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Current Status of Development of Simplified Ex-vessel Debris Bed Coolability Model

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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 breached. The cooling and stabilization of the discharged molten corium in the reactor cavity is crucial to suppress further accident progression such as molten core-concrete interaction (MCCI) which can cause the containment failure and significant release of radioactive material outside the containment.

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 the completely break-up, or the debris bed is re-melted, a continuous molten pool is produced on the floor and it leads to MCCI.

The assessment of the ex-vessel debris bed coolability (heat removal capacity) in a pre-flooding reactor cavity is one of the important tasks. Over the past decades, a significant progress has been made in understating and predicting relevant physical phenomena [1, 2, 3, 4, 5, 6]. However, the existing models have some limitation, due to the complex interactions and feedbacks between scenarios of accident progression and physical processes. Also, quantitative experiments have not been performed due to various reasons such as difficulty of decay heat simulation and proper assumptions of initial condition. In addition, many analysis codes need plenty of running time and a model for evaluating the long-term coolability has not been established

Therefore, it is necessary to develop the rapid analysis models not only the initial quenching but also the long-term cooling of ex-vessel corium. The purpose of the present study to develop the simplified ex-vessel debris bed coolability model covering important parts of the ex-vessel melt behavior, such as the melt jet break-up, debris bed sedimentation, debris bed formation, its cooling. Each model will be modified based on the existing model using TROI [7] (test for real corium interaction with water) experimental results, further experiments which will be performed at KAERI and mechanistic code data [4]. The result of this model provides the initial condition for the following MCCI.

2. Description of Model

2.1 Cooling process

So far, the cooling process of the ex-vessel corium debris can be divided like melt jet breakup, particle dynamics, debris bed formation, and the its 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. So, the coolability of the debris bed may be affected by the ex-vessel melt behaviors which are the PRV failure condition, jet fragmentation, debris solidification, two-phase flow in porous media, spreading of debris in the pool, spreading of particulate debris bed, etc.

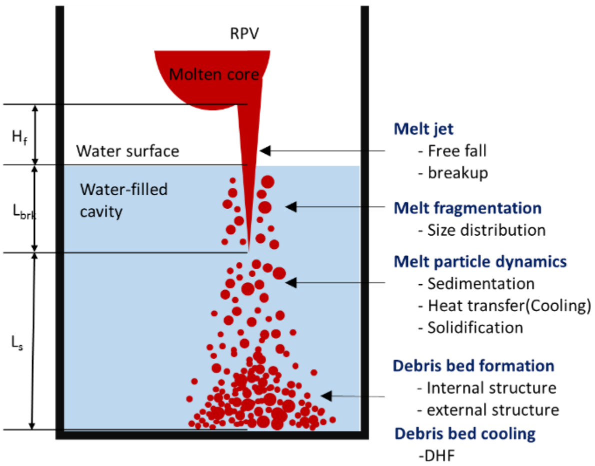

Fig. 1. Scenario of melt outflow from RPV and formation of particulate debris in pre-flooding cavity

2.2 Melt jet breakup

The purpose of this section is to determine whether the completely jet break-up or not and the debris particle size distribution. 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:

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

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

where, H_f is the free fall height form the melt release point to the water surface. The jet break-up length is given by empirical correlations:

$$\frac{L_{br}}{D_e} = 2.1\left(\frac{\rho_m}{\rho_l}\right)^{1/2}\left(\frac{V_e^2}{gD_e}\right)^{1/2} \quad (3)$$

$$\frac{1}{2E_o}\left(\frac{\rho_m}{\rho_l}\right)^{1/2} \quad (4)$$

where, ρ_m, ρ_l, and g are the density of melt and water, and the gravity, respectively. The Eq. 3 is Epstein's correlation [8] and the Eq.4 is by Saito et al. [9]. The difference between two equations is that the Eq.3 has velocity term. It makes a big difference two correlation at the high velocity regime. However, depending on the regime, the break-up length may or may not depend on the velocity. The some criteria to select the breakup correlation will be established.

The empirical correlation for the particle size distribution will be proposed using both the TROI experimental results [7] and mechanistic code analysis data.

2.3 Particle dynamics

The initial velocity of a particle is assumed V_e. The the particle temperature at the cavity floor is obtained. On a conservative assumption, the particle fall to the cavity floor along only z axis. The particle movement is tracked by the kinetic equation considering the fluid dynamic resistance.

$$\frac{\partial z^k}{dt} = U_p^k, \quad \frac{\partial U_p^{\ k}}{dt} = -F_{drag}/m_p + \left(\rho_p - \rho_l\right)/\rho_p g,$$
$$\overline{F}_{drag} = \frac{3}{4}C_d\rho_l\left(\overline{U}_p - \overline{U}_a\right)^2 \quad (5)$$

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 [10] was adopted.

