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

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Introduction

Background

✓ Recently, nuclear severe accidents, like Fukushima in 2011, have highlighted the complexity and risks of nuclear incidents leading to core damage, meltdown, and containment failures.

Previous Studies

✓ To prevent these situations, 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 full scale overall heat transfer and corium coolability in nuclear severe accident.

Limitations

✓ 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.

Objective

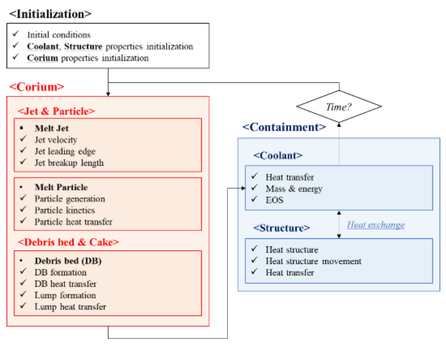
✓ In this study, the SIMBA (Simulation of Interactions in Molten fuel-coolant and debris Bed Analysis) module, the part of SAFARI code for debris bed formation and coolability during severe accidents aims analysis of the fuel coolant interaction with wet cavity (deep water pool) safety strategy through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

Concept of Corium Coolability Module

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 FCI phenomena that occur when the molten corium is relocated in the wet cavity.

✓ Molten corium is injected into a water pool, with its characteristics (velocity, diameter, temperature) being monitored, and the trajectory and heat transfer of the resulting fragmented particles are evaluated as they relocate to the lower cavity.



<Calculation structure of SIMBA>

2. Models

▪ 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. The formation of vapor film during relocation of the melt jet can be analyzed by following correlation.

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

▪ 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 following Lipinski type 1D steady state momentum equation is included.

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

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

▪ Particle Sedimentation Model

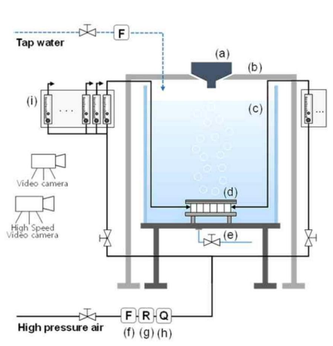
Melt jet breakup results in the particle sedimentation following debris bed formation. Likewise, the coolability is closely related to debris bed formation. For our analysis, SIMBA module is developed with the correlation of conical debris bed model

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

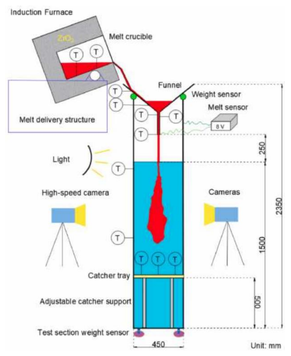
$$\theta_c = \operatorname{atan}\left(4.127\left(\frac{\rho_g \Delta h_{lg}}{(\rho_l - \rho_g)^2}\right)\left(\frac{\dot{m}^2}{q_d''' H_s^2}\right)\left(\frac{v_p^4}{\alpha v_b D_{pc}^4}\right)\right)$$

Preliminary Validation of the Module

✓ In this study to validation of SIMBA for debris bed formation and particle size distribution, DAVINCI and DEFOR-M experiment is executed.



<DAVINCI facility>



<DEFOR-M facility>

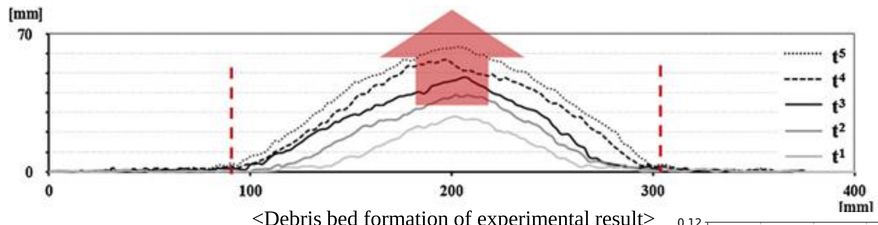
Variable form two experiments and numerical impact parameter in SIMBA

