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Simulation of CCI experiments for the sensitivity analysis with MELCOR 2.2

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1. Introduction

Molten core-concrete interaction (MCCI) is one of the important phenomena threatening the integrity of the containment. MCCI phenomenon usually occurs at the bottom of the reactor cavity with the ablation of the concrete and the pressurization of containment by generating the non-condensable gas and steam. In order to evaluate the mitigation strategies in the ex-vessel phase of severe accident, the concrete ablation, corium (mixture of molten core and metal structure) coolability, and containment pressurization should be considered.

Currently, MELCOR [1] is widely used as the numerical simulation tool, which is needed to be validated appropriately based on the experimental data for the estimation in the reactor scale. The ablation depth of concrete and heat flux between corium and water are major parameters that are highly related with the safety of the nuclear power plants (NPPs). In this study, the sensitivity analysis for selecting applicable model parameters in the reactor scale was conducted using MELCOR 2.2. The CCI tests (CCI-2, 3, 6) of OECD/MCCI project [2-3] were selected for the determination of the model parameters in MELCOR.

2. OECD/MCCI Project

2.1 Overview of OECD/MCCI project CCI tests

According to the MCCI research, many experimental works were conducted developing the database during past 40 years: BETA experiments conducted at KIT [4], ACE, MACE experiments at ANL [5-6], VULCANO experiments at CEA [7], and CCI tests conducted by OECD/NEA [2-3]. Especially, the CCI tests are an international joint research of OECD/NEA conducted by Argonne National Laboratory (ANL). The main purpose of the CCI tests was the investigation of the cooling mechanism that was shown in the MACE experiments and the decrease of uncertainty from the two-dimensional geometry in long term period of dry and wet cavity conditions.

In this research, three experimental cases (CCI-2, 3, 6) were chosen in order to investigate the effect of the concrete composition and water injection time on cooling characteristics. The limestone common sand (LCS) concrete and dry cavity condition were applied on the CCI-2 test with corium containing 8 wt% of LCS concrete. The steady input power of 120kW (equivalent to 30MW/100t of decay heat) was applied until the water flooding at 300 minutes. The siliceous (SIL) concrete and dry cavity condition were applied on the CCI-3 test with corium containing 15 wt% of SIL concrete. The input power was same with CCI-2 test until the water flooding at 108 minutes. The SIL concrete and wet cavity condition were applied on the CCI-6 test with corium containing 6 wt% of SIL concrete. However, the water was injected at the initial period of experiment with the input power of 210kW.

2.2 Result parameters in CCI tests

In order to evaluate the characteristics of MCCI phenomenon, three parameters were analyzed as the major results in CCI tests: corium temperature, ablation depth, and heat flux between melt and water.

Total 21 thermocouples (7 C-type and 14 K-type) were inserted in the bottom and side concrete for purpose of the measurement of the corium temperature. Those thermocouples not only measured the temperature of corium, but also measured the ablation depth (Fig. 1 and 2). The averaged corium temperature was usually used for the comparison with the numerical simulation, which is indicated as the black line in Fig. 1. The ablation depth of the concrete was obtained by tracking the time when the temperature of the thermocouple reached the corium temperature (Fig. 2).

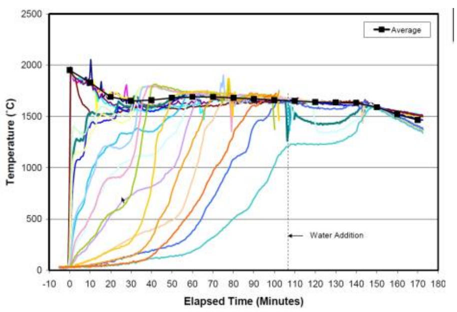


Fig. 1. Temperature history of corium (CCI-3) [3]

Also, the heat flux between the melt and the water after the water flooding was indirectly measured by calculating the condensed water form generated steam with the top surface area of the corium pool.

3. MELCOR analysis conditions

3.1 Scaling analysis for boundary and initial conditions

Since the geometry for MCCI model in MELCOR is two-dimensional cylindrical system, the scaling analysis of boundary conditions are necessary in order to simulate the CCI tests that has a two-dimensional rectangular system (Fig. 3). There were three major assumptions for the scaling analysis: 1) the ablation rate or the heat flux on the concrete wall should be identical between the experiment and the simulation 2) the ablation area ratio of the bottom to side concrete should be identical between them 3) The change of the concentration of concrete in melt pool due to the ablation should be identical between them.

