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Sensitivity analysis for CCI-2 test using CORQUENCH

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1. Introduction

Molten Core-Concrete Interaction (MCCI) is one of main phenomena that occurs during the ex-vessel corium cooling. When MCCI occurs, the concrete is gradually eroded by the high temperature corium. The erosion can damage the basemat of a containment, so evaluation of the MCCI is very important to the containment safety analysis.

There are several codes to simulate the MCCI such as CORQUENCH, COCO, CORCON, COSACO, MAAP, MEDICIS, TOLBIAC-ICB, WECHSL, and so on. To simulate the MCCI, many other phenomena should be also considered such as water ingression, melt eruption, and so on. Because there are various models for these phenomena, the effect of uncertainties have to be identified for better understanding of the simulation result.

In this research, the effects of the several uncertainty factors were analyzed using CORQUENCH 4.1b. First, result comparison of CCI-2 test between the CORQUENCH simulation and the experiment to build the reference model. Thereafter, sensitivity analysis was done by changing values for uncertainty factors based on the reference model.

2. Methods and Results

2.1 Result Comparison of CCI-2 test between CORQUENCH simulation and Experiment

CORQUENCH has been developed to assess the phenomenological model of various ex-vessel corium cooling mechanisms by ANL since the early 1990's. The code has a multi-nodal analysis capability that can treat variations in core debris distributions arising from containment geometry effects, and the extent of core debris spreading following vessel breach under either wet or dry cavity conditions [1].

Since the 1980s, a number of MCCI experiments have been conducted for the post-filled cavity condition. Among these experiments, CCI-2 test was selected to simulate because this test performed systematically for MCCI behavior analysis and can demonstrate scale effects [2]. CCI-2 test provides data on the nature and extent of debris quenching under both early- and late-phase cavity flooding conditions. This test utilized a concrete cavity that was in the shape of a 2-D notch with the square cross-sectional basemat. The two walls between the tungsten electrodes were fabricated from concrete to allow the ablation to proceed laterally as well as axially. Thermite was used to produce the melt.

The reference model of CORQUENCH for CCI-2 test was constructed based on references; [1], [2] and [3]. The main input for the model is shown in table I.

Table I: Reference model of CORQUENCH for CCI-2 test

Parameter (Variable name)	Input model/value
Concrete ablation (NABBL)	(0) Quasi-steady concrete ablation
Water ingression (NINGRS)	(2) Time dependent crust dryout limit calculated with the Lister/Epstein model.
Melt eruption and particle bed formation (NENTR)	(2) Ricou-Spalding entrainment rate correlation
Viscosity calculation (NVISC)	(1) Ishii-Zuber correlation
Maximum solid fraction (ALPMAX)	1.0
Top crust modeling (NUSGAP)	(0) Always atop the melt
Zr-SiO_2 reaction (NCHEM)	(1) Enabled
Melt-concrete heat transfer coefficient (NBOTBC, NSIDEBC)	(1) Bradley's modification to Malenkov-Kutateladze correlation

Using the reference model, a single node analysis was performed. Comparisons of ablation depth, bulk melt temperature, and upper heat flux from the CCI-2 experiment results and simulation results using reference model are shown in Fig. 1, Fig. 2 and Fig. 3 each. In these figures, simulation results from the CORQUENCH manual are also indicated for the reference.

