Transient Analysis of Corium Coolability Considering Water Ingression into Debris Bed and Corium-to-Vessel Gap

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1. Introduction

TMI-2 accident showed the possibility of maintaining the integrity of the reactor vessel by gap cooling phenomenon in the situation of the relocation of the corium to the lower head. There are two kinds of analysis for evaluating corium coolability by gap cooling; steady analysis and transient analysis. The steady analysis compares the heat released from the corium and heat loss due to the gap cooling. When the amount of heat released is more than the amount of heat removed, it is judged that the reactor vessel was ruptured. The steady analysis is simple, but it cannot estimate the effect of melt solidification, change of gap thickness, and the thermal histories of the melt and the vessel. In the TMI-2 accident, 12 tons of the corium were in the form of the debris bed, so it is important to estimate the effect of the debris bed.

This study performed the transient analysis considering water ingression into the debris bed and the corium-to-vessel gap (Fig. 1 and 2). In this study, two results of the transient analysis are shown; 19 tons and 50 tons of corium calculations. From the calculation of 19 tons of corium, not only the thermal behavior of the melt and vessel were simulated, but also a hot spot of 1400K was shown. In addition, the results of the 50tons of corium simulation were shown and discussed in this study.

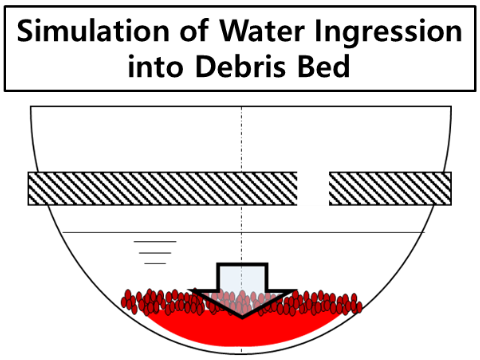


Fig. 1. Water ingression into debris bed

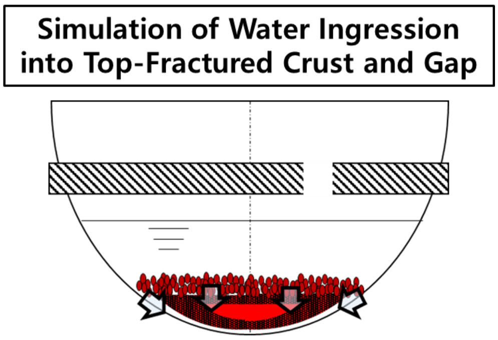


Fig. 2. Water ingression into top-fractured crust/corium-to-vessel gap

2. Brief description of the analysis tool

2.1. Water penetration into debris bed

The relations of energy balance in the debris bed calculation are as below (Fig. 3);

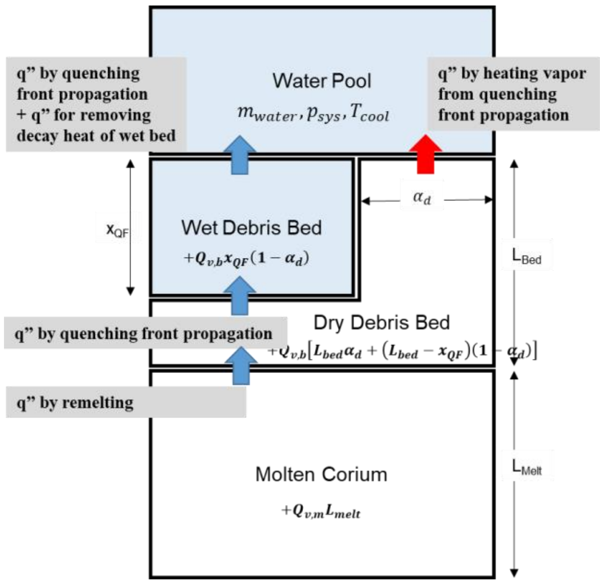


Fig. 3. Downward QFP (Quench-Front-Propagation) in debris bed

- Wet debris bed energy
  - (+) by decay heat
  - (+) by QFP (Quench-Front-Propagation)
  - (-) by bed cooling by water

- Dry debris bed energy
  - (+) by decay heat
  - (-) by QFP
  - (-) by heating vapor from QFP
  - (-) by remleting part of debris bed
- Molten corium energy
  - (+) by decay heat
  - (+) by remelting part of debris bed
- Coolant energy
  - (+) by water evaporates at QFP
  - (+) by superheated vapor
  - (+) by energy from debris bed cooling
- Total energy (summing all sections)
  - (+) decay heat of corium (all sections)

The QFP was calculated with consideration of two limits; hydraulic limit and thermal limit. Details of the QFP calculation can be seen in [1]. The output of this calculation is the time for water penetrating through the debris bed, $t_{WI,Debris}$ and heat removal rate of the melt.

