Comparative analysis of CCI-3 test simulation using COCCI and CORQUENCH

Jaehyun Ham [a*], Sang Ho Kim [a], Jaehoon Jung [a]
[a]*Korea Atomic Energy Research Institute, 111, Daedeok-daero 989 beon-gil, Yuseong-gu, Daejeon, Republic of Korea 34057*
[*]*Corresponding author: jhham@kaeri.re.kr*

1. Introduction

There are currently efforts underway to develop innovative nuclear power plants, such as small modular reactors, that have a reduced risk of severe accidents. However, it is important to estimate how these plants would respond to a Molten Core Concrete Interaction (MCCI), as in the event that residual heat removal is insufficient, the molten core would ultimately fall into the cavity beneath the reactor vessel. While the probability of this occurrence is extremely low, it remains a critical consideration for all types of nuclear power plants.

KAERI is currently developing the Code Of Corium-Concrete Interaction (COCCI) to analyze MCCI using C++, with a focus on improving its applicability and making it more widely usable. The main purpose of COCCI is to reduce the uncertainty in MCCI analysis based on various physical model options and geometric options [1]. There are multiple codes available for simulating MCCI, including CORQUENCH, COCO, CORCON, COSACO, MAAP, MEDICIS, TOLBIAC-ICB, WECHSL, and others. Among these, CORQUENCH was selected to compare with COCCI for better understanding the simulation results because this code provides various model options.

In this research, the simulation of CCI-3 test was conducted using COCCI and its results were compared to those obtained from CORQUENCH simulation.

2. Method

The OECD conducted a series of CCI tests at ANL between 2002 and 2010. The purpose of these six tests was to gather data on MCCI, such as ablation rate and temperature, to develop simulation codes. CCI tests were designed to provide information in several areas, including: i) lateral vs. axial power split during dry core-concrete interaction, ii) integral debris coolability data following late phase flooding, and iii) data regarding the nature and extent of the cooling transient following breach of the crust formed at the melt-water interface. Among these tests, CCI-3 test was conducted on September 22, 2005 to investigate the interaction of a fully oxidized 375 kg PWR core melt, initially containing 15 wt % siliceous concrete, with a specially designed two-dimensional siliceous concrete test section with an initial cross-sectional area of 50 cm x 50 cm. Test specifications for CCI-3 are provided in Table I [2]. The test experienced extensive melt foaming and so heat losses to the non-ablating sidewalls were higher than planned. Thus, the effective input power to the melt is shown in Fig. 1 [3]. In the test, the dry cavity operations were kept up for 108 minutes.

For COCCI and CORQUENCH simulations of CCI-3 test, several assumptions were used commonly. Firstly, no melt eruptions were observed during the test, as the cavity was immediately flooded after the concrete basemat touched the melt. Secondly, input power was only assumed to be deposited in the melt zone, with no heat input to the crust or particle bed regions. Lastly, the heat transfer coefficients for both horizontal and vertical concrete surfaces were calculated using the Bradley's modification to Malenkov-Kutateladze correlation.

There were several differences in assumptions. For CORQUENCH analysis, a concrete dryout model with initial crust growth was used, assuming that the crust was permeable to ablation-produced gas. Meanwhile, for COCCI, heat conduction from the melt to concrete was considered without initial crust growth. Additionally, only for CORQUENCH analysis water ingression model was considered using the modified Lister-Epstein model. Furthermore, while a radial heat transfer coefficient multiplier three times higher than the axial multiplier was used for CORQUENCH, the same values were assumed for both sides for COCCI analysis.