Based on above assumptions, the radius of the cylinder in MELCOR model had same value with the length of the bottom area (50 cm for CCI-2, 3 and 70 cm for CCI-6) and the height of melt pool had the same height with the experiments. Since the melt mass increased by π times of the original one, the input power was also increased to π times of that. The boundary and initial conditions are summarized in Table 1.

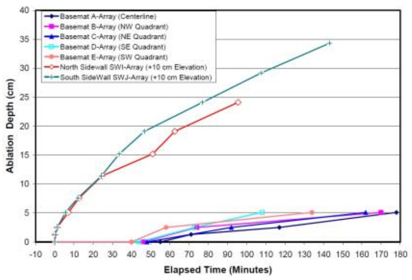


Fig. 2. Maximum axial/radial ablation depth (CCI-3)

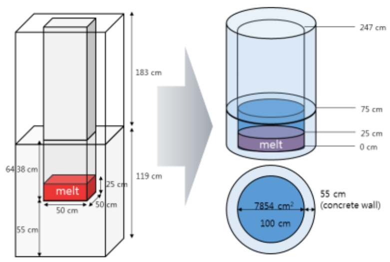


Fig 3. Scaling analysis for geometry (CCI-3): experiment (left), and MELCOR (right)

Table 1. Scaling analysis for initial/boundary condition

Scaling parameters	Value (CCI-3)		Unit
	Exp.	MELCOR	
Corium mass	375	1178	kg
Density	6500	6500	kg/m^3
Bottom surface area	0.25	0.785	m^2
Corium height	0.25	0.25	m

3.2 Test matrix for sensitivity analysis

The test matrix for sensitivity analysis of model parameters was determined in order to validate the effect of concrete type and the water flooding time. The major model parameters for the sensitivity analysis are 'BOILING', 'HTRBOT', 'HTRINT', 'HTRSIDE', 'EMISS', 'COND.OX', 'COND.MET', 'GFLIMBOT', 'GFLIMSIDE', 'TABLCT', 'Mixing', 'WATINGR', and 'ERUP', which are explained in the MELCOR user guide [1] in detail. Based on the Humphries et al. [1], the base case was chosen as the default value of MELCOR version 2. The test matrix is summarized in Table 2.

4. MELCOR simulation results

4.1 Corium temperature

The time histories of the corium temperature with the best combination of model parameters on each test are shown in Fig. 4, 5, and 6. The results of MELCOR simulation were composed of five molten layers: the Surface, LOX (light oxide layer), LMX (light mixture layer), MET (metal layer), HMX (heavy mixture layer), and HOX (heavy oxide layer). The type of the molten corium in the simulation changes with the effect of the concrete ablation: from HMX to LOX in CCI-2, from LMX to LOX in CCI-3, and HMX in CCI-6.

In the case of the CCI-2 results, the corium temperature of case 8 was well matched with the experiments until the water flooding. The temperature after the water flooding decreased significantly than the experimental results, which increased slightly. In case of the CCI-3 results, the corium temperature of case 17 was generally well matched except for the initial period of the experiment. In case of the CCI-6 results, the corium temperature of case 17 showed a similar trend with the experiment.

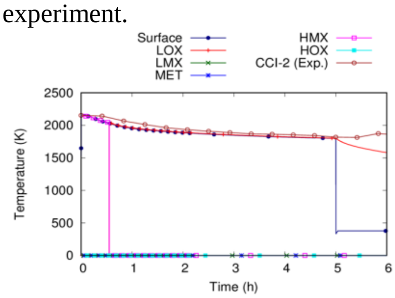


Fig. 4. Corium temperature history of CCI-2 (case 8)

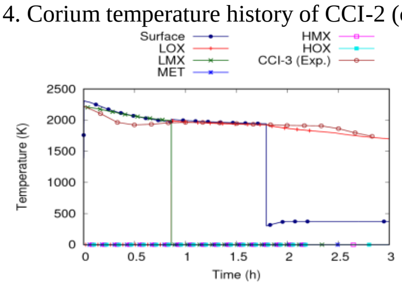


Fig. 5. Corium temperature history of CCI-3 (case 17)

