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Preliminary Validation of MCCI Module for Coolability Assessment of Ex-Vessel Corium

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1. Introduction

During a severe nuclear accident, the formation of a molten core (corium) is a critical concern, and it must be cooled to maintain the integrity of the nuclear power plant. If the cooling strategy fails, the corium can penetrate the reactor vessel, leading to various ex-vessel phenomena such as Fuel Coolant Interaction (FCI) and Molten Core-Concrete Interaction (MCCI). MCCI happens when the corium and concrete of the reactor cavity react directly, resulting in concrete ablation form the extreme heat of the corium. To predict and mitigate severe nuclear accidents, it is crucial to use an integrated code such as MELCOR, MAAP, RELAB-SCD, ASTEC, or SAMPSON. These codes can simulate and analyze various accident scenarios, from the initial damage to the nuclear fuel in the reactor core, to the damage to the containment building. By using these integrated codes, we can better understand and plan for potential severe accidents, and take steps to mitigate their impact.

We aim to develop a module for the molten core-concrete interaction (MCCI) analysis as part of a larger research project titled 'Development of Computational modules for Risk-Significant Severe Accident Phenomena in Reactor Containment Building.' The objective of the project is to develop an integrated nuclear severe accident analysis code capable of analyzing severe accident phenomena that may occur in the reactor system. The proposed MCCI module utilizes a lumped parameter approach, dividing the MCCI geometry into several nodes and calculating the movement of physical quantities between each node based on empirical correlations.

To ensure the accuracy and reliability of the developed MCCI module, preliminary validation has been conducted. The preliminary validation conducted in this study was based on a simple MCCI scenario, and the proposed MCCI module was compared with the CORQUENCH code [1]. The following sections will provide a detailed description of the methodology and preliminary validation.

2. Methodology

In this section, we will provide a comprehensive overview of the developed MCCI module and describe key modeling related to heat transfer in corium. [2]

The proposed code is based on a lumped parameter approach, where MCCI configuration is divided into five nodes: corium, top crust, sidewall crust, bottom crust, and concrete, using commonly used constituents in the major LWR reactor. To calculate the movement of physical quantities for each node, the proposed module solves the mass and energy conservation equations, which consider a various physical phenomenon in MCCI.

Heat transfer from corium is considered in two main mechanisms in the code, namely upper heat transfer and concrete ablation. Separate models are employed for each heat transfer mechanism. For upper heat transfer, the current code considers only dry cavity situation using convection and radiation heat transfer. [3] The proposed module uses the simplest model, namely the quasi-steady model as the concrete ablation model. [4]

The proposed module updates 10 state variables using governing equations and heat transfer models at each step for calculation. (Fig. 1)

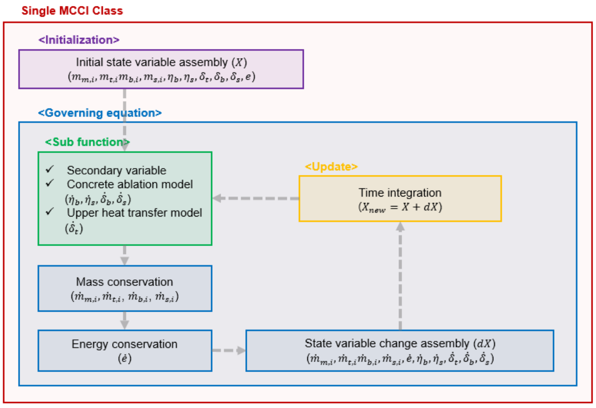

Fig. 1. Flow chart of the proposed MCCI module

3. Preliminary validation

Preliminary validation using the proposed module was conducted to evaluate its performance. In this section, we will describe the approach and conditions for the preliminary validation, followed by the explanation of the results of preliminary validation.