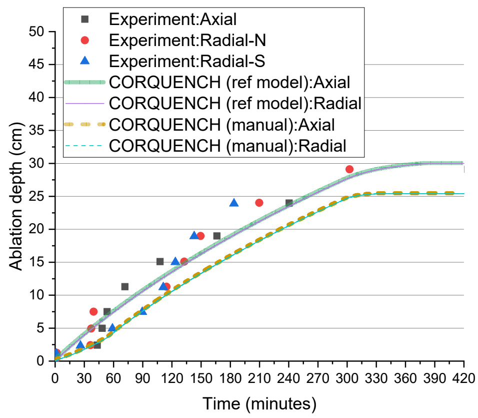

Fig. 1. Comparison of Ablation Depth

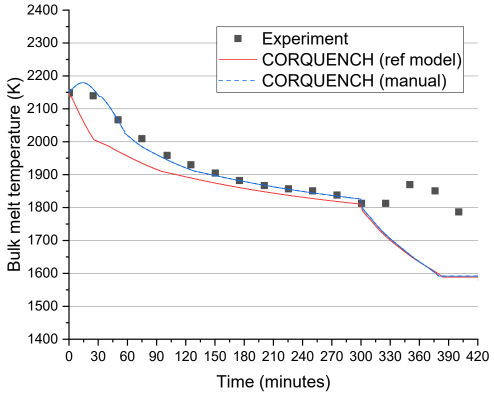

Fig. 2. Comparison of Bulk Melt Temperature

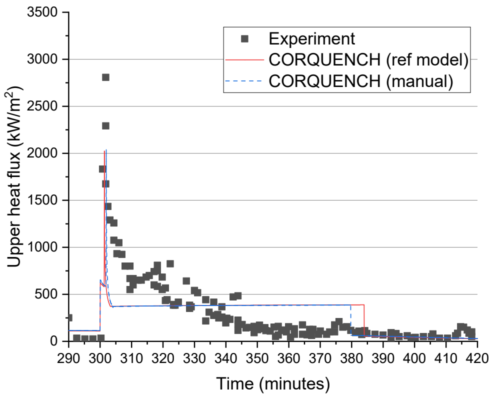

Fig. 3. Comparison of Upper Heat Flux

In the simulation, axial and radial ablation depths were resulted as same because the same heat transfer coefficients from the Bradley's correlation are used to axial and radial interface for melt-concrete heat transfer coefficient (NBOTBC, NSIDEBC) of the reference model. The simulation result using reference model fit the experiment result well in terms of the ablation depth, on the other hand, the simulation results from the manual under-predicts the ablation depth as shown in Fig. 1. In terms of bulk melt temperature, simulation results from the manual fit the experiment result better than the simulation results using reference model until the water injection (< 300 minutes). It is because concrete ablation models are different. In the reference model, quasi-steady concrete ablation (NABBL=0) was assumed, so the evolution and failure of crust layer between the melt and concrete are not considered. However, the transient dry-out model (NABBL=2) crust was assumed in the manual model. Therefore, early heat transfer from melt to concrete is larger in the result using reference model than in the result from the manual.

The bulk melt temperatures in the experiment result and the simulation results are different after water injection (> 300 minutes) as shown in Fig. 2. The melt temperature decreases under the wet cavity condition in the simulation results, but rather the melt temperature increases in the experiment results. However, the upper heat flux increases rapidly right after the water injection in both the experiment result and the simulation results as shown in Fig. 3. After the bulk cooling phase, the upper heat flux steadily decreases as the crust is formed in the experiment result, on the other hand, it maintains constantly after rapid decrease in the simulation results. Although the results show different inclination, the overall upper heat flux of the simulation results fit well the experiment result under the wet-cavity condition. Thus, it seems that the difference of the heat flux within the melt is the reason why the bulk melt temperatures in experiment and simulation results are different. In the simulation, the whole melt is considered as a pool condition with a single temperature, on the other hand, the melt nearby the centerline in the experiment can be presumed as a locally solid based on the bulk melt temperature and upper heat flux results. Therefore, the difference in the melt temperature under the wet-cavity condition cannot be covered by the current analysis method in the CORQUENCH. In conclusion, the CCI-2 test simulation result using CORQUENCH 4.1b with the reference model reasonably fit the experiment result although the simulation result doesn't fit well the experiment result in terms of the bulk melt temperature under the wet-cavity condition.

2.2 Sensitivity analysis

Based on the CCI-2 test simulation result, three sensitivity variables were considered for concrete ablation (NABBL), concrete decomposition temperature (TDCL), and initial melt temperature (TMELTIC). Sensitivity analysis conditions are shown in Table II. Reference model inputs are marked with gray color.

