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Preliminary Modelling of Ex-vessel Debris Bed Formation in a Pre-flooded Reactor Cavity

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1. Introduction

When a severe accident occurs in light water nuclear power plants, molten corium can be released from the reactor vessel to the pre-flooded cavity. Then, molten corium is fragmentized into small solid particles and particulate debris bed is formed at the bottom of cavity. Debris bed is cooled by water ingression into the bed and its coolability is related to the property and geometrical shape of debris bed [1]. Several researches on the parameters affecting debris bed shape have been studied experimentally and numerically [2-4]. However, because the debris bed shape is determined by various factors, it was difficult to predict debris bed shape precisely.

In this study, the parameters related to debris bed shape were organized from previous integrated experiments, named DEFCON [5] and DEFCON-S [6]. After that, the effects of each parameter on formation of ex-vessel debris bed were summarized. Consequently, preliminary modelling of ex-vessel debris formation was conducted.

2. Phenomena Related to Debris Bed Formation

Figure 1 shows process of debris bed formation. It was assumed that molten corium is fully fragmentized into particles without a cake (a lump of non-fragmented melt). In this section, phenomena related to debris bed formation and related parameters were organized.

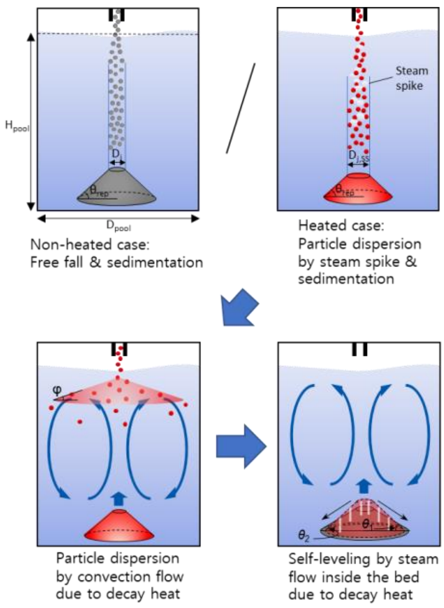

Fig. 1. Debris bed formation process.

2.1 Avalanche of particles during sedimentation

It can be assumed that particles are heaped up with a certain maximum slope angle during free fall. When particles are piled up over this maximum angle, an avalanche of the particle bed will occur. So, slope angle is maintained at this specific angle called angle of repose. With this assumption, basic shape of debris bed can be calculated from total mass of particles and porosity of the bed. Related parameters are listed below.

Initial bed shape = $f\,(m_{\mathrm{bed}}, \varepsilon, \theta_{\mathrm{repose}}, D_{\mathrm{jet}}, \ldots)$

2.2 Particle dispersion by steam spike

Steam spike induced by interaction between heated particles and coolant can lead to particle dispersion during the particle falling into the coolant. Therefore, change of jet diameter by steam spike should be considered. Related parameters about steam spike are listed below.

$\mathrm{D}_{\mathrm{j,SS}} = f\,(D_{\mathrm{j}}, m_{\mathrm{particle}}, T_{\mathrm{particle}}, \ldots)$

2.3 Particle dispersion by convection flow

In the process of removing decay heat from the debris bed, steam is generated continuously and convection flow can be created in the pool. This convection flow can force particles to be dispersed and change the slope angle of particles during the particle sedimentation. Related parameters about convection flow are listed below.

Convection amp. = $f\,(T_{\mathrm{particle}}, q_{\mathrm{decay}}, H_{\mathrm{pool}}, D_{\mathrm{pool}}, \ldots)$
Slope angle $\varphi = f\,(q_{\mathrm{decay}}, U_{\mathrm{terminal}}, H_{\mathrm{pool}}, D_{\mathrm{pool}}, \ldots)$

2.4 Self-leveling

Decay heat of debris bed also results in further change of a debris bed shape after the particle sedimentation. Steam flow formed inside the debris bed by decay heat pushes particles from center to aside. As a result, slope angle of debris bed is getting lower. Related parameters about self-leveling are listed below.

Slope angle $\theta_2 = f\,(\theta_1, q_{\mathrm{decay}}, U_{\mathrm{terminal}}, H_{\mathrm{pool}}, D_{\mathrm{pool}}, \ldots)$

3. Preliminary Modelling of debris bed shape

The effects of phenomena described at Sec. 2 on debris bed shape were confirmed from DEFCON [5] and DEFCON-S [6] experiments. Then, modelling parameters and constants were determined from the experimental results. In this chapter, two DEFCON test results were exemplified for the modelling of debris bed shape. One of the DEFCON test results, CM3R0-2R test result is shown in Fig. 2. In this case, cylindrical stainless steel particles with 3 mm both in diameter and height were used. Particles were just free falling into the pool, and there was no additional heat or forces. As shown in Fig. 2, the bed of a truncated cone shape rather than a simple cone was formed with an angle of repose at the edge. From this result, basic debris bed shape model equation for free falling particles was developed as follows, where ε and θ_{rep} are porosity and angle of repose, respectively.

