Simulation of Particulate Bed Coolability according to Accident Scenarios

Jaehoon Jung[a*], Sang Ho Kim[a], Sang Mo An[a]
[a]*Korea Atomic Energy Research Institute, 111 Daedeok-daero 989beon-gil,*
Youseong-Gu, Daejeon 305-353, Republic of Korea
[*]*Corresponding author: jhjung@kaeri.re.kr*

1. Introduction

During severe accidents at PWRs (Pressurized Water Reactors), when the RPV (Reactor Pressure Vessel) fails, the molten corium is discharged into the reactor cavity. It can lead to increase the containment pressure due to a molten core-concrete interaction (MCCI). Therefore, the cooling and stabilization of the discharged molten corium in the reactor cavity is important task.

The strategy of pre-flooding of coolant into a reactor cavity for ex-vessel corium cooling and stabilization was adopted for the most operating Korean NPPs. It is expected that the molten corium breaks up in the water pool, and accumulated on the cavity floor in the form of a particulate debris bed. Also, it can be coolable. However, if the molten corium reaches the cavity floor without completely breaking up or the debris bed is re-melted, a continuous molten pool, which is called "cake," is produced on the floor, and it can lead to a MCCI [1].

Through the recent research results [2], one of the most important parameters is the debris bed geometry. KAERI is performing the experiment to develop the representative models of the multi-dimensional geometrical configuration of the debris bed and dryout criteria [3], also is developing the ex-vessel COrium cOolabilty aNAlysis module(CORONA) [1]. In this study, we focused on the development of the ex-vessel debris bed coolability analysis module base on the existing models. It is performed the preliminary analysis of ex-vessel debris bed coolability according to severe accident scenarios with the initial version of CORONA.

2. Description of Model

2.1 simplified ex-vessel debris bed coolability module [1]

The cooling process of the ex-vessel corium debris can be divided into several categories which are melt jet breakup, particle dynamics & debris bed formation, and the bed cooling (Fig.1). When the molten corium release from the RPV and goes into the water, the melt jet may break and will fragment simultaneously. The fragmented particles fall into the cavity floor and accumulate on the cavity floor in the form of a debris bed. The heat generated by the debris bed can be removed by natural circulation of coolant through the porous bed.

The simplified ex-vessel debris bed coolability module which covers the melt jet break-up, debris bed sedimentation, debris bed formation and its cooling is under development. Two modules, DEJET and DECOOL, were developed (Fig. 2). DEJET deals with both the melt jet break-up and debris bed sedimentation. The results of the DEJET module, which are the debris particle size distribution, the particle temperature and mass, and the cake temperature and mass are provided to the DECOOL module. DECOOL deals with the debris bed formation and its cooling. The detailed models of DEJET and DECOOL are described in ref. 1.

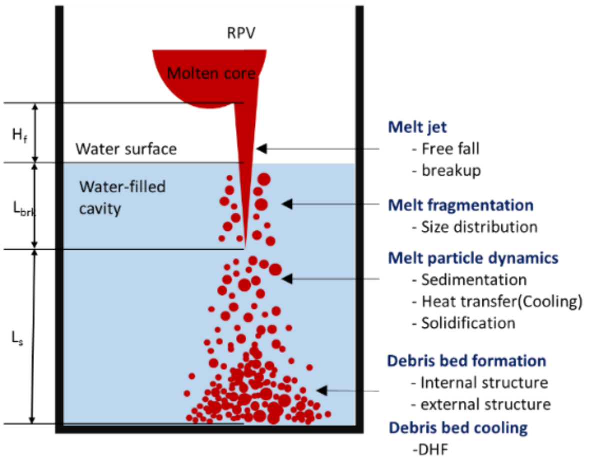

Fig. 1. Scenario of melt outflow from RPV and formation of particulate debris in pre-flooding cavity

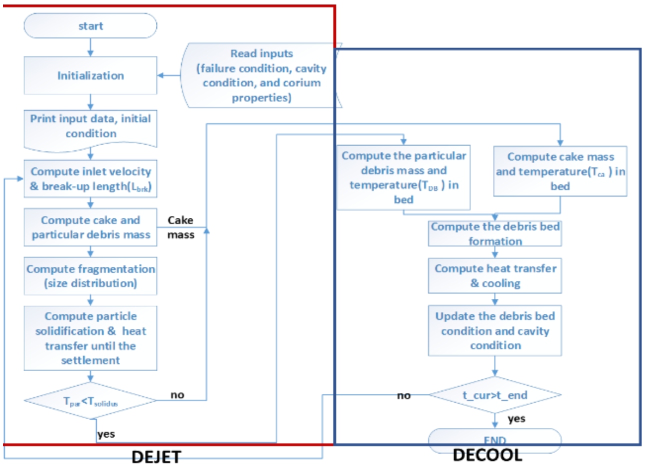

Fig. 2. Debris bed coolability analysis flow chart [4]

