Application of CINEMA code to CCI-5 analysis

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1. Introduction

Molten core-concrete interaction (MCCI) is a phenomenon in which the corium discharged from the reactor vessel interacts with concrete, accompanied by complex multi-physics and multiphase flows. Because of the complexity, the analysis of MCCI has been developed by lumped parameter approach.

Many experiments have been conducted to validate the developed codes, and each experiment has a different type of concrete, geometry, and cavity condition. Among them, CCI tests are experiments conducted in the OECD-MCCI program, and the purpose is to measure MCCI results in 2D cavity. [1]

Code for integrated severe accident evaluation and management, CINEMA, is possible to interpret the phenomena related to the severe accident of PWR. In this study, CCI-5 test is analyzed using CINEMA code and the results are compared with another MCCI analysis code, CORQUENCH. Furthermore, MCCI analysis can be applied to the type of reactors in operation, which will lead to an improvement in nuclear safety.

2. Methods and Results

2.1 CINEMA code

The MCCI analysis codes use different models depending on the purpose and phenomenon of the analysis, which causes differences in results among each code. CINEMA code defines melt as the uppermost crust layer, the upper metal layer, the mixed oxide layer, and the lower metal layer in consideration of the stratification of melt. Through the stratification model, the reversal of the metal layer and the oxide layer can be simulated, which is caused by the density difference according to concrete ablation.

CINEMA analyzes MCCI by solving the mass conservation (1) and energy conservation (2) equations in each layer.

$$\frac{dm_{Layer}}{dt} = \dot{m}_{Layer,in} - \dot{m}_{Layer,out} \quad (1)$$

$$W_{Layer} = W_{Layer,in} - W_{Layer,out} + W_{Layer,int} \quad (2)$$

In the process of solving the conservation equations, CINEMA calculates the physical properties of oxide layer, metal layer and concrete through a weighted average for the mass fraction or mole fraction. If the temperature of corium is between solidus and liquidus, it is called mushy zone and the physical properties are calculated using the interpolation method. Based on the physical properties, thermophysical and thermochemical behavior can be predicted by calculating interlayer heat transfer and concrete ablation. The convective heat transfer coefficient is calculated using a different heat transfer correlation for each interface. In particular, Green correlation is used for the metal-oxide interface and Kutateladze correlation is used for the corium-cavity boundary. The concrete ablation volume is calculated using the heat transfer coefficient obtained at the corium-cavity boundary, and the concrete ablation depth is obtained by calculating the area before and after ablation as shown in Fig 1. Hence, the coolability of the melt can be evaluated.

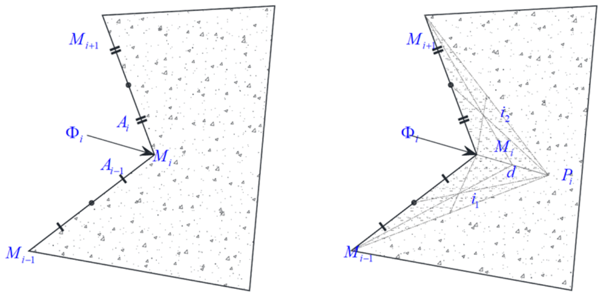

Fig. 1. Concrete ablation depth calculation

2.2 CCI-5 test

CCI-5 is an experiment conducted in 2D rectilinear geometry (50 cm x 79 cm) and dry cavity condition for MCCI analysis. The test section of CCI-5 contains siliceous concrete for ablation, so the corium is composed of oxidized fuel mixed with siliceous concrete, as shown in Table I.

Table I: Corium compositions for CCI-5 test [2]

Constituents	wt %	Mass [kg]
UO_2	56.32	332.29
ZrO_2	23.13	136.47
SiO_2	11.17	65.90
Al_2O_3	0.64	3.78
MgO	0.12	0.70
CaO	2.21	13.04
Cr	6.41	37.82
Total	100.00	590.00

CCI-5 simulates decay heat using a constant direct electrical heating (DEH) of about 145 kW. Concrete ablation occurs due to the heat source, and the shape of the cavity at the end of CCI-5 is shown in Fig 2. [2]

