Sensitivity Analysis for MCCI and Corium Coolability Models in MAAP5

Sung-Min Cho*, Sang-Woo Shin, Hoon-Goo Oh
KEPCO E&C, 269 Hyeoksin-ro, Gimcheon-si, Gyeongsangbuk-do, Korea. 39660
**Corresponding author: sungmin@kepco-enc.com*

1. Introduction

In this paper, the parameters related to MCCI (Molten Core-Concrete Interaction) and corium cooling models in MAAP5 (Modular Accident Analysis Program) are divided into five areas: i) FCI (Fuel-Coolant Interaction) cooling and particle bed generation; ii) Heat transfer from particle bed to water; iii) Heat transfer coefficients in MCCI; iv) Water ingression model; v) Melt-eruption model. Then, while changing the detailed modeling parameters in each divided area, it has been studied for the erosion depth change of the concrete floor in the reactor cavity.

2. Analysis methodology

This study is based on the following information and assumptions.

2.1. Computer code and Target plants

The computer code used in this study is MAAP5 version 5.05. In addition, the Zion-like hypothetical power plant, which has Westinghouse 4-Loop PWR RCS with a large dry containment, was used as the target plant for confirming the erosion depth change according to the modeling parameters.

2.2. Scenario to be analyzed and Initial conditions

The selected scenario is initiated from LBLOCA (Large Break Loss of Coolant Accident) assuming 0.769 m^2 of double-ended cold leg break, and the code-run period is 24 hours. The reactor vessel failure occurred around 11,200 seconds, and the initial mass of the molten core discharged at this time was about 83,600 kg in all cases. The reactor cavity has the pre-flooded condition continuously more than 10 m of water elevation from the onset of the vessel failure to the end of code-run due to operations of safety injection system and containment spray system. The cavity floor was modeled using the properties of LCS (Limestone Common Sand) concrete.

2.3. Classification of MCCI and Corium Cooling Models of MAAP5

Parameters related to MAAP's MCCI and corium cooling models are classified as shown in Table I. The default, minimum, and maximum values were determined by code developers based on benchmarking of experiments. It can be shown for the description of each variable in Table I.

3. Calculation results

3.1. FCI cooling and particle bed generation

MAAP5 assumes particle bed can be generated through two sources: i) Corium jet break-up during FCI; ii) Corium entrained by off-gas during melt eruption. Corium is released from reactor vessel as corium jet. If the jet enters a pre-flooded reactor cavity, strong FCI can strip off corium droplets from the jet. It is possible that the particles generated through FCI are sufficiently cooled by water when they finally settle down. Corium jet break-up in MAAP5 is modeled with a formulation similar to Ricou-Spalding entrainment correlation and the parameter ENT0C can affect the quantity of particle bed produced from FCI. If the parameter IPBRB is turned on, particles generated through FCI settle on top of continuous corium bed as particle bed, otherwise it merges back into the continuous bed. In all cases in Fig. 1, the larger the value of ENT0C, the more particles are generated, which leads to better MCCI cooling, resulting in a smaller erosion depth. It can also be seen that the erosion depth is reduced due to the rapid cooling when IPBRB is turned on.

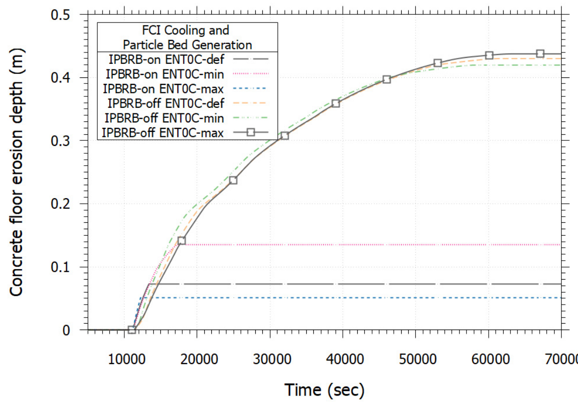

Fig. 1 Effect of FCI cooling and particle bed generation

3.2. Heat transfer from the particle bed to water

MAAP5 considers the nucleate boiling, critical heat flux, and film boiling to calculate the heat transfer from the particle bed to water. Based on water availability and stored corium energy, the heat transfers for particle bed and water, and continuous pool (liquid pool and