The melt jet initial diameter (D_i) and velocity ($V_i = \left(\frac{2\Delta P}{\rho_{melt}}\right)^{0.5}$) is determined by scenarios of accident progression. The jet diameter (D_e) and the velocity (V_e) at the water surface is as follow:

$$D_e = D_i\left(1 + \frac{2gH_f}{v_i^2}\right)^{-0.25} \quad (1)$$

$$V_e = \left(V_i^2 + 2gH_f\right)^{0.5} \quad (2)$$

where, H_f is the free fall height form the melt release point to the water surface. There are 3 correlations to obtain the jet break-up length in DEJET, the default correlation is the Epstein's correlation [5].

The particle movement is tracked by the kinetic equation considering the fluid dynamic resistance.

$$\frac{\partial z^k}{dt} = U_p^k, \quad \frac{\partial U_p^{\,k}}{dt} = -F_{drag}/m_p + \left(\rho_p - \rho_l\right)/\rho_p g, \qquad (3)$$
$$\overline{F}_{drag} = \frac{3}{4} C_d \rho_l \left(\overline{U}_p - \overline{U}_a\right)^2$$

where, U_p, m_p, z, and C_d are the particle velocity, the particle mass, the particle location, drag coefficient. For the drag model, Schiller and Naumann drag model [6] was adopted.

The heat release from a particle during a sedimentation. To evaluate the particle temperature, it is assumed that the particles are lumped. The particle temperature during a sedimentation is evaluated by the energy conservation law. Before particles completely solidify, the heat release from a particle is used for the phase change (Eq.4) and the particle temperature does not change during this processes. After that, the particle temperature is evaluated by Eq. 5.

$$\Delta m_s = \left(\int A_p h_{eff}\left(T_m - T_w\right)dt - \int m_p Q_{de} dt\right) / \left(h_{sf} + c_m\left(T_m - T_{s,sf}\right)\right) \quad (4)$$

$$T_m^{\,new} = T_m - \left(\int A_p h_{eff}\left(T_m - T_w\right)dt - \int m_p Q_{de} dt\right) / m_p c_m \quad (5)$$

where, h_{eff}, T_w, Q_{de}, and A_p are the effective heat transfer coefficient, the water temperature, the decay heat, and the particle surface area. The effective heat transfer coefficient is evaluated by various correlations which are Ranz-marshall, Kutateladze, Zuber, Dhir and Purohit[7] depending on the particle surface temperature.

The cooling limitation of the debris bed is often used as the DHF (dryout heat flux). Most of the debris coolability studies have assumed a cylindrical debris bed shape in which the bed is flooded either through its top or bottom surface. The realistic debris bed geometry has not been considered at all in classical analyses. Recently, the geometry of the debris bed has become an important parameter because it determines which type of flooding mode is possible for the infiltration of water into the pores of the bed. KAERI plans to perform a debris bed formation and coolability test to propose an empirical correlation for the debris bed shape and DHF.

The current status of the DECOOL is shown in Fig. 3. The debris bed shape is assumed as a conical shape. When the angle is 90°, the debris bed becomes a cylindrical debris bed. The heat transfer in the debris bed and cake is calculated with Eqs. 11 and 12:

$$Q_{bed} = A_{bed}h - Q_{decay} - Q_{btm} \quad (11)$$
$$Q_{cake} = Q_{MCCI} + Q_{btm} - Q_{decay} \quad (12)$$

, where Q_{bed} is the heat transfer in the debris bed; A_{bed} is the top surface area of the bed; Q_{decay} is the decay heat; Q_{btm} is the heat input at the debris bed bottom from the cake; Q_{MCCI} is the heat released by a MCCI, and h is the heat transfer coefficient, which is determined by comparing the effective heat transfer coefficient and DHF to a smaller value.

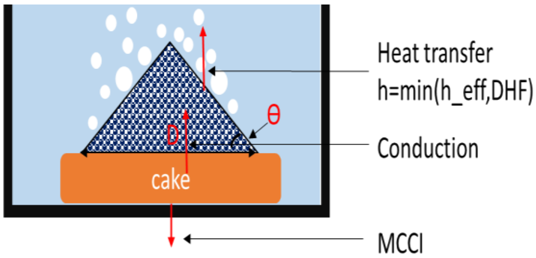

Fig. 3. Heat transfer in the debris bed and cake

2.2 Modified heat transfer model

The particulate corium temperature is evaluated by the energy conservation law because heat is released from a particle during a sedimentation. Before the particles completely solidify, the heat released from a particle is used for the phase change, and the particle temperature does not change during this process. After that, the particle temperature is evaluated. The effective heat transfer coefficient is evaluated by various correlations. In the film boiling region, the natural convection film boiling correlation which is proposed Dhir and Purohit was used. However, during the sedimentation if Re is enough high, the forced convection film boiling correlation should use. So, the forced convection film boiling correlation is added.