3.1 Validation approach and conditions

A virtual nuclear reactor cavity was created for preliminary analysis, assuming the presence of corium released from the reactor vessel following an In-Vessel Retention (IVR) failure. (Fig. 2) [1]

The analysis conditions of the preliminary validation are summarized in Table I. The MCCI geometry is a 2-D cylindrical shape with a radius of 5.0576m, which is a shape commonly considered by most MCCI analysis codes. The type of concrete that makes up the cavity is siliceous concrete with a high SiO_2 content, and the molar fraction of its constituent components are summarized in Table Ⅱ.

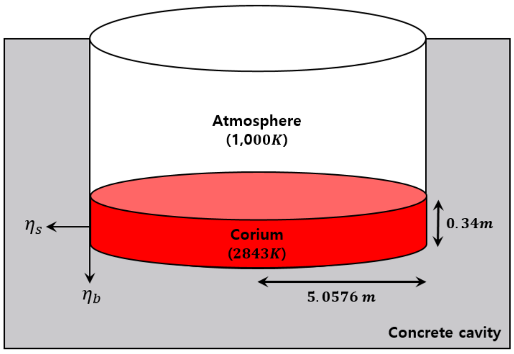

Fig. 2. MCCI geometry for preliminary validation

The initial corium temperature is 2,843K, and a total of 208,100 kg of corium, consisting of various constituents (Table Ⅱ), was considered. It is assumed that a dry cavity situation with an atmosphere of 1,000K existed at the top of the corium. The decay heat was initialized to 26.5MW, and it was decreased as the simulation progressed. The time step was 0.2 seconds, and a total of 15,000 seconds of calculation were performed.

Table I: Analysis conditions for preliminary validation

Conditions	**Value**
Geometry	2-D cylindrical
Concrete type	Siliceous
Initial corium temperature [K]	2,843
Initial corium height [m]	0.34
Initial cavity radius [m]	5.0576
Initial corium mass [kg]	208,100
Atmosphere pressure [MPa]	0.1
Cavity condition	Dry cavity
Boundary Temperature [K]	1,000
Decay heat [MW]	26.5
Time step [s]	0.2
Total time [s]	15,000

Table Ⅱ: Initial composition of corium and concrete for preliminary validation

Constituent	**Corium**	**Concrete**
	Mass [Kg]	**Weight fraction [%]**
CO_2	0	2.31
H_2O	0	5.28
K_2O	0	2.41
Na_2O	0	1.89
TiO_2	0	0.6
SiO_2	0	59.03
CaO	0	13.57
MgO	0	1
Al_2O_3	0	10.68
Fe_2O_3	0	3.23
Fe	48,100	0
FeO	0.01	0
Cr	11,700	1
Ni	5,200	0
Zr	11,700	0
ZrO_2	18,200	0
UO_2	113,200	0
Total	*208,100*	*100*

3.2 Result parameters in validation

To evaluate the results of the preliminary validation using the proposed module, several parameters that well demonstrate the characteristics of MCCI phenomenon were selected.

First, since the main objective of the proposed module is to evaluate the coolability of the corium, the corium temperature was selected. Secondly, to evaluate the concrete ablation phenomenon which can affect the design of the reactor cavity and is important in the heat transfer of corium and concrete, the concrete ablation depth was selected. Finally, to assess the corium mass, which continuously changes due to various MCCI phenomena, its mass was selected.

4. Preliminary validation results

In this section, the results of the preliminary validation are analyzed for the selected 3 parameters. In addition, a comparison of the results was carried out between the proposed module and the CORQUENCH code for evaluating the performance of the proposed module. To facilitate a fair comparison with the proposed module, the quasi-steady concrete ablation model, one of the 3 concrete ablation models in CORQUENCH code, was utilized.

4.1 Corium temperature

Figure 3 is a graph showing the corium temperature, and the results of the proposed module converges to a certain value after an initial sharp temperature decrease. We analyzed that the initial sharp temperature decrease was due to vigorous concrete ablation caused by high corium temperature, resulting in rapid heat transfer.

