1022
6	1	1.86	8.66	633
	1.5	3.32	7.66	1004
	2	4.37	7.21	1204
	2.5	4.98	6.95	1295
	2.7	5.14	6.87	1321

Postulated model conditions are same in all cases ; debris bed porosity : 0.4, ambient pressure : 1 bar, debris bed height : 1 m, particle density : 8000 kg/m^3.

3.3 DHF Calculation Results

DHF of each cases are compared in Table II and Fig. 3. The DHF increases as MMD increases due to the low pressure drop. As the distribution constant becomes smaller, d_a becomes smaller and DHF also becomes lower with same MMD.

DHF increases by the factor of 2 when the distribution constant change from 1 to 2 with same MMD. The average distribution constants for low temperature alloy and high temperature melts are 1.5 and 2, respectively, and the variation exists even among the cases of FARO experiments, I.E. 1.17 - 2.06. So, for the variation in existing data, n = 1.2 – 2.1, the corresponding variation of DHF is factor of 2. That indicates the presently obtained variation of DHF should be considered as an uncertainty.

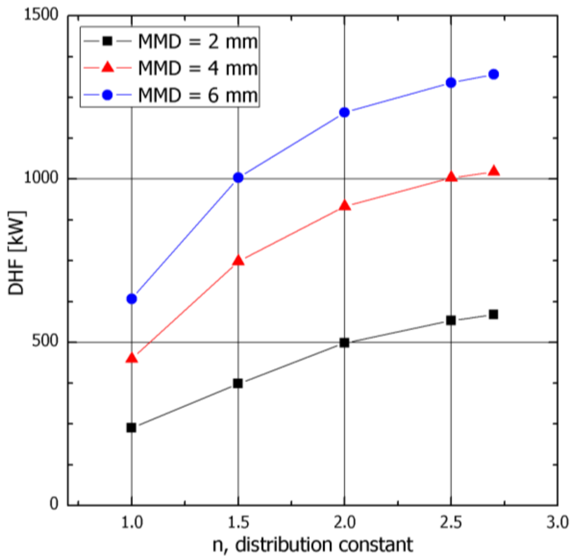

Fig. 3. DHF Results according to the Distribution Constant

4. Conclusions

The debris size distribution was examined for the debris bed obtained by a series of low-melting point alloy melt jet breakup experiment, MATE. The result was well expressed by the Rosin-Rammler distribution of distribution constant, n = 2, and characteristic size, MMD = 3.4 mm. It was found the present and other experiments with low temperature melting alloys commonly showed the distribution constant, ~2, different from, ~1.5, observed in existing high temperature oxide FCI experiments.

The impact of the distribution constant on the debris bed coolability was evaluated by, 1-D DHF model. Analyses were conducted for 15 test cases with debris MMD 2 mm – 6 mm and the distribution constants 1 – 2.7, by applying the surface area average diameter, d_a as a representative particle diameter. As the distribution constant value become smaller when keeping the same MMD, DHF becomes lower. DHF changes by the factor of about 2.3 for the variation of the distribution constant by available experimental data including FARO tests. Currently, particle size distribution data of FARO tests is most similar available data with the real severe accident condition because it is largest experiments using corium (UO_2 + ZrO_2). Thus, FARO tests is chosen as a reference data, which the particle size distribution of the real severe accident condition is considered having similar distribution, in this paper.

The characteristic size of the debris and the debris bed porosity would have stronger impact on the DHF, as well as multidimensional effects. Consistent correlation for all those aspects are wanted. Moreover, Sensitivity analysis of other variables (bed porosity, ambient porosity, bed height and etc.) having an effect on the DHF should be conducted in order to apply to real severe accident conditions.

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