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COCCI for a simulation of molten core and concrete interaction during a severe accident

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1. Introduction

A nuclear power plant is designed under the concept of multiple physical barriers which consist of fuel, cladding, reactor vessel and containment. Even though there are various safety systems to prevent the occurrence of an accident and mitigate the progress of an accident, a concrete accident management strategy is needed for unexpected accident progress and conditions. Even though the integrity of a reactor vessel is not maintained, there is still a final barrier, containment. The integrity of the containment must be secured to prevent the large release of the radioactive materials. One of the threatening issues for the integrity of the containment is molten corium and concrete interaction (MCCI). It must be proven that the molten corium is sufficiently cooled in a severe accident scenario of a nuclear power plant.

As the MCCI phenomenon includes the physical state of the mixed object, the heat transfers among the core melt layers, concrete, water and air, chemical reactions, and fission product behaviors, various experimental and analytic studies have been performed.

Based on the review of existing computer codes that simulate the MCCI phenomenon, uncertainties in the analysis of the MCCI are largely divided into the following three categories.

The first is the uncertainty caused by the spatial inconsistency between the system in which the actual phenomenon occurs and the system in which it is calculated and simulated. The inconsistency of the spatial coordinate system causes the inconsistency of scalability for heat transfer in the two analysis systems, which results in distortion of the concrete ablation shape in the MCCI simulation. That is, there should be no distortion in the spatial coordinate system of the actual phenomenon and the spatial coordinate system of the simulation analysis code.

The second is the uncertainty induced from the assumed lumped control volumes existing in the spatial coordinate system assumed and set in the analysis code. In a typical MCCI analysis code, actually physically complex objects are simulated by dividing them into lumped control volumes represented by typical characteristics. Therefore, each assumed lumped control volume should be specified to minimize uncertainty from representing real objects.

Finally, there is uncertainty from the models computed for the constructed control volumes. It includes models of mass and energy calculated inside and between each control volume and physical property models that simulate the state of the control volumes. Detailed physical models and correlation equations have been developed from various experimental studies, and the accuracy of these simulated models is directly reflected in the uncertainty of the actual analysis results. In order to quantitatively estimate the uncertainty of the analysis result, sensitivity analysis or uncertainty analysis for a specific variable or analysis model is performed.

The COCCI (Code-Of-Corium Concrete Interaction) has been developed for a simulation of molten core and concrete interaction during a severe accident. The purpose of this paper is to develop and propose the characteristics of the COCCI having the analysis system that can reduce the uncertainty in the MCCI analysis. The characteristics are also linked to those proposed as problems in previous studies. The analysis systems for various coordinate system and control volumes of the COCCI are provided. The simulation analyses for the CCI (Core-Concrete Interaction) experiment as a representative MCCI test are performed and the analysis results are discussed for the validation of the analysis system and models in the COCCI.

2. Characteristics of the COCCI Analysis System

In this chapter, two characteristics of the COCCI are proposed to reduce the uncertainty in the code simulation for MCCI.

The first is the uncertainty arising from analytical geometries. The main MCCI experiments performed so far have been performed under limited spatial conditions with a specific surface composed of concrete or insulated surfaces. In three (M1b, M3b and M4) of the four MACE tests, the initial core melt was set to a rectangular shape, and the four sidewalls of the apparatus were constructed from inert MgO [1]. That means it was only intended for axial concrete ablation as one dimension. In the CCI tests in an OECD/MCCI program performed following the MACE tests, the test section was redesigned to incorporate two concrete sidewalls and two insulated sidewalls [1]. Concrete was ablated in the radial and axial directions in the Cartesian coordinate system with two surfaces insulated. In other BETA, COMET, COTELS, and MOCKA experiments, the initial core melt was set to a cylindrical shape [2, 3, 4]. Accordingly, the surrounding concrete was ablated to the radial and axial directions. On the other side, the core melt in the reactor cavity of an actual nuclear power plant initially spreads under a three-dimensional shape. In the state where the core melt is not fully spread, the side of the core melt is not surrounded by concrete.