Table I: Classification of MCCI and Corium Cooling Models of MAAP5

Classification	Parameter	Definition	Min. (or Off)	Max. (or On)	Default
FCI cooling and particle bed generation	IPBRB	Flag controlling particle bed formation due to FCI	0	1	1
	ENT0C	Rico-Spalding entrainment coefficients controlling number of particles formed due to FCI	2.50E-02	6.00E-02	4.50E-02
Heat transfer from particle bed to water	EPSPB	Porosity of particle bed	0.26	0.53	0.4
Heat transfer coefficients in MCCI	HTCMCR	Nominal downward heat transfer coefficient	500.0 W/m^2-C	10000.0 W/m^2-C	3500.0 W/m^2-C
	CDU	Exponent accounting for effect of viscosity increase	1	3	2.75
Water ingression model	IQDO	Control flag specifying the method to calculate dry-out heat flux from the top of a contiguous corium pool to water (if =0: parametric method (FCHF); =1: mechanistic method)	0	1	1
	FCHF	Modeling parameter for heat flux from a contiguous corium pool to water when IQDO = 0	0.0036	0.3	0.1
	FIWNGS	Specifies permeability of materials cracking due to thermal stress of quenching when IQDO = 1	1	5000	280
Melt-eruption model	IMLTERP	Control flag activating melt eruption model	0	1	1
	ENT0RB	Coefficient in Rico-Spalding entrainment correlation which controls the efficiency of melt eruption generating particles	0.025	0.1	0.08
	XDENTRB	Average diameter of particles entrained by off-gas	1.E-4 m	1.E-2 m	0.004 m

solid bed) and water are modeled to be limited to a certain heat transfer rate. In the cases we analyzed, it was confirmed that nucleate boiling heat transfer rates limits all other heat transfers, so in this study, we performed an analysis to change the variables affecting nucleate boiling. Since the number and size of particles, which are the most important in calculating the nucleate boiling heat transfer, are internally determined by the MAAP5 code, we changed the EPSPB parameter that can be controlled by the user. As the porosity increases, it can be predicted that the corium cooling occurs better, but the results in Fig. 2 showed that it did not significantly affect the depth of concrete erosion. This is because the EPSPB variable affects not only the calculation of the MCCI in the reactor cavity, but also the heat transfers of the particle layer in the lower head of reactor vessel before the vessel failure. The smaller EPSPB value, the MCCI erosion starts faster than others in Fig. 2, indicating that the MCCI initial conditions have been changed.

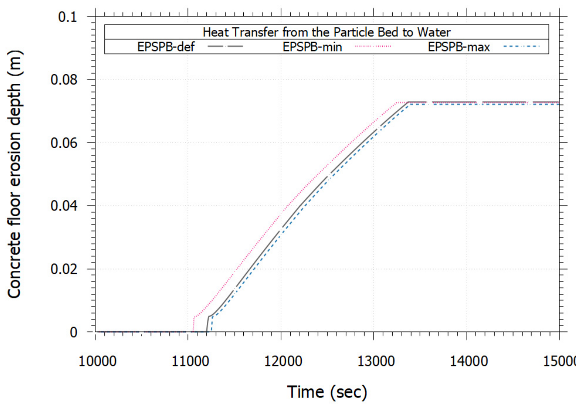

Fig. 2 Effect of heat transfer from the particle bed to water

3.3. Heat transfer coefficients in MCCI

For the cooling of corium, MAAP5 analyzes the heat transfer between the particle layer and water and the heat transfer between the continuous bed and water separately. Here, the continuous bed means a region in which the solidified layer and the liquid melt layer exist. As the core melt is generally located below the water, the bottom concrete of the reactor cavity comes into contact with the continuous bed, so the convective heat transfer coefficient (HTCMCR) in the continuous bed can directly affect the erosion depth. In addition, the effect on the parameter CDU, which can be changed by the user considering the viscosity of corium, was also checked. In Fig. 3, it can be seen that the higher the HTCMCR value, the more heat transfer to the concrete and the more erosion occurs. Likewise, the larger the CDU value, the more likely the concrete erosion will occur.

