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Development of Computer Code for Analysis of Molten Corium and Concrete Interaction

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1. Introduction

The integrity of the containment must be protected and maintained in any kinds of accidents as it is the final physical barrier to prevent the release of the fission products. Proper actions must be taken so as to protect the physical barriers. In order to establish the proper mitigation strategy, the phenomena in accidents must be well identified and predicted.

After the reactor vessel breach in a severe accident of a conventional pressurized water-cooled reactor, the corium falls down into the reactor cavity. The basemat concrete ablation by the molten corium can threaten the containment pressure boundary. Therefore, a cooling by a specific facility or water injection system is needed for the corium on the reactor cavity. In addition, the accurate analysis for the molten corium-concrete interaction (MCCI) and the cooling of the corium by water is needed.

In simulating the MCCI, there are various specific phenomena for consideration and also various models for each phenomenon. The uncertainties on the models have to be compared and identified. In addition, the analytical uncertainties on scheme and system in a computer code have to decrease.

For this reason, the necessity of a computer code capable of analyzing various coordinate system and having various parameters for an uncertainty analysis has been raised. The objective of this paper is to develop the analysis system of a computer code named Code Of Corium-Concrete Interaction (COCCI). The general characteristics were also described.

2. General Description and Characteristics of COCCI

COCCI is being developed to simulate the molten corium and concrete interaction in condition with or without coolant at the top.

Before the development of the COCCI, QuCCI (Quasi-stationary parametric simulation code for Corium-Concrete Interaction) was developed with Python 3.6. As QuCCI has quasi-stationary energy term for concrete ablation and absorption with thermal equilibrium on melt, the modeling on mass transfer through a stable crust was simplified. The sensitivity analysis was carried out for finding out the key variables in MCCI using QuCCI and MELCOR codes [1, 2]. It was also estimated that the effect of heat transfer models and thermal conductivity on maximum crust thickness in the equilibrium condition using QuCCI [3]. Based on the results of these calculation tests for sub-functions, the COCCI is being developed with C++ code focused on wider usability and improved applicability.

COCCI has the following general characteristics.

First, COCCI is capable of modeling the physical transient phenomena. A governing equation for each layer is set. The formation and growth of each crust layer on the top, side, and bottom of the corium pool is modeled. Options for transient concrete ablation and conduction heat transfer to side and bottom concrete layers are included in COCCI.

Second, a variety of analysis geometry coordinate systems are included in COCCI, which leads to a decrease in the uncertainty from the scale ability and coordinate system of an analysis code in the validation analysis for experimental tests. Otherwise, the methodology for cavity shape change is simplified.

Third, COCCI has wide usability. Options for models recently developed and employed in CORQUENCH code are provided to users with value recommendations [4]. The models were reviewed for MCCI mitigation strategy in the recent research paper [5].

3. Calculation Flow of COCCI

Overall calculation flow of COCCI is illustrated in Fig. 1. When it is executed, all the input variables are read. All the initial and boundary conditions, parameters and matrices are initialized for the time zero.

During one time step, transfer rates for mass and energy are solved. Then, the governing equations for mass and energy are solved. There are various layers set in the COCCI. Those include a center mixture liquid and each solid crust for top, side and bottom. The crust formation and growth for each solid layer are calculated based on mass and energy equations. The concrete layers are divided into side and bottom. Each concrete layer is ablated according to the option for the heat transfer in the concrete layer. The first option is the conventional ablation based on the decomposition temperature as the interface temperature. In the second option, the conduction heat transfer in the concrete layer is considered. In the third option, the transient ablation is modeled in the code. On the top of the corium layer, the water and air layers are defined. The cooling mechanism of water ingression or melt eruption can be selected and included in the modeling as an user option.

After the calculation for mass, energy governing and transfer equations, the convergence criteria are checked to calculate again with the reduced time step. If the calculation is completed for a time step, the concrete geometry is updated and variable data are stored. After the calculation is complete for the total simulation time, the data specified by an user are printed and the COCCI code terminates.

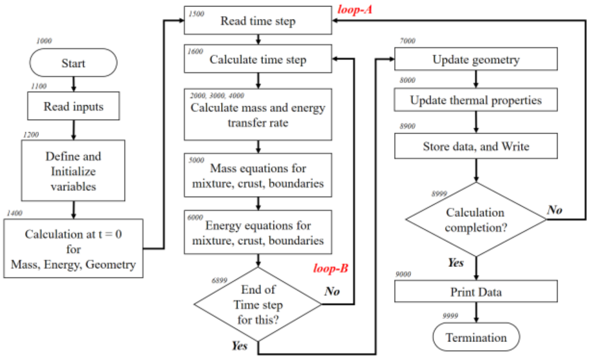

Fig. 1. Overall Flow Diagram of COCCI

4. Validation Work

The development of COCCI is in progress. To check the calculation flow of the code and the variations of thermal values in layers, some representative experimental tests have been modeled and analyzed.