2.2. Water penetration into top-fractured crust/corium-to-vessel gap

After the quench front reaches the bottom of the debris bed, the calculation of water ingression into top-fractured crust/gap is started. The calculation logic and details are shown in [2] and Fig 4. To consider decay heat effect of the melt, the heat transfer models of the melt were modified with the same as [3]. The constitutive relations are as below;

- (Melt) Natural convective heat transfer to upper/down crust: [4] with angle effect
- (Crust) Temperature profile: Linear
- (Crust) Heat enhancement factor at the bottom: 8 on θ < 10 [Deg.].
- (Gap) Gap size: Inverse Leidenfrost effect, thermal deformations of the crust and vessel, thermal fracture of the crust
- (Gap) Heat transfer coefficient from the vessel: h = 8,000 [W/m^2.K]
- (Gap) Rewetting temperature: T_{sat}+100 [K]

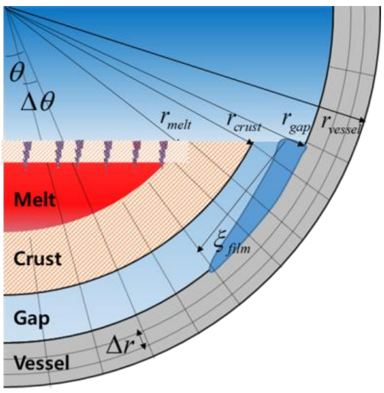


Fig. 4. Schematic of water ingression into top-fractured crust/gap

Major outputs of this calculation are as follows;

- Temperature histories of the melt/crust/vessel
- Transient thickness of crust/gap
- Heat removal rate of the melt

3. Simulation Conditions

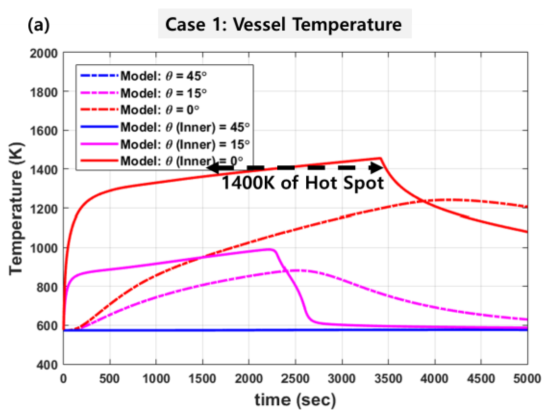
Table I shows conditions for simulations of the water ingression into debris bed and corium-to-vessel gap. Case 1 simulates the conditions of the TMI-2 accident. Case 2 simulates the conditions in which the mass of the melt is larger than that of case 1.

Table I. Simulation conditions of case 1 and 2

	Case 1	Case 2
Decay heat level	1.0 [MW/m^3]	
Mass of cake (hard debris)	7,000 [kg]	30,000 [kg]
Mass of debris (particulate debris)	12,000 [kg]	20,000 [kg]
Melt superheat	50 [K]	
Weight fraction of UO_2 and ZrO_2	80% UO_2 and 20% ZrO_2	
System pressure	100 [bar]	
Subcooling	10 [K]	
Vessel thickness	0.127 [m]	
Vessel radius	2.2 [m]	

4. Results and Discussion

Fig. 5 shows the temperature histories of the vessel, melt, and crust of the simulation of the case 1. In Fig. 5-(a), it can be seen that a hot spot of 1400K formed for about 2000 sec and then disappeared. It is consistent with the observation of the hot spot in the TMI-2 accident. Fig. 5-(b) shows the thermal behavior of the melt and crust. In Fig 5-(c), the time of water ingression into debris bed can be found as about 880 sec. After the stage of water ingression into the debris bed, it can be seen that the water ingression into the top-fractured crust/side gap begins.