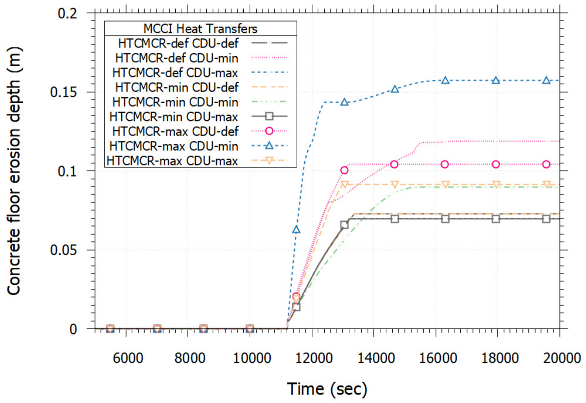

Fig. 3 Effect of heat transfer coefficients in MCCI

3.4. Water ingression modeling

MAAP5 supports the solution method through empirical correlation and mechanical analysis model for the water ingression phenomenon that occurs during heat transfer between the crust layer of the continuous bed and water. In this study, the effect on concrete erosion was confirmed by changing the detailed variables in the two models as shown in Fig. 4. When the empirical correlation was used and the FCHF value was minimized, it was found that the corium cooling did not complete quickly and MCCI proceeded very slowly. This proves that the water ingression model plays a significant role in MAAP's corium cooling analysis.

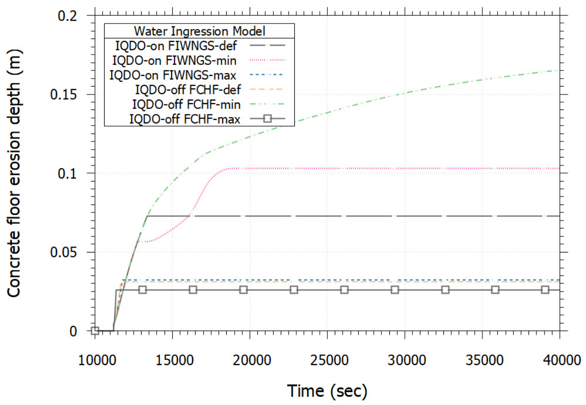

Fig. 4 Effect of water ingression model

3.5. Melt-eruption modeling

In the case of melt eruption model in MAAP, the amount of off-gas emission is determined according to the properties of concrete. Similar to the cooling analysis of the jet break-up model, a formulation similar to Ricou-Spalding entrainment correlation is used to add the entrained particles ejected by off-gas to the mass of the existing particle bed. As a result of the analysis in Fig. 5, it was confirmed that a lot of erosion was observed when the melt eruption model was not used, and the cooling was performed better when the melt eruption mode model was used and the ENT0RB value was increased.

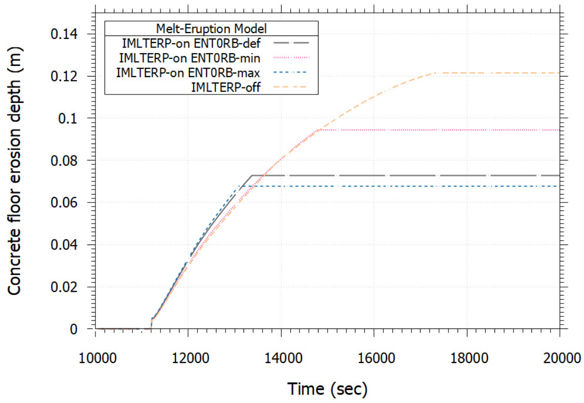

Fig. 5 Effect of melt eruption model

4. Conclusions

In this study, detailed variables related to the MCCI and corium cooling model of MAAP5 were divided into five areas, and the changes in the depth of concrete erosion according to the changes of each detailed variable were confirmed. Although the results are limited to the current analysis for a hypothetical power plant and pre-flooded conditions with LCS concrete, Fig. 6 including all the case results simultaneously shows which part of the MAAP5 modeling contributes more to the corium cooling and concrete erosion.