$$V = \frac{m_{\text{bed}}}{(1-\varepsilon)\rho_p} = \frac{\pi}{3}\left(R_{bed}^3 - R_{jet}^3\right)\tan\theta_{rep}$$

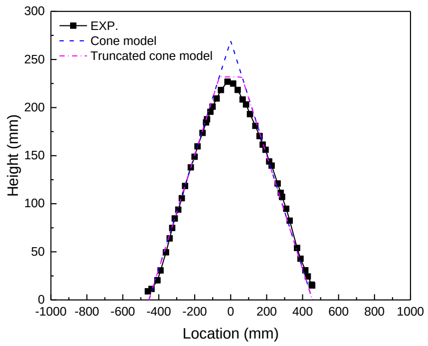

Fig. 2. Debris bed shape of CM3R0-2R case from experiment and modelling.

Figure 3 shows DEFCON CM3R2-2R test result. In this case, air was gradually injected from bottom of the bed with respect to mass of particle bed to simulate steam flow caused by decay heat. The debris bed with a steep angle near the center and relatively a low angle at the edge was observed as Fig. 3. It was regarded that steep center part was formed by avalanches of particles during initial sedimentation and outer part with low slope angle was caused by convection flow. With this concept, debris bed shape for the case of convection flow could be modelled by superposing initial shape (blue line in Fig. 3) and post shape after convection flow (red line in Fig. 3). At this time, maximum slope angle was fixed at the angle of repose. Consequently, final debris shape from modelling was drawn as green line in Fig. 3, and related empirical parameters were decided. Empirical model equation for slope angle of outer part affected by convection flow was developed as follows, where h_{fg} is latent heat of water.

$$\tan\varphi = A\chi^{B} = 0.11\left(\frac{h_{fg}\rho_g}{q_{decay}H_{pool}}U_{terminal}\right)^{0.13}$$

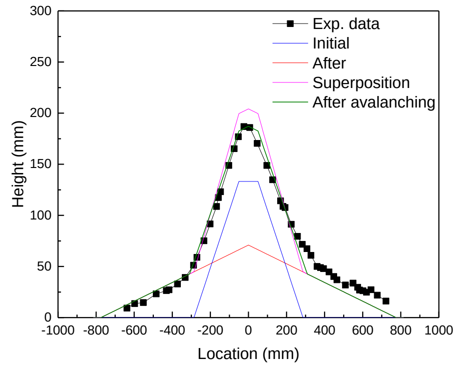

Fig. 3. Debris bed shape of CM3R2-2R case from experiment and modelling.

The effect of self-leveling was simplified to change of slope angle θ_2/θ_1 caused by the steam flow. Empirical model equation was shown as follows. From several experimental results, empirical coefficients K, a, b and c were determined as 0.260, -0.139, 0.465 and 0.184, respectively. By applying this self-leveling effect to previous result (Fig. 3), modelling of debris bed shape with considering integral effects of initial sedimentation, convection flow and self-leveling was conducted, as shown in Fig. 4.

$$\frac{\theta_2}{\theta_1} = K\left(\frac{U_{\text{gas}}}{U_{\text{terminal}}}\right)^{a}\left(\frac{\rho_{\text{p}}-\rho_{\text{l}}}{\rho_{\text{l}}}\right)^{b}\left(\frac{H_{\text{pool}}}{D_{\text{pool}}}\right)^{c}$$

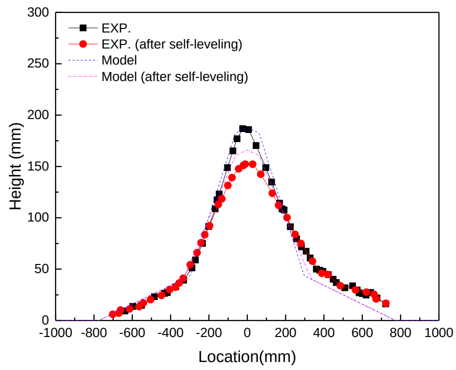

Fig. 4. Debris bed shape of CM3R2-2R case from experiment and modelling including self-leveling.

Thermal related parameters will be found later from other experiments and modelling about heating effects will be supplemented. Also, the effect of poly-dispersed particles on debris bed shape will be integrated. Consequently, integrated empirical model for ex-vessel debris bed formation will be constructed.

4. Conclusions

In this study, process of ex-vessel debris bed formation was summarized, and parameters related to debris bed formation were extracted. By using the experimental results, preliminary modelling on debris bed shape was conducted. By expanding modelling to all experiment cases including heated case and poly-dispersed particle case, integrated empirical model for ex-vessel debris bed shape will be constructed.

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