There are three models for the concrete ablation (NABBL); Quasi-steady concrete ablation, dryout model, and transient dryout model. Input values for concrete decomposition temperature (TDCL) are considered between the solidus temperature and the liquidus temperature of a limestone/common sand concrete. In this analysis, the initial melt temperature (TMELTIC) was considered from 2050 K to 2250 K, which the range is above the melt freezing point, 1975 K in the CORQUENCH 4.1b.

Table II: Sensitivity analysis condition

Parameter (Variable name)	Input model/value
Concrete ablation (NABBL)	(0) Quasi-steady concrete ablation
	(1) Dryout model
	(2) Transient dryout model
Concrete decomposition temperature (TDCL)	1395 K
	1430 K
	1465 K
	1500 K

	1535 K
	1565 K
Initial melt temperature (TMELTIC)	2050 K
	2100 K
	2150 K
	2200 K
	2250 K

Axial ablation depth and bulk melt temperature results according to the concrete ablation model are shown in Fig. 4 and Fig. 5 each.

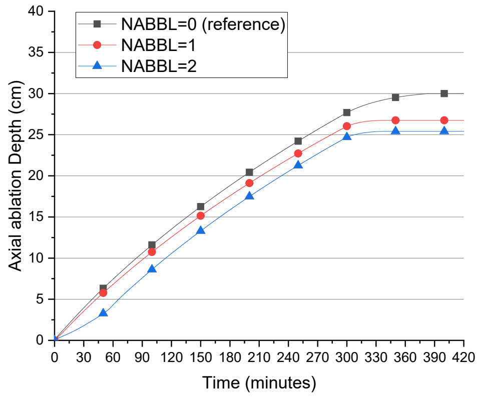

Fig. 4. Axial Ablation Depth according to Concrete Ablation Model (NABBL)

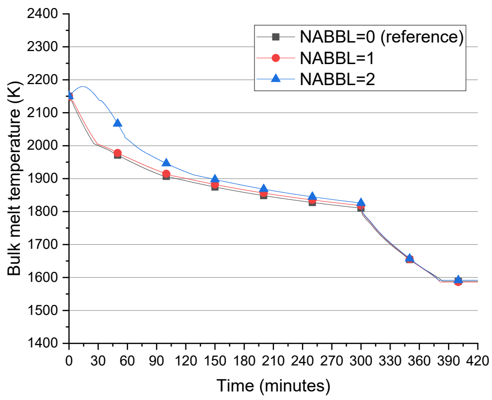

Fig. 5. Bulk Melt Temperature according to Concrete Ablation Model (NABBL)

The difference of ablation depth based on the reference result according to the concrete ablation model is within 5 cm during the whole simulation time. There is not much difference among bulk melt temperatures. The largest depth was shown when the quasi-steady ablation model (NABBL=0) was used for the concrete ablation model, because conduction heat transfer into the concrete behind the ablation front, as well as the initial surface temperature rise to the ablation point, are neglected in the model. On the other hand, the least depth was shown when the transient dryout model (NABBL=2) was used because conduction into the concrete and the initial concrete heatup phase are both considered, along with interfacial corium crust growth in the model.

Axial ablation depth and bulk melt temperature results according to the concrete decomposition temperature are shown in Fig. 6 and Fig. 7 each.

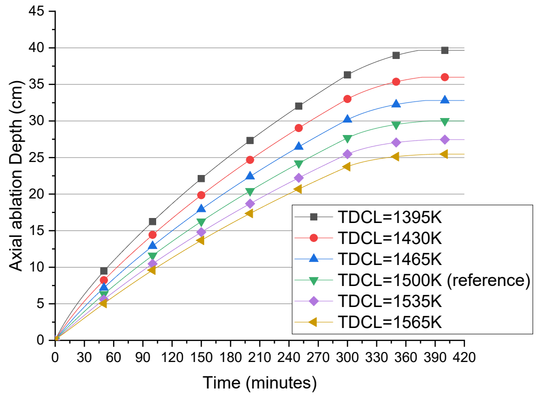

Fig. 6. Axial Ablation Depth according to Concrete Decomposition Temperature (TDCL)