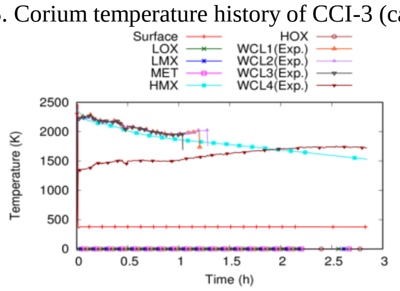


Fig. 6. Corium temperature history of CCI-6 (case 17)

4.2 Axial / radial ablation depth of concrete

The axial and radial ablation depth results with the best combination of model parameters on each test are shown in Table 3. The simulation results showed a similar trend with the experimental data in case of the CCI-2 and CCI-3 by changing the conductivity coefficient parameter (CCI-2 and CCI-3) and the heat transfer coefficient ratio between the bottom and side (CCI-3), because the anisotropic ablation behavior was found with the SIL concrete (CCI-3 and CCI-6). However, the ablation behavior of the CCI-6 was not simulated well with the MELCOR model. As shown in Table 3. (bottom), the radial ablation was abruptly progressed within the short period and the axial ablation was delayed until 0.5 hours, though, the slope of the axial ablation (ablation rate) behavior was simulated similarly.

4.3 Heat flux between melt and water

The decay heat of corium is mainly consumed by the ablation of concrete or transferred to the coolant above the melt pool. If the heat transfer to the coolant becomes identical with the generated decay heat, MCCI is terminated. On the other side, the transferred heat generates the steam and pressurizes the containment. Thus, proper prediction of the heat flux to the coolant is an important parameter.

In the case of the CCI-2, the heat flux was underestimated in the early period and was overestimated in the late period. That deviation was originated from the scaling of MELCOR code for the early period and from the lower corium temperature of MELCOR results for the late period.

Since we validated the ablation depth not the ablation mass, the ablation mass of cylindrical geometry (MELCOR) becomes different with that of rectangular geometry (Exp.) (Fig. 3). This situation is noticeable in the CCI-3 case (Fig. 8); the trend is similar even with the large deviation. The reason why the experiments has five times higher value than the simulation is the high heat flux to concrete than heat flux to water. The uncertainty of heat flux to water could be exaggerated by the uncertainty of heat flux to concrete, because the sum of the heat flux should be constant as the input power considering the latent heat of melt pool.

Since the heat flux to the water was relatively small compared to the heat flux to the concrete, in the CCI tests, other one-dimensional MCCI experiments would be more suitable for the investigation of the heat flux to the water. In the case of the CCI-6, the high heat flux during the melt eruption was not simulated appropriately (Fig. 9)

Table 3. Comparison of axial/radial ablation depth: (top) CCI-2: case 8, (middle) CCI-3: case 17, (bottom) CCI6: case 17

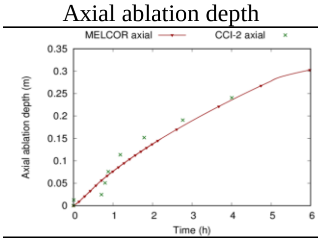
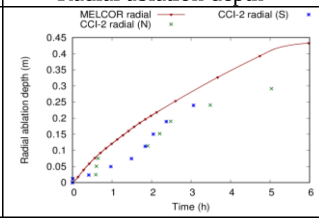
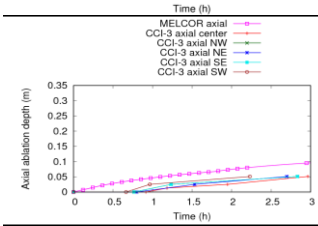
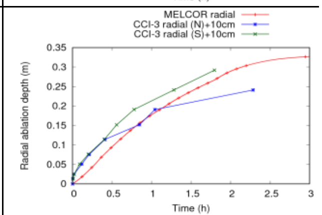
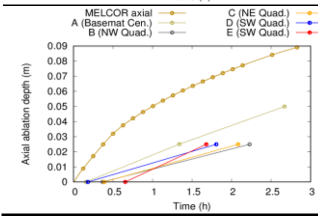
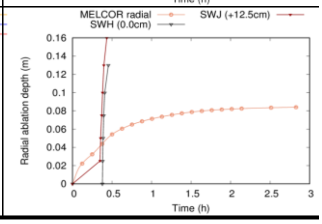
Axial ablation depth	Radial ablation depth
	
	
	

Table 2. The test matrix for model parameters in the sensitivity analysis using MELCOR

