Current Status of Development of Heat Transfer Model to Predict Temperature Distribution in Particulate Debris Bed

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1. Introduction

During the late phase of severe accidents in PWRs (Pressurized Water Reactors), the molten corium may be discharged into the reactor cavity if the lower head of the reactor vessel is failed. The cooling and stabilization of the discharged molten corium in the reactor cavity is important to prevent further accident progression such as molten core-concrete interaction.

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 jet is completely fragmented in the water pool, and accumulated on the cavity floor in the form of a particulate debris bed. Also, it can be cool down. 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].

KAERI is developed the module for the ex-vessel debris coolability [1]. In the initial version of the coolability module, the average temperature of the debris bed could be obtained because the particulate debris bed was assumed to be one lump. However, it is necessary to know the temperature distribution in the particle bed, to know the local zr oxidation and dry-out, etc. In this study, the module is modified to obtain the temperature distribution in the debris bed, and the results were compared with Ref.2 results.

2. Description of Model

2.1 Models for the ex-vessel corium coolability module [2]

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. To obtain the jet break-up length, the the Epstein’s correlation [3] was used.

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

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

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 [4] 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 depending on the particle surface temperature.

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 is performing a debris bed formation test to propose an empirical correlation for the debris bed shape.

In, the initial version of the coolability module, 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:

$$Q_{bed} = A_{bed}q''_{bed} - Q_{decay} - Q_{btm} = m_{bed}c_{p,bed}\Delta T_{bed} \quad (6)$$

$$Q_{cake} = Q_{MCCI} + Q_{btm} - Q_{decay} = m_{cake}c_{p,cake}\Delta T_{cake} \quad (7)$$

, where Q_{bed} is the heat transfer in the debris bed; A_{bed} is the front 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 q'' is the heat flux at the particle debris bed surface, which is determined by comparing the effective heat transfer and DHF(dryout heat flux) to a smaller value.

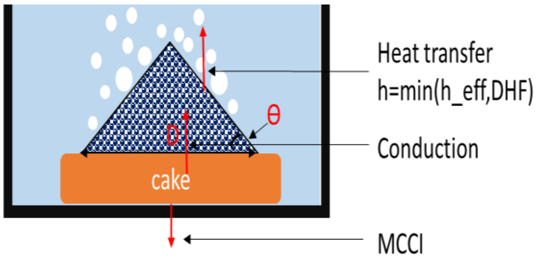

Fig. 1. Heat transfer in the debris bed and cake

2.2 Modified heat transfer model

To obtain the temperature distribution of the particulate debris bed, we seek to solve the unsteady one-dimensional heat conduction equation.

$$\rho_{eff} c_{eff} \frac{\partial T_{bed}}{\partial t} = \frac{\partial}{\partial z}\left(k_{eff}\frac{\partial T}{\partial z}\right) + S \qquad (8)$$

where, $\rho_{eff} = \varepsilon\rho_{bed} + \varepsilon_l\rho_{liquid} + \varepsilon_v\rho_{vapor}$, $c_{eff} = \varepsilon c_{bed} + \varepsilon_l c_{liquid} + \varepsilon_v c_{vapor}$, $k_{eff} = \varepsilon k_{bed} + \varepsilon_l k_{liquid} + \varepsilon_v k_{vapor}$, S are density, specific heat, thermal conductivity of porous media, and source term. The definition of $\varepsilon, \varepsilon_l, \varepsilon_v$ are the porosity of debris bed, the fraction of the volume occupied by the liquid phase and gas phase, $\varepsilon_l = \frac{V_l}{V}$, $\varepsilon_v = \frac{V_v}{V}$. In the dry zone in Fig. 2, $\varepsilon_l = 0$. The boundary conditions of Eq. 8 are shown in Fig. 2.

$$q''(z) = \frac{Q_{btm}}{A_{bed}} \text{ or } 0, \text{ at } z=0$$
$$q''(z) = -q''_{bed} \text{ , at } z=H$$