2.3 Analysis results and discussion

To investigate how the debris bed temperature changes depending on the debris bed geometry, a preliminary analysis was performed. The two geometries are selected; one is the cylindrical shape and the bottom area varies, another is the conical shape and the angle of the debris bed is obtained the preliminary experiment result from KAERI. The melt properties and initial failure condition such as the failure diameter and corium temperature, and pressure, etc. were obtained through the accident scenario analysis using MELCOR 2.2. Code. In preliminary analysis, we select SBO among the several accident scenarios. Properties of ex-vessel corium are summarized in table I. The initial conditions of the pool and the cavity are in table II. We assumed that pool height is 5.858 m, free fall height is 1m, and the failure diameter in reactor vessel is 0.2 m. Also the pool temperature assumes the saturation temperature at 1 bar.

Table I. Melt properties [8]

Material property	Unit	value
Material		70% UO_2 and 30%ZrO_2
Density liquid	Kg/m^3	8000
Cp-liquid	J/kg/K	510

Cp-solid	J/kg/K	450
$T_{solidus}$	K	2840
$T_{liquidus}$	K	2870
Latent heat	J/kg	320000
Emissivity		0.79
Decay heat	W/kg	80

Table II. Initial conditions

Variable	Unit	value			
Particle diameter	mm	3			
Pool height	m	5.858			
Free fall height	m	1			
Pool temperature	K	373			
Cavity pressure	bar	1			
Failure diameter	m	0.2			
Mass in LVH	ton	130			
Scenarios		LLOCA	SLOCA	SLCOA-CRF	SBO
Corium temp	K	2400	2300	2300	2600
Pressure difference	bar	1	5	5	14

Figure 4 shows the evolution of the average debris bed temperature over time with different bed shapes. In this case, we used the forced convection film boiling heat transfer coefficient instead of the natural convection film boiling heat transfer. It is observed that the initial particulate debris temperature at the cavity is decrease more than 400K compared with the natural convection film boiling heat transfer coefficient. It is also observed that the debris bed temperature increases initially until the heat removal capacity of the debris bed is larger than the decay heat, after that the temperature is stabilized. The stabilized temperature of the debris bed was observed to be directly related to the heat transfer area, as we expected.

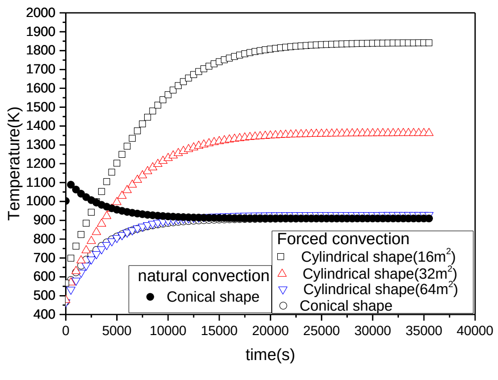

Fig. 4. Debris bed temperature with various shape for SBO

The experimental studies in the COOLOCE program at VTT showed that the debris coolability for five beds compared to a top-flooded cylinder bed increased by up to 70 %. The reason is the larger surface area for heat transfer and the flooding modes which determine the DHF. However, in this preliminary analysis, only the effect of the heat transfer area on the shape could be observed, because both there are few heat transfer models depending on the shape and the current module does not consider the change of the heat transfer coefficient according to the shape. So, the heat transfer model is needed for the realistic debris bed coolability analysis. In future work, KAERI plans to perform a debris bed formation and coolability test to propose an empirical correlation for the debris bed shape and the heat transfer coefficient according to the shape.

3. Conclusions

When molten corium is discharged out of the reactor vessel during a severe accident, the strategy of pre-flooding of coolant into a reactor cavity for ex-vessel corium cooling and stabilization was adopted for the most operating Korean NPPs. It is expected that the ex-vessel corium debris bed would be formed with the completely solidified particles rather than a continuous molten phase and it can be coolable.

In this study, we focused on the development of the ex-vessel debris bed coolability analysis module base on the existing models. KAERI developed the initial version of the ex-vessel debris bed coolability analysis module. The preliminary analysis was performed to investigate the debris bed temperature behavior according to accident scenarios and shapes. A lot of effort is needed to make improvements. Among them, the geometry of the debris bed has become an important parameter. In the future work, the new correlation for the debris bed shape and the its heat transfer will be developed.

ACKNOWLEDGMENTS

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