As FCI cooling affects the particle layer mass at the initial stage of MCCI, the effect on the concrete ablation depth was found to be the greatest. Regarding the heat transfer between the particle bed and water, only the effect of porosity size was confirmed, but it was found to be insignificant. As the heat transfer coefficients of MCCI directly affects the heat transfer between the concrete-crust layer, the result of the erosion depth was proportional to the degree of changing the variable value. In the water ingression model, it was confirmed that this phenomenon could be important in terminating the MCCI. In the melt ejection model, the effect of adding a particle layer mass favorable for cooling to the existing particle layer after concrete erosion was confirmed.

Through this analysis, it was found that MAAP5 calculates the corium cooling and the erosion depth by applying various models in combination. However, since the selected scenario and MCCI initial conditions are limited, in order to confirm the specific and quantified sensitivity or contribution of each model, the more case studies under various conditions will be required in the future.

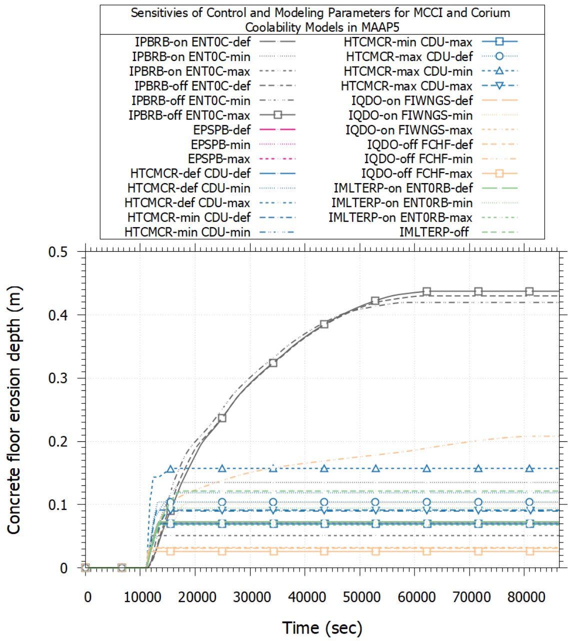

Fig. 6 Sensitivities of MCCI and corium cooling models in MAAP5

REFERENCES

[1] Hu Luo, Jeff Gabor, “Transmittal Document for MAAP5 Code Revision MAAP 5.05 January 2019”, EPRI, Jan.24, 2019

[2] M. T. Farmer, S. Lomperski, and S. Basu, “The Results of the CCI-2 Reactor Material Experiment Investigating 2-D Core-Concrete Interaction and Debris Coolability,” 11th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-11), Avignon, France, October 2-6, 2005

[3] Chan Y. Paik, Paul McMinn, Christopher Henry, and Wison Luangdilok, "Validation Status of Maap5 Core Melt Progression Model", Proceedings of the 2014 22nd International Conference on Nuclear Engineering (ICONE22), Prague, Czech Republic, July 7-11, 2014

[4] Quan Zhou, Chan Y. Paik, and Paul McMinn, "Benchmark of MCCI Model in MAAP5.02 against OECD CCI Experiment Series", Proceedings of ICAPP 2014, Charlotte, USA, April 6-9, 2014

[5] Byung Jo Kim, In Chul Ryu, Young Tae Moon, "Effects of New MCCI Models Implemented in MAAP5 on MCCI in NPP Application", Transactions of the Korean Nuclear Society Autumn Meeting, Gyeongju, Korea, October 27-28, 2016

[6] Sung-Min Cho, In-Chul Ryu, Byung-Jo Kim, "Containment Model Enhancements for MCCI in MAAP 5.04", Transactions of the Korean Nuclear Society Autumn Meeting, Yeosu, Korea, October 25-26, 2018