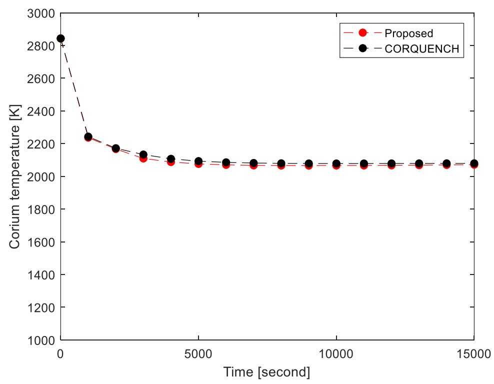

Fig. 3. Corium temperature history

Furthermore, the results of the proposed module show a very similar trend to the results of the CORQUENCH code, indicating that the proposed module based on the CORQUENCH code calculate the correct results.

4.2 Concrete ablation depth

The concrete ablation depth results of the preliminary validation are shown in Figure 4, exhibiting a rapid increase in ablation depth during the early stages of the analysis, followed by a decrease in the rate of increase in ablation depth after the middle stages of the analysis.

The rapid increase in ablation depth during the initial stages of the calculation is due to the high temperature of the corium, while the decrease in the rate of depth increase thereafter is attributed to the convergence of the corium temperature to a lower level. The results of the proposed module show a very similar trend to the results of the CORQUENCH code, due to the same reason as the corium temperature.

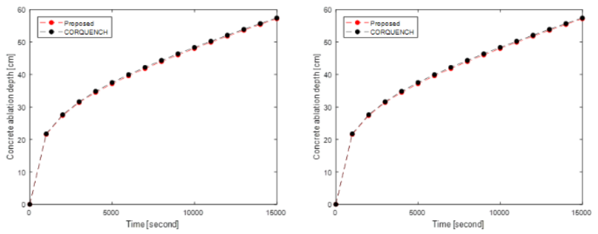

Fig. 4. Axial/Radial concrete ablation depth history

4.3 Corium mass

The final validation result is the corium mass, which is influenced by various MCCI phenomena. The preliminary validation was carried out under dry cavity conditions, where continuous decay heat was generated, resulting in no crust formation as confirmed by the simulation results. As a results, the element that exerts the most significant influence on the change in corium mass is the mass of the concrete that is combined by concrete ablation. Therefore, the trend in corium mass is similar to the trend in concrete ablation depth.

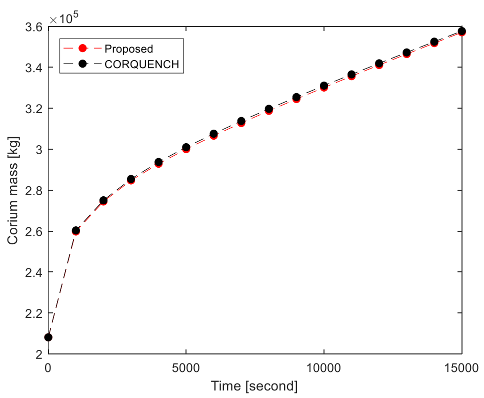

Fig. 5. Corium mass history

5. Conclusions and Future works

In this paper, as part of the 'Development of Computational modules for Risk-Significant Severe Accident Phenomena in Reactor Containment Building.' project, we developed an independent MCCI analysis module and performed preliminary validation to evaluate the module's performance.

The proposed module is based on the CORQUENCH code developed by the Argonne National Laboratory and simulates the MCCI phenomenon by updating 10 state variables through solving the governing equations and heat transfer modeling.

To verify the performance of the proposed module, we conducted a preliminary validation assuming a virtual reactor cavity situation. The result parameters selected for validation were the corium temperature, the concrete ablation depth, and the corium mass. The results for each parameter were compared with the results from the CORQUENCH code to evaluate the performance of the proposed module. The proposed module calculated physically plausible results for each result parameter considering MCCI phenomena and showed a generally similar trend of results to the CORQUENCH code.

The proposed MCCI module will be incorporated into the integrated nuclear severe accident analysis code being developed, and its capabilities will be expanded to cover various types of MCCI scenarios (wet cavity condition). Validation using experiments that consider both dry and wet cavity scenarios, such as the CCI-2 experiment will be carried out for evaluating the advanced MCCI module.

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