The heat release from a particle during a sedimentation. To evaluate the particle temperature, it is assumed that the particle 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.6) and the particle temperature does not change during this processes. After that, the particle temperature is evaluated by Eq. 7.

$$\Delta m_s = \left(\int A_p h_{eff}\left(T_m - T_w\right)dt - \int m_p Q_{de}dt\right)/\left(h_{sf} + c_m(T_m - T_{s,sf})\right) \quad (6)$$

$$T_m^{\ new} = T_m - \left(\int A_p h_{eff}\left(T_m - T_w\right)dt - \int m_p Q_{de}dt\right)/m_p c_m \quad (7)$$

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 [11], Kutateladze [12], Zuber [13], Lienhard and Dhir [14] depending on the particle surface temperature.

2.4 Debris bed formation & cooling

The cooling limitation of debris bed is often used as DHF (dryout heat flux), which is defined by the maximum heat flux through the bed without dryout. Most of the debris coolability researches assumed the cylindrical debris bed shape in which the bed is flooded either through its top or bottom surface. The realistic debris bed geometry is not considered at all in classical analyses. Recently, the geometry of the debris bed dealt with important parameter because it determines which type of flooding mode is possible for the infiltration of water into the pores of bed. The experiments studies in the COOLOCE program at VTT [15] have performed the six variations of the debris bed geometry with different flooding modes including a top-flooded cylinder and five beds with more complex, heat-like geometries. The debris coolability for five beds compared to a top-flooded cylinder bed increased by up to 70 %. It indicates that the debris bed geometry and the flooding modes are key parameters to determine the coolability of the debris bed.

The correlations which determine the debris bed shape and DHF are very limited although the some groups proposed models [16, 17]. KAERI is plan to perform the debris bed formation and coolability test to propose the empirical correlation for debris bed shape and DHF.

2.5 Code

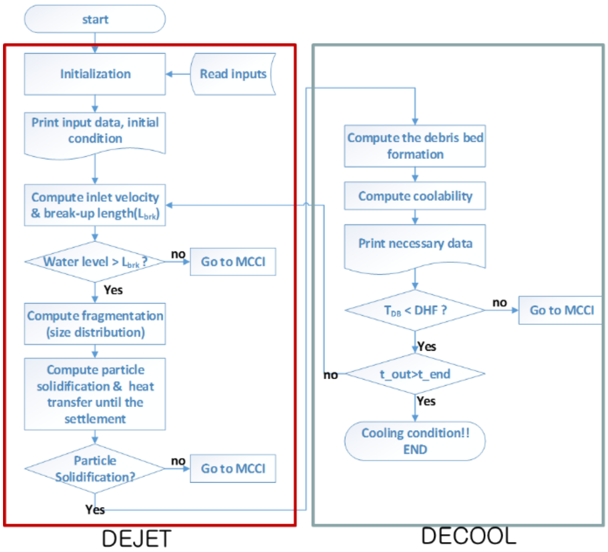

Fig. 2. Debris bed coolability analysis flow chart

The purpose of the present study to develop the simplified and the rapid analysis model covering important parts of the ex-vessel melt behavior, such as, the melt jet break-up, debris bed sedimentation, debris bed formation, and its cooling. Two modules which are DBJET and DBCOOL will be developed (Fig. 2). DEJET will deal with both the melt jet break-up and debris bed sedimentation. The results of DEJET module which are the particle size distribution, the particle falling velocity, and the particle temperature provide the initial condition for DECOOL module. The coolability of the formed debris bed is determined by DECOOL module.

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.

Phenomena of the ex-vessel core melt behaviors in a wet cavity are briefly described, and description of the some analytical model and the state of the art for the pre-flooding strategy in a reactor cavity is also included. The existing models have some limitation, due to the complex interactions and feedbacks between scenarios of accident progression and physical processes. In addition, many analysis codes need plenty of running time and a model for evaluating the long-term coolability has not been established. Therefore, the purpose of this work to develop the simplified ex-vessel debris bed coolability model covering important parts of the ex-vessel melt behaviors. Each model will be modified based on the existing model using existing experiment results, further experiment results and mechanistic code data.

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