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Concept of Corium Coolability Module for Debris Bed Formation during Severe Accidents

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1. Introduction

In recent years, severe nuclear accidents have raised concerns about the safety strategies following the Fukushima nuclear accident on March 11, 2011. Severe accidents are intricate situations that could lead to core damage or meltdown, reactor vessel and containment failure. To prevent these situations, an integrated module is needed to assess full scale overall heat transfer and corium coolability.

Some integrated modules, for example, MELCOR, MAAP, RELAP-SCD in U.S., ASTEC in Europe, SAMSON in Japan, and recently CINEMA in Korea have been developed to analyze overall process of the severe nuclear accident.

Recently, development of such codes in Korea has been initiated since without own safety regulatory tools, the limitations of assessment the integrity of national specific Nuclear Power Plants (NPPs) result in the significant risks. Comparing to the CINEMA code, regulatory based severe accident analysis SAFARI (Safety Analysis code For severe Accident Risk Identification) module has recently launched to be developed.

In this study, the SIMBA (Simulation of Interactions in Molten fuel-coolant and debris Bed Analysis) module, the part of SAFARI code for debris bed formation and coolability during severe accidents aims analysis of the fuel coolant (deep water pool) interaction with wet cavity safety strategy through validation of the particle sedimentation experiment, DAVINCI and particle size distribution experiment, DEFOR-M.

2. Concept of corium coolability module

2.1 Configuration of SIMBA

In the current alpha version of SIMBA, some models for particle fragmentation, sedimentation, and heat transfer have been developed to analyze fuel-coolant interaction phenomena that occur when the molten corium is relocated in the wet cavity. SIMBA is composed of corium and containment. Molten corium is injected into the water pool as characteristics of melt jet (velocity, diameter, temperature, etc.), and the fragmented particles are subsequently relocated to the lower cavity. The particle trajectory and heat transfer are evaluated during this tracking. Fig. 1 shows a calculation structure of SIMBA module.

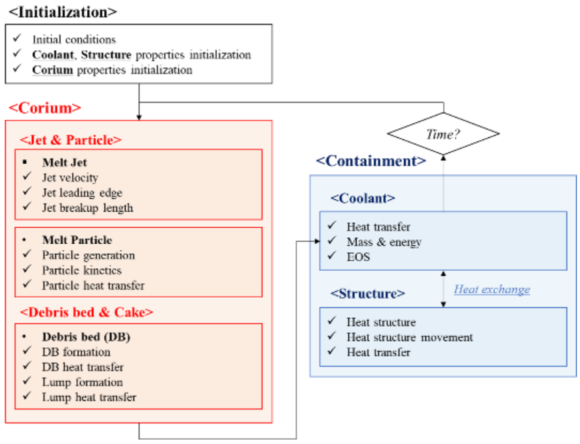

Fig. 1. Calculation structure of SIMBA

In this section some of the techniques used to model the debris bed formation are described.

2.2 Models

The model includes jet breakup, particle size distribution, sedimentation models.

2.2.1 Jet Breakup Model

The melt jet breakup length directly affects the coolability of ex-vessel corium, which determines the likelihood of mitigation of severe accidents. Based on MATE experiments and various experimental results, a jet breakup model (1) that considers thermal-hydraulic conditions is additionally included [1]. The formation of vapor film during relocation of the melt jet can be analyzed by following correlation.

$$\frac{L_{br}}{D_{ji}} = 3.3C_{br}\left(\frac{\rho_m}{\rho_l}\right)^{0.5} Fr^{0.5\left[1-\frac{1}{21354Q+1}\right]} \quad (1)$$

2.2.2 Particle Size Distribution Model

The coolability of the molten corium that occurs dryout at high temperature depends on the particle size composing debris bed. To consider the flow of inner particles of debris bed, the Truncated Rosin-Rammler distribution model (2) following Lipinski type 1D steady state momentum equation (3) is included [2].

$$F = 1 - \exp\left(1 - \left(\frac{d_p^{1.5} - d_{min}^{1.5}}{d_e^{1.5}}\right)\right), \qquad (d_p \geq d_{min}) \quad (2)$$

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$$\frac{dP_g}{dz} - \frac{dP_l}{dz} = (\rho_l - \rho_g)g + \frac{\mu_l j_l}{KK_{r.l}} + \frac{\rho_l |j_l| j_l}{\eta\eta_{r.l}} - \frac{\mu_g j_g}{KK_{r.g}} - \frac{\rho_l |j_g| j_g}{\eta\eta_{r.g}} - \frac{F_i}{\varepsilon}\left(\frac{1}{1-\alpha} + \frac{1}{\alpha}\right) \quad (3)$$