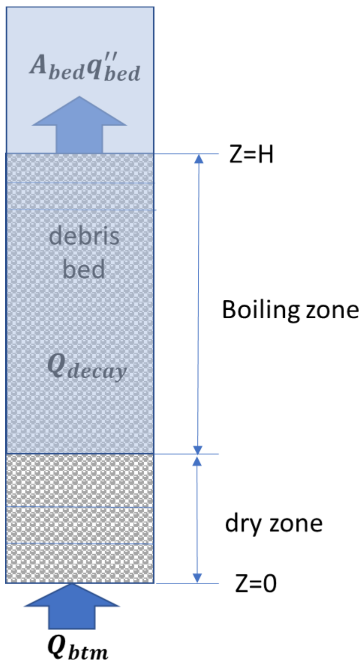

Fig. 2. Schematic of debris bed heat transfer problem

Source term indicates the decay heat from the debris. The length of boiling zone for some decay heat should be obtained first. We can obtain the length of boiling zone from solving the equation for energy conservation, mass conservation and momentum conservation are

$$\frac{d}{dz}\left(\rho_g h_{lg} V_{sg}\right) = Q$$
$$\frac{d}{dz}\left(\rho_g V_{sg} + \rho_l V_{sl}\right) = 0$$
$$-\frac{dp_i}{dz} - \rho_i g = \frac{\mu_i}{K} V_{si} + \frac{\rho_i}{\eta} V_{si}^2$$

2.3 Preliminary analysis results and discussion

For comparison with reference 2, we assumed that the debris bed shape is the cylindrical shape and the bottom area varies. 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. These values were obtained through the SBO accident scenario analysis using MELCOR 2.2. Code[2].

Table I. Melt properties [5]

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

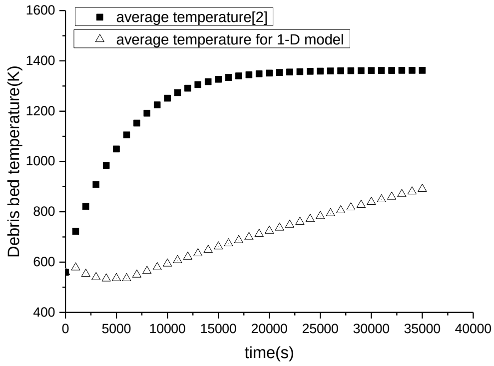

Fig.3. Debris bed temperature at bottom area = 32 m^2

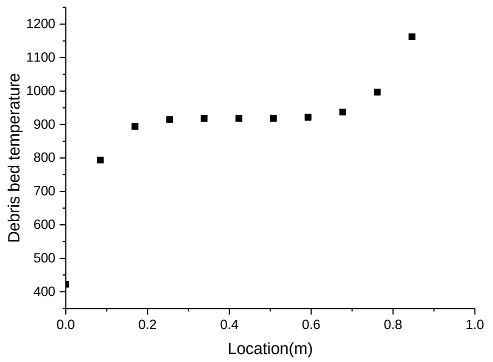

Fig.4. Debris bed temperature as locations at 35000s for bottom area = 32 m^2

For 1-D calculation, analysis was conducted by dividing the debris bed into 10 layers. We find the temperature distribution using the explicit method based on Eq.(8). There is large temperature difference between two methods as shown in Fig. 3. Furthermore, we check the temperature of the debris bed as the locations in Fig.4. Here, the location means that the distance from the top surface of debris bed. As we expected, the top surface temperature is the lowest, and the bottom temperature is the highest. However, unexpectedly, the temperature rose rapidly at the bottom of the debris bed. Heat transfer analysis of porous media is sensitive to effective properties such as effective density, specific heat and thermal conductivity. Now, analysis for the effect of both the effective properties of porous media and the number of layer with time is in progress. The next revision will be included these results.

We focused on the development of the debris bed coolability analysis model to investigate the local dry-out in the particle debris bed. It is still underway to develop the debris bed coolability module. Once we will develop the debris bed coolability analysis model for the cylindrical shape of debris bed, then the new coolability model for various debris bed shape will be developed because the geometry of the debris bed has become an important parameter.

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.

To development the debris bed coolability module, we are focusing on the development of the debris bed coolability analysis model with the various debris bed shape. In this study, we try to develop new method to calculate the local debris bed temperature. It is still underway to develop the debris bed heat transfer model. After developing 1-D analysis model, it will be expanded to analyze the local temperature of various shaped debris bed.

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