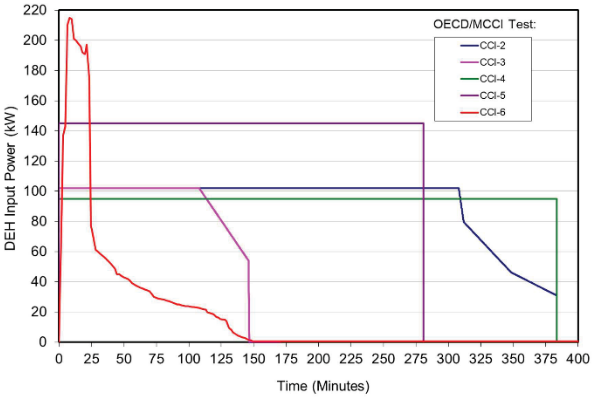

Fig. 1. Input power for OECD/MCCI CCI tests

Table I: Main specifications for CCI-3

Parameter	Specification
Corium	100 % oxidized PWR with 15 wt % siliceous
Concrete type	Siliceous concrete
Initial basemat dimension	50 cm × 50 cm
Initial melt mass	375 kg
System operating pressure	Atmospheric
Melt formation technique	Chemical reaction
Initial melt temperature	1950 ℃
Melt heating technique	Direct Electrical (Joule) Heating

Power supply operation prior to water addition	Constant power at 120 kW
Criteria for water addition	1) 5.5 hours of operation with DEH input, or 2) lateral or axial ablation reaches 30 cm
Inlet water temperature	20 ℃
Inlet water flow rate	2 liters/second
Sustained water depth over melt	50 ± 5 cm
Test termination criteria	1) melt temperature falls below concrete solidus, 2) concrete ablation is arrested, or 3) maximum lateral/axial ablation limit of 35 cm is reached.

3. Result

COCCI and CORQUENCH simulation results are presented in this section. Fig. 2 shows cross view of test section, and Fig. 3 to Fig 5 show comparison of ablation depth, bulk melt temperature, and upper heat flux.

CORQUENCH simulation result is fairly accurate in terms of the melt temperature. However, the axial erosion is slightly overestimated, while the radial erosion is underestimated. The model underestimates the debris-water heat flux throughout the interaction, as it predicts that the melt sparging rate is not high enough to prevent stable crust formation.

In the test, a high asymmetry in concrete erosion was observed in the lateral and bottom directions. However, in COCCI simulation results, the same depth of concrete erosion was calculated for the lateral and bottom directions. The reasons for this are as follows: First, the code assumes that gas components generated from eroded concrete enter the core melt, but in the test, gases generated by the heating and erosion of concrete seem to have been released in large quantities through the boundary between the core melt and concrete. Due to this difference, in the code, the top height of the core melt is maintained to a significant degree because the released gas is assumed to exist inside the core melt, whereas in the test, the top height of the core melt continues to decrease as the volume of released gas is excluded and filled with the part of the actual concrete that was occupying the space. Accordingly, in the test, the overall lateral boundary area and bottom boundary area continue to change over time. For the same reason, the bulk melt temperature is higher in COCCI simulation results. The temperature decreases rapidly after water is injected into the upper part.