2.2.3 Particle Sedimentation Model

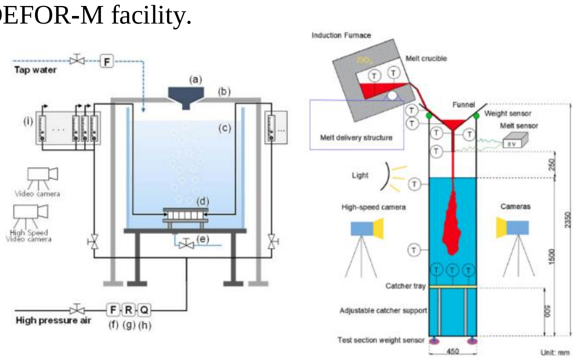
Melt jet breakup results in the particle sedimentation following debris bed formation. Likewise, the coolability is closely related to debris bed formation. For our analysis, SIMBA module is developed with the correlation of conical debris bed model (4), (5) [3].

$$R_c = 0.614\left[\left(\frac{(\rho_l - \rho_v)^2}{\rho_p \rho_g \Delta h_{lg}}\left(\frac{q_d''' H_s^2 \tau}{\dot{m}}\right)\left(\frac{\alpha v_b D_{pc}^4}{(1-\varepsilon) v_p^4}\right)\right)\right]^{\frac{1}{3}} \quad (4)$$

$$\theta_c = \mathrm{atan}\left(4.127\left(\frac{\rho_g \Delta h_{lg}}{(\rho_l - \rho_g)^2}\right)\left(\frac{\dot{m}^2}{q_d''' H_s^2}\right)\left(\frac{v_p^4}{\alpha v_b D_{pc}^4}\right)\right) \quad (5)$$

3. Preliminary validation of the module

In this study to validation of SIMBA for debris bed formation and particle size distribution, DAVINCI [3] and DEFOR-M [4] experiment is executed. Fig. 2(a) and (b) shows a schematic diagram of the DAVINCI & DEFOR-M facility.



(a) (b)

Fig. 2. A schematic of the DAVINCI facility (a), DEFOR-M facility (b)

To investigate the effect of numerical parameters (debris bed porosity, repose angle, modification factor for particle diameter) on the formation of debris bed, SIMBA was simulated by varying the values of numerical parameter and comparing them with the results of experiments. The valid values were then presented in Table 1.

Table. 1. Variable from two experiments and numerical impact parameter in SIMBA

Variable from experiments	**DAVINCI**	**DEFOR-M**
Melt material	SS304	Tin
Melt mass (kg)	5	20
Jet diameter (m)	0.0145	0.02
Jet release height (m)	0.855	1.75
Water pool depth (m)	0.76	1.5
Jet temperature (K)	298.15	652.15
Water pool temperature (K)	298.15	353.15
Particle diameter (m)	Fixed value (0.0023)	Distribution correlation
Debris catcher diameter (m)	0.58	0.45
Numerical parameter	**DAVINCI**	**DEFOR-M**
Debris bed porosity (Def.: 0.5)	0.6	0.2
Repose angle for late in-side avalanche (deg)	10	30
Modification factor for particle diameter (Def.: 1.0)	1.0	0.5

3.1 DAVINCI test for sedimentation model

DAVINCI experiment was constructed at POSTECH in Korea to investigate the characteristics of debris beds with fixed size under a condition of two-phase flow with steam bubble due to the decay heat of the debris bed. In this study, DAVINCI validation scenario was under quiescent pool conditions without steam generation, expected to result in the form of a narrow cylindrical column.

Fig. 3(a) and (b) show the experimental and SIMBA results using a gap-tooth time stepwise approach for the growth of debris bed formation in the vertical direction.

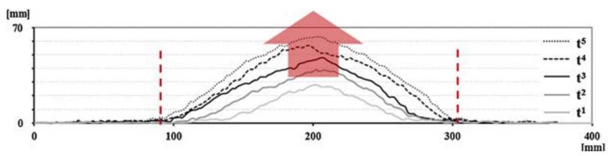


Fig. 3(a). Debris bed formation of experimental result

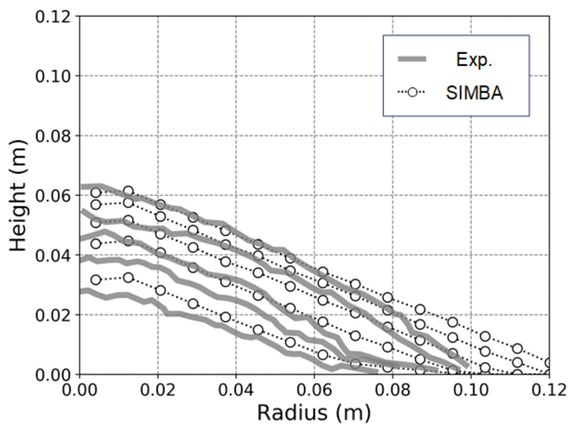


Fig. 3(b). Debris bed height comparison between experimental and SIMBA results

As shown Fig. 3(a), the growth of the debris bed was investigated to have a radius of 0.1m and a height of 0.06m, approximately. It was found that the difference in height between the experimental and SIMBA result was hardly substantial, but the radius of SIMBA was slightly overestimated than experimental result, 0.01m, shown in Fig. 3(b). It can be concluded that the difference in simulant material between cylindrical particle of DAVINCI experiment and sphere particle of SIMBA results in the differences in characteristics of debris bed formations.