For example, in the MELCOR code, which is a representative severe accident integrated-analysis code, the MCCI is simulated only in a cylindrical coordinate system [5]. When it is used for the simulation of the test designed in a two-dimensional Cartesian coordinate system with one insulated side, the similarity between the experiments and code analysis cannot be maintained. According to the limitation, the COCCI adopted various coordinate systems such as the Cartesian coordinate system, the cylindrical coordinate system, and the hemispherical coordinate system to reduce uncertainty from the analysis geometry as shown in Table I.

Table I: Coordinate System in the COCCI

Coordinate System	Abbreviation
Cartesian -2D	CAC-2D
Cartesian -3D	CAC-3D
Cylindrical	CYC
Upper Hemispherical	UHC
Lower Hemispherical	LHC

In addition, existing codes use the ray-method or bisecting line method to calculate the shape of ablated concrete. When the ablation depth derived from the actual calculation using the calculation method predicts the change in the shape of the containment cavity, the absolute value differs from the actually calculated value by reflecting the vector values from the reference point and the ablation direction. Due to that, the calculated ablation rate is applied to each side under the coordinate system without adjusting the directionality in the COCCI.

The second is the uncertainty coming from predefined control volumes in a defined spatial coordinate system. In the existing MCCI analysis codes, as the physical values in each lumped layer are calculated as one representative value, the uncertainty is caused by not being able to simulate all the phenomena actually occurring in each defined layer. The representativeness in a specific lumped layer also can cause the overall uncertainty in the analysis of the MCCI phenomenon.

Accordingly, in the COCCI, the layers in each axial direction are defined as various objects. Each layer is named ‘abbc’. ‘a’ means the relative position of the layer. ‘bb’ denotes a representative constituent material of the layer. ‘c’ stands for the dominant state of the layer. The names of representative layers were defined in the COCCI and their meanings as shown in Table II.

In addition, when the concrete ablation is calculated with a constant ablation temperature and its decomposition enthalpy, the transition phenomenon of concrete ablation and the conduction heat transfer to the internal volume of concrete cannot be calculated. Accordingly, the transition phenomena that can occur inside the concrete volume are modeled in the COCCI.

Table II: Abbreviation names and meanings of layers

Full Name	Abbreviation
Central mixture liquid	CMXL
Upper mixture solid	UMXS
Side mixture solid	SMXS
Lower mixture solid	LMXS
Upper mixture particle-bed	UMXP
Side concrete gas	SCNG
Side concrete solid	SCNS
Bottom concrete gas	BCNG
Bottom concrete solid	BCNS
Top water liquid	TWTL
Top air gas	TARG

3. Heat Transfer between Core Melt and Concrete

In order to calculate the heat transfer between the core melt and concrete, various models were proposed and validated. In the COCCI, the standard Kutateladze, modified Kutateladze, BALI, and Kutateladze and Malenkov of the models are included so that it can be used according to the preference of code users.

In addition, a layer of slag or gas as the interfacial layer between the core melt and concrete can be defined by a code user. The layer is counted as a heat-resisting layer.

In order to compare the analysis results according to the selection for the heat convection model, the CCI-2 experiment was adopted as the validation test. The initial masses of melt compositions are presented in Table III. The slag layer was set to exist in the front section of the concrete.

Table III: Initial masses of melt compositions

Constituent	Mass [kg]
UO_2	242.48
Zr	0.00
ZrO_2	99.60
Cr	25.64
Fe	0.00
SiO_2	13.56
CaO	12.52
MgO	4.56
Al_2O_3	1.64
Sum	400.00

The superficial gas rising velocity calculated from the gas content in the ablated concrete is the main factor in the function for the heat convection coefficient. Kutateladze number varies with the superficial gas rising velocity, and the equations for Nusselt number are divided into intervals of dimensionless gas velocity.

