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Modified Rosin-Rammler distribution for debris particle size : Effect of minimum particle size on DHF

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1. Introduction

With the respect of 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 issue assessing the integrity of containment. Final goal of accident mitigation is complete cooling of debris bed until the decay heat becomes extremely low.

The DHF (dryout heat flux) is a typical parameter for assessment of the debris bed coolability, which has close relation with the pressure drop inside the debris bed. Among several parameters (porosity, shape factor, ambient pressure and etc.), the debris size (Sauter mean diameter, SMD) also has strong effect on the pressure drop of the debris bed.

Therefore, many research works were conducted to predict the representative particle diameter after FCI (fuel-coolant interaction) phenomenon, such as Abe et al. [1] and Bang et al. [2]. Not only the representative diameter, but also the size distribution was studied by Moriyama et al. [3], reporting that the Rosin-Rammler distribution well models the particle size distribution obtained by FCI experiments. In our previous research, Jung et al. [4] practically quantified and compared the distribution constant of the Rosin-Rammler distribution based on the previous experiments, and emphasized the importance of small particles in terms of the coolability by conducting the sensitivity analysis of the distribution constant with the 1-D top flooded DHF calculation.

Even though the particle size distribution of debris bed was extensively investigated previously, there was little discussion about the possibility of the minimum particle diameter inside the debris bed. In this paper, we introduce the concept of minimum particle diameter in the debris bed because of the steam flow generated by the decay heat. Modified Rosin-Rammler distribution was suggested in order to apply the minimum diameter concept. As a result, through 1-D DHF calculation, the effect of the minimum diameter on the debris bed coolability was investigated.

2. Rearrangement concept of small particles in the debris bed

During the severe accident in NPPs, molten core continuously generates the decay heat and increase its temperature up to ~3000 K. Since its temperature is very high and generates massive heat, the debris bed, which is formed after the FCI in the water, significantly vaporizes the coolant leading to the internal steam flow

Due to this steam flow, it is possible that small particles are blown away from the debris bed (Fig. 1). The size criteria for blown particle would be determined differently according to the accident scenario: Decay heat, debris density, radius and height of the debris bed. Since the important region for the predicting debris bed coolability is the center of the debris bed, where is the most probable region to be dried out, the rearranged particle to the periphery would not be significant to the coolability.

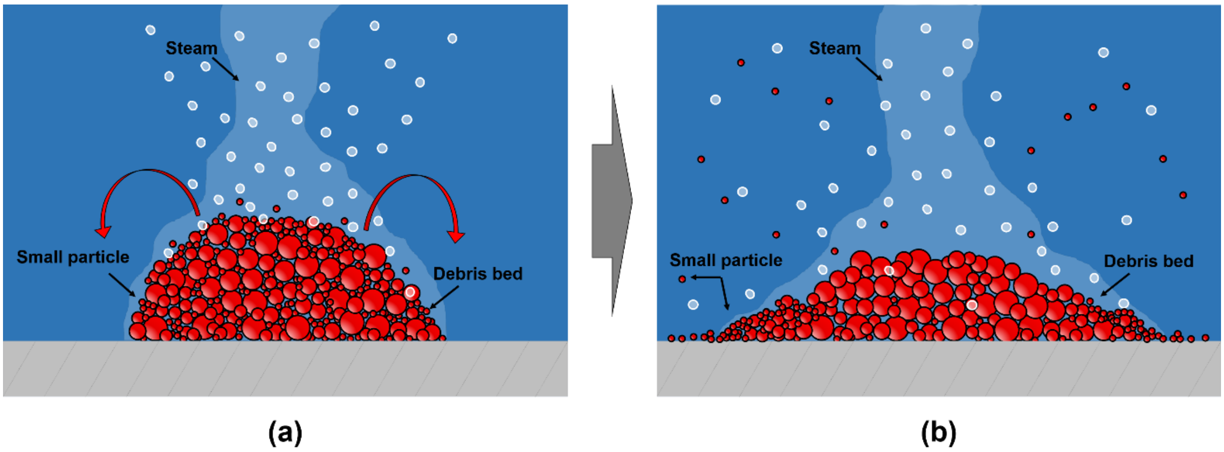

Fig. 1. Rearrangement of the small particle due to the steam flow; (a) Original state, (b) Rearranged state