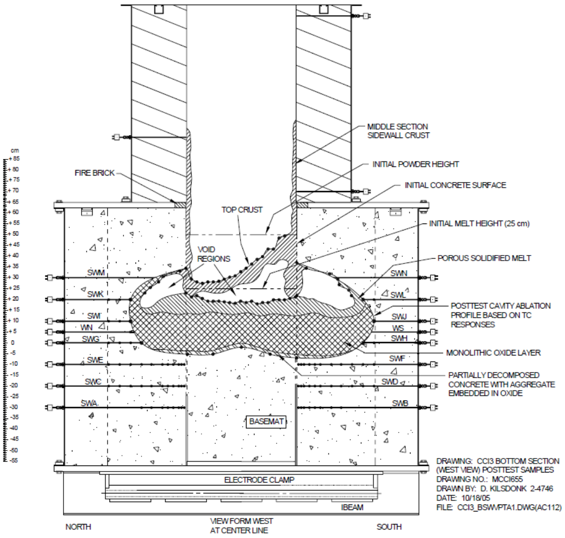

Fig. 2. Cavity erosion profile based on TC data and limited posttest exams

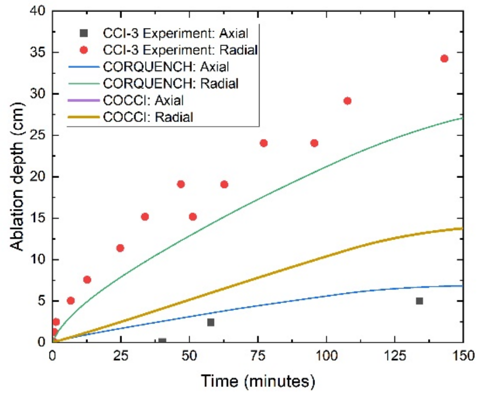

Fig. 3. Comparison of ablation depth

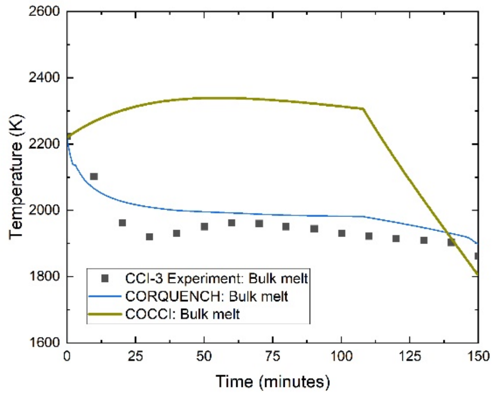

Fig. 4. Comparison of bulk melt temperature

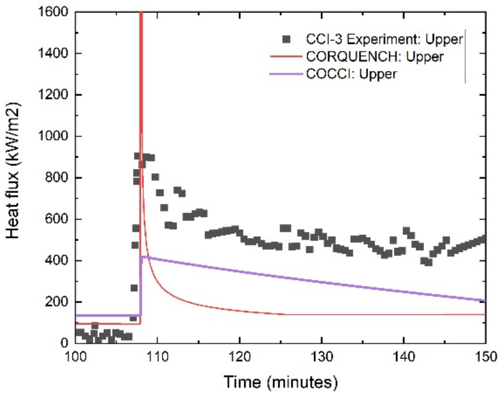

Fig. 5. Comparison of upper heat flux

4. Conclusion

In this research, comparative analysis of CCI-3 test simulation results that were performed using COCCI and CORQUENCH was done. While CORQUENCH is accurate in predicting melt temperature, it underestimates debris-water heat flux and overestimates axial and radial erosion. In COCCI, it was assumed that gas components generated from eroded concrete enter the core melt, resulting in higher bulk melt temperature and symmetrical erosion depths. However, in the test, gases seem to have been released through the boundary between the core melt and concrete, causing the top height of the core melt to decrease over time, and leading to asymmetrical erosion depths. For further work, following developments will be updated in COCCI to obtain simulation results that better match the test: the concrete dryout model with initial crust growth, the water ingression model, application of different heat transfer coefficient multipliers for the radial and axial directions, the bubble sparging model and the gas flow model in the melt.

Acknowledgement

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korean government (Ministry of Trade, Industry, and Energy) (No. 20193110100090).

REFERENCES

[1] Sang Ho Kim, Jae Hyun Ham, Hwan-Yeol Kim, Rae-Joon Park, Jaehoon Jung, COCCI for a simulation of molten core and concrete interaction during a severe accident, Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 19-20, 2022.

[2] M. T. Farmer, S. Lomperski, D. J. Kilsdonk, and R. W. Aeschlimann, OECD MCCI Project 2-D Core Concrete Interaction (CCI) Tests: CCI-3 Test Data Report-Thermalhydraulic Results, OECD/MCCI-2005-TR04, Rev. 0 October 15, 2005.

[3] M. T. Farmer, CORQUENCH Code for Modeling of Ex-Vessel Corium Coolability under Top Flooding Conditions: Code Manual – Version4.1-beta, ANL-18/22, August 2018.