The analysis results from the models of standard Kutateladze, modified Kutateladze, BALI, and Kutateladze and Malenkov were compared in the absence of top coolant.

The simulation with the Kutateladze and Malenkov model showed the analysis results similar with those in the experimental test. As the simulation results with the BALI model overestimated the heat transfer from the core melt to the concrete, the temperature of the melt mixture sharply decreased at the initial simulation time.

There were quasi-steady and fully developed concrete ablation models in the COCCI. The analysis results according to the selection of the concrete ablation model were compared.

Fig. 1 shows the analysis results of core melt mixture temperature according to the concrete ablation model. Fig. 2 shows the ablation depth according to the concrete ablation model.

Fig. 3 shows the variations of the superficial gas velocity and heat transfer coefficient in the simulation case with the Kutateladze and Malenkov model.

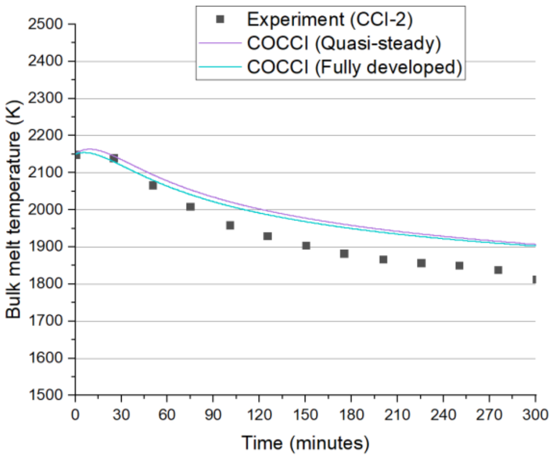

Fig. 1. Variation of core melt mixture temperature according to the concrete ablation model

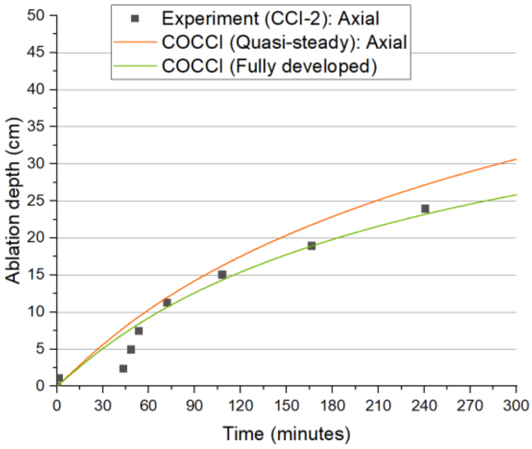

Fig. 2. Variation of the axial ablation depth according to the concrete ablation model

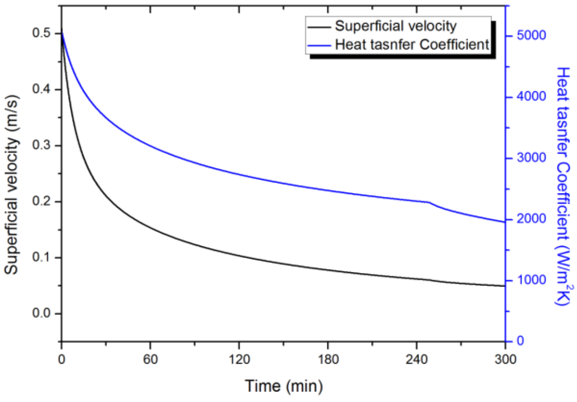

Fig. 3. Superficial gas velocity and heat transfer coefficient in the simulation case with Kutateladze and Malenkov model

4. Conclusions

The characteristics of the COCCI developed were proposed comparing with those by the existing MCCI analysis code. Those contribute to the reduction of uncertainty. The validation calculation using the material property package for the core melt mixture is presented as a study to be performed later.

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