In other words, the mean particle diameter of the debris bed could be increased by considering the rearrangement of the small particles. This would increase the DHF limit also, leading to the more steam generation. Then, it recursively makes larger particles to be rearranged. Finally, particular debris size will be determined, which is the limit participating in the rearrangement. These steps are summarized in Fig. 2. Determination procedure for searching the rearrangement size should be iteratively calculated with the computer code.

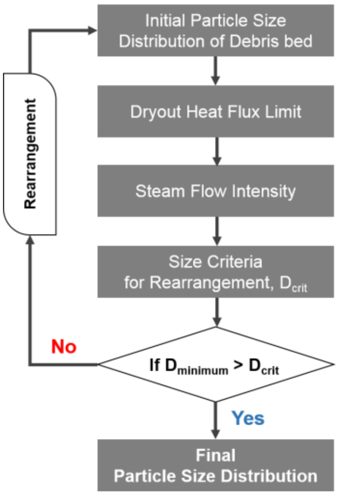

Fig. 2. Flow chart for the determination of particle size distribution considering the rearrangement

Practically all the calculation for the debris bed coolability will be conducted by the computer code, thus the model for the particle size distribution of debris bed is mandatory, the Rosin-Rammler distribution in this case. However, the existing Rosin-Rammler distribution has no capability to express the minimum particle diameter parameter. In conclusion, the Rosin-Rammler distribution was modified in order to consider the minimum particle diameter and it is elucidated in the next section.

3. Modified Rosin-Rammler distribution

3.1 Original 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 is described by

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

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.

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

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

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

The Rosin-Rammler distribution is characterized by absolute size constant and distribution constant. Moriyama et al. [3] suggested the distribution constant n = 1.5 for FCI experiments with high temperature materials.

In definition, the Sauter mean diameter (SMD) can be expressed as Eq. (4).

$$SMD = \overline{D_{3,2}} = D_e\Gamma\left(1 - \frac{1}{n}\right) \qquad (4)$$

where, SMD is Sauter mean diameter, Γ( ) is gamma function.

3.2 Modified Rosin-Rammler distribution for minimum particle diameter

At the situation mentioned in the section 2, the mass fraction of particles smaller than the minimum diameter becomes zero (truncated) and the sum of other mass fraction is stretched to 1, because we assume that only the smaller particles than the minimum diameter are rearranged without any movement of the larger particles.

According to this concept, the Rosin-Rammler distribution can be truncated as Eq. (5).

$$\text{F} = 1 - \exp\left[-\left(\frac{D_p}{D_e}\right)^n\right]\exp\left(\frac{D_{min}}{D_e}\right)^n \qquad (5)$$

where, D_{min} is minimum diameter. Additional exponential term regarding the minimum diameter is included based on Eq. (1).

Since the form of distribution function is changed, the absolute size constant and SMD also have different form than the original Rosin-Rammler distributin as Eq. (6) and (7).

$$D_e = (\frac{MMD^n - D_{min}^n}{ln2})^{1/n} \qquad (6)$$

$$SMD = \overline{D_{3,2}} = \frac{D_e\Gamma\left(1,\left(\frac{D_{min}}{D_e}\right)^n\right)}{\Gamma\left(1-\frac{1}{n},\left(\frac{D_{min}}{D_e}\right)^n\right)} \qquad (7)$$

where Γ(,) is upper incomplete gamma function.

Both the gamma function and the upper incomplete gamma function are can be calculated in the computer code.