In CCI-2 experiment, initial melt mass was 400 kg. Concrete type was Limestone/Common Sand (LCS). Density of the concrete was 2320 kg/m³. The initial mass of the melt was 400 kg. Initial melt temperature was 2153 K. Power supply operation was constant at 120 kW. The top surface was open to air for 5 hours. Water was injected after 5 hours. The water injection flow rate was 2 liter/sec.

In addition, the simplified methodology for geometry update in COCCI has been tried. The initial melt geometry was cuboid whose volume was 0.5 (width) x 0.5 (thickness) x 0.25 (height) m³ in the atmospheric pressure. However, as two of four side-walls were insulated, the other two side-walls and a bottom-wall were modeled. The two side-walls and bottom-wall ablation were calculated in the axis-symmetric two-dimensional Cartesian geometry.

The results of COCCI code are compared with those of WECHSL code developed in FZK, Germany [6] and also CCI-2 test. Fig. 2 shows the ablation depths for CCI-2 test and simulations. In the COCCI simulation, stable crusts were formed on the side of the corium layer for 36 minutes. The posttest examination for CCI-2 showed the final axial ablated depth at the bottom wall was about 29 cm. Therefore, the COCCI simulation overestimated the axial ablation of concrete by 5 cm. In the case of the calculation results by the WECHSL code, the radial ablation was quite underestimated due to the different modeling for gases behavior near the side-wall and bottom-wall.

Fig. 3 shows the corium temperature for CCI-2 test and code simulations. At 300 min from the initiation, the corium bulk temperature was about 1,600 ℃ higher than that in WECHSL code simulation. It is caused by the overestimation of the melt and concrete interface temperature, about 1500 ℃ at 300 min. It is estimated that the deviation is caused by the constant thermal property and the absence of specific phenomenon models in the code system of COCCI.

5. Conclusions

The basic analysis system and general characteristics for COCCI code were described in this paper. COCCI is capable of modeling the physical transient phenomena in MCCI condition. In addition, as a variety of analysis geometry coordinate systems are included in COCCI, the uncertainty from the scale ability and coordinate system will be reduced. The code analysis system was tested by modeling the CCI-2 experiment. Detailed specific models and material properties functions will be included in the COCCI hereafter. The COCCI will be coupled with an ex-vessel corium coolability analysis code (COCCA) for the comprehensive estimation with overall sequence and geometry in a reactor cavity.

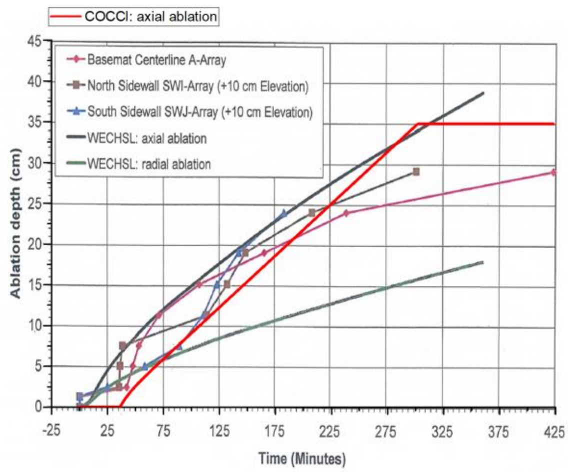

Fig. 2. Ablation Depth in CCI-2 test, and Code Simulations by COCCI and WECHSL code

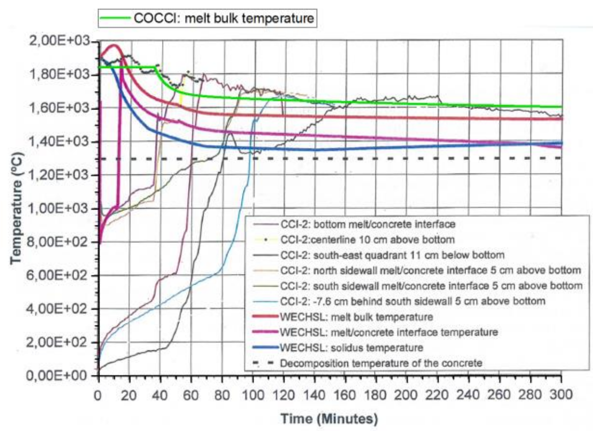

Fig. 3. Corium Temperature in CCI-2 test, and Code Simulations by COCCI and WECHSL

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