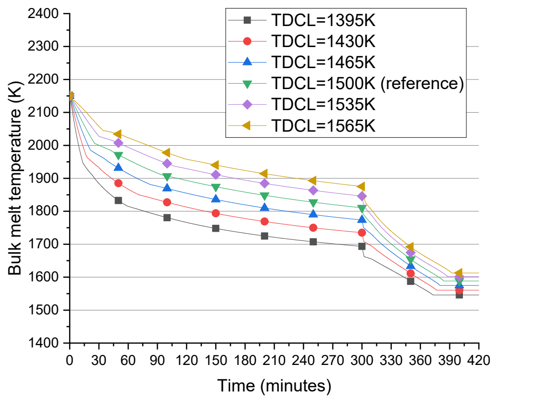

Fig. 7. Bulk Melt Temperature according to Concrete Decomposition Temperature (TDCL)

The difference of ablation depth among all results according to the concrete decomposition temperature is almost 15 cm during the whole simulation time. The difference of bulk melt temperature among all results is almost 200 K until 300 minutes, which is the dry cavity condition. When the concrete is decomposed at higher temperature, the ablation depth gets lower and the bulk melt temperature gets higher because the temperature on the crust/concrete interface gets higher.

Axial ablation depth and bulk melt temperature results according to the initial melt temperature are shown in Fig. 8 and Fig. 9 each.

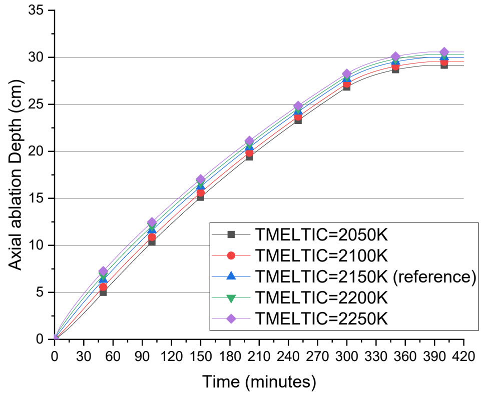

Fig. 8. Axial Ablation Depth according to Initial Melt Temperature (TMELTIC)

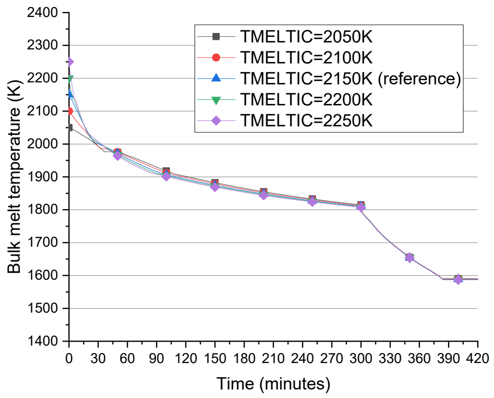

Fig. 9. Bulk Melt Temperature according to Initial Melt Temperature (TMELTIC)

The result shows that axial ablation depth gets higher with higher melt temperature. The ablation rates are different according to the initial melt temperatures only within about 30 minutes. So there are not much difference among results. The bulk melt temperature becomes same regardless of the initial melt temperature after about 30 minutes. Because constant decomposition temperature on surface between melt and concrete is considered for the heat transfer without the crust layer when quasi-steady ablation model (NABBL=0) is used for the concrete ablation.

3. Conclusions

The result comparison of CCI-2 test between CORQUENCH simulation and experiment, and sensitivity analysis were performed in this research. The effect of concrete ablation model, concrete decomposition temperature, and initial melt temperature on the simulation result were identified by the sensitivity analysis. It was analyzed that concrete decomposition temperature affects largely on the ablation depth and the bulk melt temperature. Current MCCI codes including CORQUENCH consider the concrete decomposition temperature as a constant, however, the temperature should be considered with detailed model based on the result of this research.

For further study, a confirmation on the effect of the sensitivity factor related with water injection such as water ingression model, and so on are recommended based on other MCCI tests which are more focused on the wet cavity condition than CCI-2 test. Also, the mitigation capability evaluation of MCCI for the nuclear power plant using an advanced code based on this research are recommended.

Acknowledgement

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