The modified Rosin-Rammler distribution is three parameter function (absolute size constant, distribution constant, minimum particle size), thus the effect of the minimum diameter on the SMD is studied with the comparison of the Original Rosin-Rammler distribution. In every cases and every distribution constant, SMD value is smaller than the MMD. Also, as the minimum diameter becomes increased, SMD also increases.

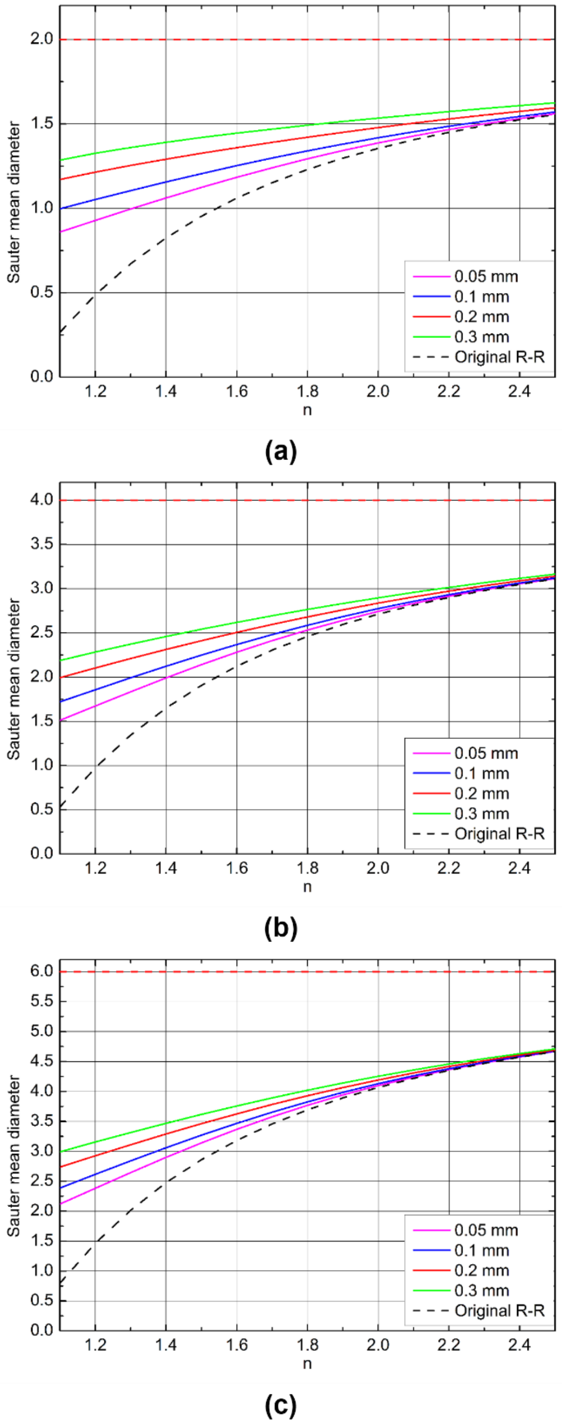

Fig. 3. Effect of minimum diameter on the SMD; (a) MMD: 2 mm, (b) MMD: 4 mm, (c) MMD: 6 mm
; dashed red line: MMD of each case

4. Effect of minimum diameter on DHF

We investigated the effect of minimum diameter on DHF of debris bed using a 1-D top flooded debris bed model.