Case #	CCI-3										
	Boiling	HTRINT	HTRBOT	HTRSIDE	EMISS	COND.OX	COND.MET	GFLIMBOT	GFLIMSIDE	TABLCT	Mixing
Base	Value 10	MULT 1	MULT 1	MULT 1	0.9	MULT 5	MULT 5	Gas	Gas	∆T = 73	Enforce
1	15	-	-	-	-	-	-	-	-	-	-
2	5	-	-	-	-	-	-	-	-	-	-
3	-	5	5	5	-	-	-	-	-	-	-
4	-	0.2	0.2	0.2	-	-	-	-	-	-	-
5	-	-	-	-	0.6	-	-	-	-	-	-
6	-	-	-	-	0.3	-	-	-	-	-	-
7	-	-	-	-	-	3	3	-	-	-	-
8	-	-	-	-	-	1	1	-	-	-	-
9	-	-	-	-	-	-	-	SLAG	-	-	-
10	-	-	-	-	-	-	-	-	SLAG	-	-
11	-	-	-	-	-	-	-	SLAG	SLAG	-	-
12	-	-	-	-	-	-	-	-	-	0	-
13	-	-	-	-	-	-	-	-	-	-	Calc.
14	-	-	-	-	-	1	1	-	-	-	Calc.
15	MOD3	-	-	-	0.6	1	1	-	-	-	-
16	-	1	1	5	-	1	1	-	-	0	-
17	-	1	1	5	-	1	1	-	-	-	-

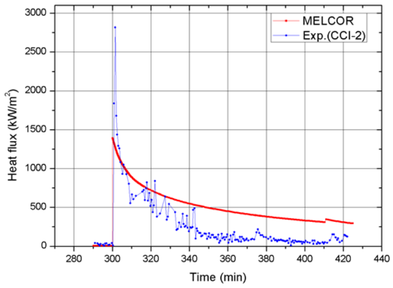


Fig. 7. Heat flux between corium and water of CCI-2: experi mental data (blue dot); case 8 (red line)

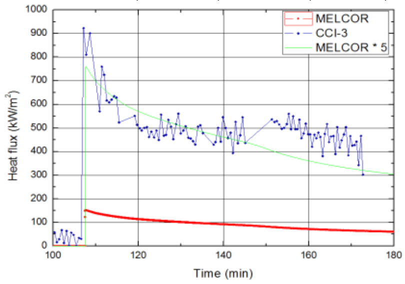


Fig. 8. Heat flux between corium and water of CCI-3: experimental data (blue dot); case 17 (red line); five times of case 17 (green line)

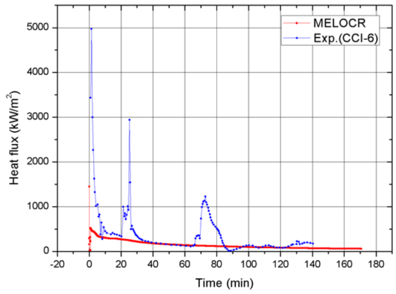


Fig. 9. Heat flux between corium and water of CCI-6: experimental data (blue dot); case 17 (red line)

5. Conclusions

Analysis of the CCI tests from OECD/MCCI project using MELCOR 2.2 was conducted for the tuning of the MCCI model parameters. CCI-2, 3, and 6 were selected as reference cases considering variation of the concrete type (LCS and SIL) and the water injection time (early and late flooding).

CCI-2 test (LCS concrete, late flooding) showed the isotropic ablation behavior and the results of the case 8 well matched; the conductivity of oxide and metal layer was changed from 5 to 1. CCI-3 test (SIL concrete, late flooding) showed the anisotropic ablation behavior and the results of the case 17 well matched; the conductivity of oxide and metal layer was changed from 5 to 1, and the factor for the heat transfer to the side orientation was changed from 1 to 5 in order to simulate the anisotropic ablation.CCI-6 test (SIL concrete, early flooding) showed the similar behavior with CCI-3; the best parameter set was case 17, also. However, the heat flux to the water considering the melt eruption phenomenon was not well simulated in this study.

According to this study, the model parameters for the MELCOR code can be suggested as follows: change the conductivity coefficient from 5 to 1 and change the heat transfer coefficient to side wall from 1 to 5 in the case of the SIL concrete. The range of the tuning factor, 1-5, mentioned above includes the variation of default values for different versions of MELCOR (1.8.x and 2.x) suggested by the developer [1]. Considering that the default values are based on the validation work with a large database and the best fit values in the present study might not be the best for other cases, this range of parameters, a factor of five, could be considered as an uncertainty range in the application of the code to the reactor scale.

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