3.2 DEFOR-M test for particle size distribution model

The fuel coolant interaction experiment, DEFOR-M was conducted with 20kg of tin at Royal Institute of Technology (KTH) to investigate the formation characteristics of debris bed. To investigate properties of the melt jet, debris bed formation and particle size distribution, the DEFOR-M12 test was employed to validate SIMBA. The melt jet breakup length was shown in Fig. 4.

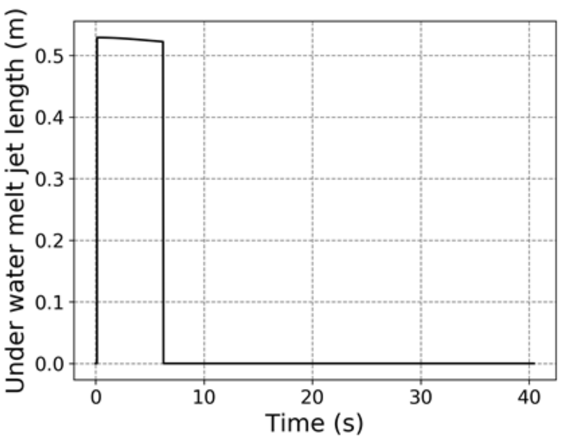
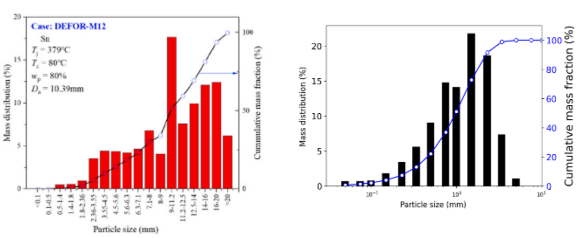


Fig. 4. Jet breakup length under water pool

In Fig. 4, It can be concluded that the melt jet completely fragmented, resulting in a breakup length of approximately 0.5m, without re-melting under conditions of no decay heat.

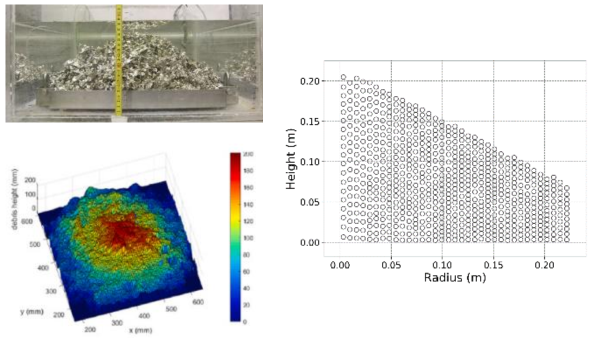
The particle size was fixed in the DAVINCI experiment. In contrast, it is determined by Truncated Rosin-Rammler distribution model (2). Fig. 5(a) and (b) shows the particle size distribution.



(a) (b)

Fig. 5. Particle size distribution of DEFOR-M12 (a) and SIMBA (b)

In Fig. 5, both the experimental and SIMBA results showed a generally consistent trend in cumulative mass fraction, but differences were observed in particle size distribution. The range with the maximum size of particle was investigated to have a diameter of 9mm and 0.5mm, approximately.



(a) (b)

Fig. 6. Debris bed formation of DEFOR-M12 (a) and SIMBA (b)

Fig. 6(a) and (b) shows the debris bed formation of DEFOR-M12 and SIMBA result. Quantitative measurement of the position of each particle was intricate, but debris bed height of centerline was approximately equivalent to about 200mm.

4. Conclusions

SIMBA is a 1D lumped-parameter module developed with the aim of evaluating coolability of molten corium in the wet cavity.

Various correlation models were developed to analyze the melt jet fragmentation, sedimentation, and heat transfer resulting from fuel coolant interaction.

The DAVINCI and DEFOR-M12 experiments, investigating the characteristics of debris bed formation, were employed to validate SIMBA module. The validation was established through the consistency between the experimental results and estimated value of SIMBA module.

However, the developed SIMBA (alpha version) is constrained with its performance to analyze the melt spreading without jet fragmentation during sedimentation. The SIMBA module is being developed to enhancement of performance to analyze overall severe accident scenarios by integrating a melt spread model in future work. Furthermore, it is expected that the results of SIMBA module can be employed as inputs for the SCAR (steam explosion/spike) module and PUMBAA (Molten Corium Concrete Interaction) module so that Korean unique regulatory severe accidents analysis module will be developed.

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