4.1 1-D Top Fluooded debris bed pressure drop Model for DHF Calculation

Basic concept and the detailed calculation process is described in the reference [5]. DHF is calculated by solving the first order ordinary differential equation as follows:

$$\nabla p_g - \nabla p_l = \nabla p_c = (\rho_l - \rho_g)\vec{g} + \frac{\overrightarrow{F_{pl}}}{\varepsilon(1-\alpha)} - \frac{\overrightarrow{F_{pg}}}{\varepsilon\alpha} \tag{8}$$

$$-\nabla p_g = \rho_g \vec{g} + \frac{\overrightarrow{F_{pg}}}{\varepsilon\alpha} \tag{9}$$

$$-\nabla p_l = \rho_l \vec{g} + \frac{\overrightarrow{F_{pl}}}{\varepsilon(1-\alpha)} \tag{10}$$

$$P_c = P_g - P_l = \sigma cos\theta \sqrt{\frac{\varepsilon}{K}} J(s) \tag{11}$$

$$\overrightarrow{F_{pg}} = \varepsilon\alpha\left(\frac{\mu_g}{KK_{rg}}\vec{J_g} + \frac{\rho_g}{\eta\eta_{rg}}|\vec{J_g}|\vec{J_g}\right) \tag{12}$$

$$\overrightarrow{F_{pl}} = \varepsilon(1-\alpha)\left(\frac{\mu_l}{KK_{rl}}\vec{J_l} + \frac{\rho_l}{\eta\eta_{rl}}|\vec{J_l}|\vec{J_l}\right) \tag{13}$$

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 [6], $\boldsymbol{\mu}$ is the viscosity and $\mathbf{J(s)}$ is a function of saturation, suggested by Lipinski [7]. Through iterative calculations of Eq. (8) with increase of heat flux, DHF ids obtained when the dryout occurs in the bed.

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

4.2 Sensitivity analysis of minimum diameter on DHF

Sensitivity analysis of minimum diameter on DHF was conducted with the range of MMD : 2 ~ 6 mm and with the distribution constant of 1.5. The minimum particle diameter range was chosen from 0 mm to 0.5 mm. The calculation results are summarized in Fig. 4. The results with the minimum diameter of 0 mm is can be interpreted as the result from the original Rosin-Rammler distribution.

If we assume that the minimum diameter is 0.3 mm, then the DHF with the modified Rosin-Rammler distribution is 62.4 % (2 mm case), 30 % (4 mm case), and 18.8 % (6 mm case) larger than the original one, respectively. However, it should be prudent to assess the effect of the minimum diameter, because if MMD is large, then the minimum diameter would be large also (refer Fig. 2).

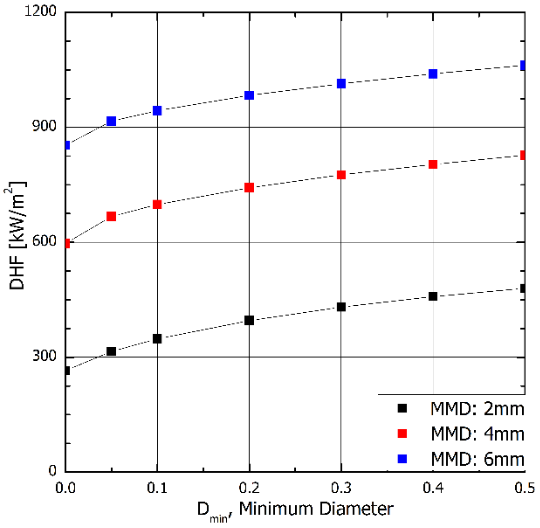

Fig. 4. Effect of minimum diameter on DHF

5. Conclusion

The concept of the rearrangement of the small particles was suggested. In order to consider the minimum diameter of debris bed, the Rosin-Rammler distribution was modified to have three parameters by truncating the small particle domain.

The sensitivity analysis was conducted for the minimum diameter effect on DHF with the 1-D top flooded DHF calculation using the modified Rosin-Rammler distribution (truncated Rosin-Rammler distribution). According to the calculation results, the great impact of the minimum diameter was observed (Fig. 4). As the minimum diameter would be also function of DHF (Fig. 2), the correlation determining the minimum particle diameter is needed. Therefore, further study will be conducted to obtain the proper correlation for the minimum diameter parameter. Currently, the minimum fluidization velocity concept is being expected and is being investigated as the candidate for the minimum diameter correlation.

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