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

- **DAVINCI test for sedimentation model**

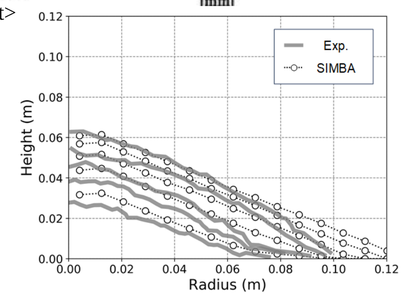
✓ DAVINCI experiment was constructed at POSTECH in Korea to investigate the characteristics of debris beds with fixed size under a condition of two-phase flow with steam bubble due to the decay heat of the debris bed.

✓ 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.



<Debris bed formation of experimental result>

Parameter	Experimental Results	SIMBA Results	Difference
Radius (m)	0.10	0.11	~0.01
Height (m)	0.06	0.06	Negligible
Material Shape	Cylindrical Particle	Spherical Particle	-



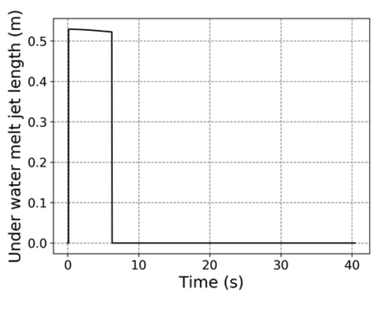
<Comparison of debris bed characteristics between DAVINCI and SIMBA results>

➢ 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.

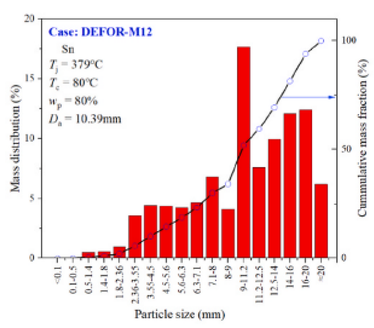
- **DEFOR-M test for particle size distribution model**

✓ 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.

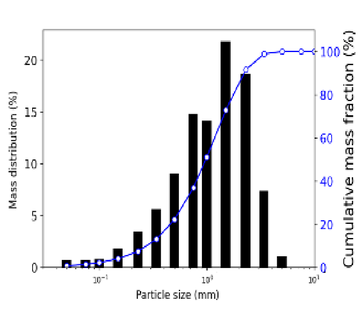
✓ To investigate properties of the melt jet, debris bed formation and particle size distribution, the DEFOR-M12 test was employed to validate SIMBA.



<Jet breakup length under water pool>



<Size distribution of DEFOR-M12>

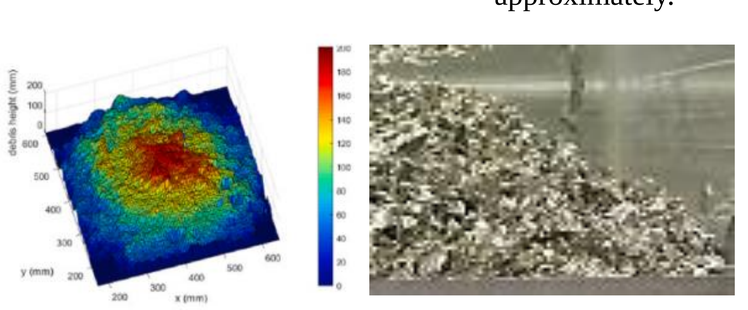


<Size distribution of SIMBA>

➢ 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.

➢ 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.



<Debris bed formation of DEFOR-M12>
<Debris bed formation of SIMBA>

➢ Quantitative measurement of the position of each particle was intricate, but debris bed height of centerline was approximately equivalent to about 200mm.

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 validation was established through the consistency between the DAVINCI & DEFOR-M12 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.

ACKNOWLEDGEMENT

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