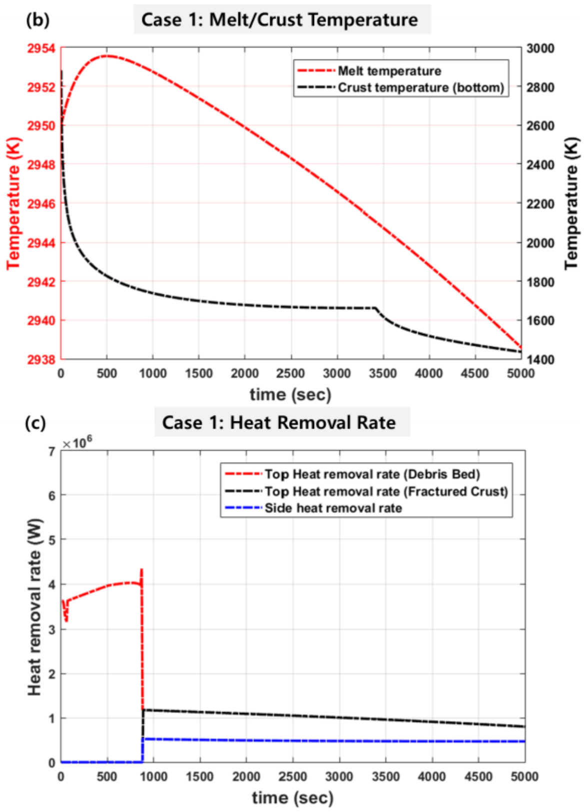


Fig. 5. Calculation results of the case 1
(a) temperature of the vessel (b) temperature of the melt/crust
(c) heat removal rate of the melt

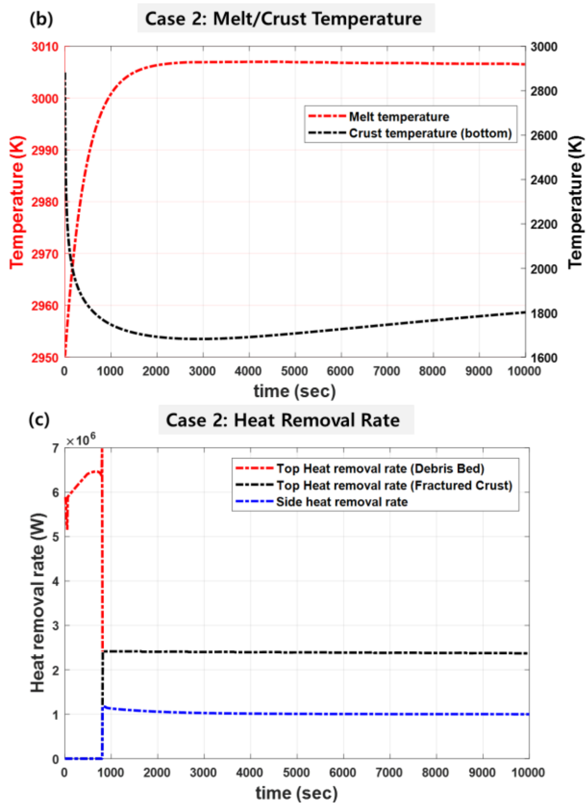
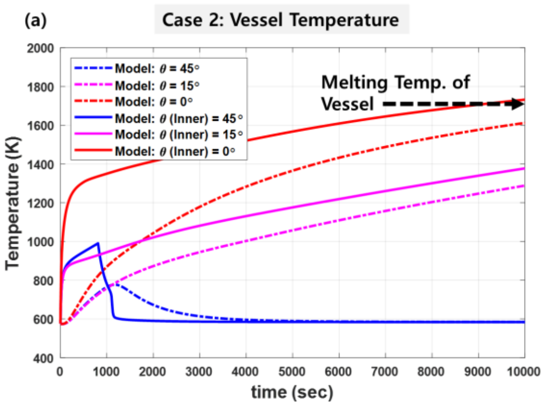


Fig. 6. Calculation results of the case 2
(a) temperature of the vessel (b) temperature of the melt/crust
(c) heat removal rate of the melt

As can be seen in Fig. 6-(a), the vessel temperature reaches its melting temperature. Moreover, the melt temperature in Fig. 6-(b) was saturated to 3,007 K. The reason why the cooling of the melt and the vessel is not effective in the case 2 simulation is that the water ingression into the gap is not active. Because the heat transfer rate to the crust by the natural circulation of the melt is large, the water ingression becomes significantly slow. In Fig. 6-(c), the $t_{WI,Debris}$ was about 810 sec. Although the cooling in the case 2 is less effective than case 1, the heat removal rate of case 2 is larger than that of case 1. The reason is that the heated surface of case 2 is larger than that of case 1.



In summary, in case 1 similar to the TMI-2 accident, the 1400K of hot spot found in the TMI-2 accident was successfully simulated. 50 tons of melt (30 tons of cake/20tons of debris bed) simulation showed that the vessel temperature reached the melting point. This is because more heat was transferred from the melt to the gap, the water ingression became ineffective. For future studies, we will compare the results of these simulations with the conventional melt coolability analysis.

ACKNOWLEDGEMENT

This research was supported by the KUSTAR-KAIST INSTITUTE, KAIST, Korea.

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