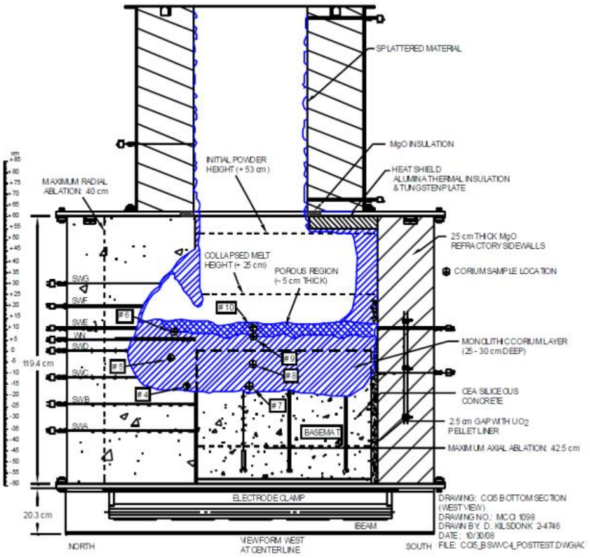

Fig. 2. CCI-5 cavity shape configuration

2.3 Initial conditions

Since CINEMA input needs weight fractions of oxide and metal separately, weight fractions as shown in Table II are applied to each component. Initial temperatures of oxide and metal are both given at 2200K. Unlike the experiment, CINEMA performs a simulation in which corium is ejected in the form of jet and accumulated in cavity. As a characteristic of CINEMA, an integrated severe accident analysis code, the occurrence of MCCI after fuel-coolant interaction (FCI) occurs is considered.

Table II: Corium compositions input for CINEMA

Constituents		wt %	Mass (kg)
Oxide	UO_2	60.18	332.29
	ZrO_2	24.72	136.47
	SiO_2	11.93	65.90
	Al_2O_3	0.68	3.78
	MgO	0.13	0.70
	CaO	2.36	13.04
	Total	100.00	552.18
Metal	Cr	100.00	37.82
	Total	100.00	37.82

To compare the result values with CORQUENCH, the properties of concrete in CORQUENCH manual [1] are used, as shown in Table III.

Table III: Concrete properties for CCI-5 test [1]

Constituents	wt %	Solidus Temp. (K)
CO_2	9.50	1403.0
H_2O	4.79	
K_2O	0.80	
Na_2O	0.49	Liquidus Temp. (K)
TiO_2	0.15	1523.0
SiO_2	58.30	
CaO	20.21	
MgO	0.92	Ablation Temp. (K)
Al_2O_3	3.51	1500.0
Fe_2O_3	1.33	
Total	100.00	

The 145 kW of DEH power is applied from 114 s to 16,848 s after the start of the simulation, and the simulation is calculated to 20,000 s.

2.4 Analysis results

Fig. 3 shows the radial concrete ablation depth at CINEMA and CORQUENCH for CCI-5 test. In the experiment, onset of ablation was delayed until about 150 mins because of a resilient crust that protected the concrete wall. [3] Since both CORQUENCH and CINEMA do not consider the effect of the crust, there is a discrepancy with the experiment.

Fig. 4 shows the axial concrete ablation depth at CINEMA and CORQUENCH for CCI-5 test. Since ablation delay by crust does not occur in the axial direction, both CORQUENCH and CINEMA show results close to the experiment.

Fig. 5 shows the melt temperature results at CINEMA and CORQUENCH for CCI-5 test. Ablation in the radial direction acts as a cause of discrepancy with the experiment. In the case of CINEMA, it can be seen that in the later stage of the experiment, when radial ablation occurs, it tends to be consistent with the result of the experiment.

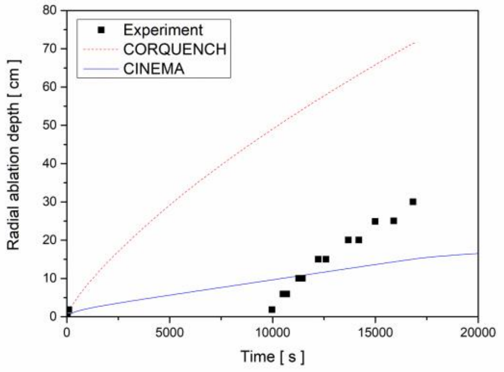

Fig. 3. Radial concrete ablation depth prediction for CCI-5 test

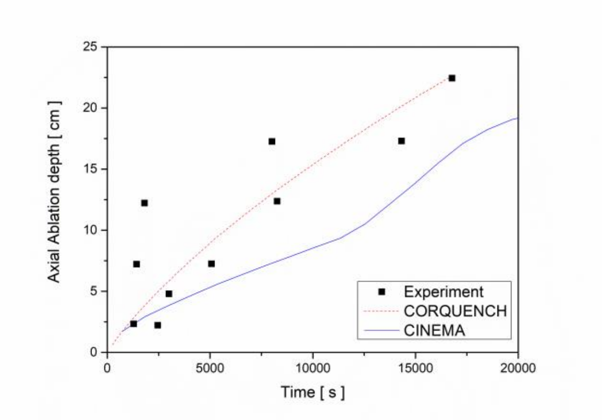

Fig. 4. Axial concrete ablation depth prediction for CCI-5 test

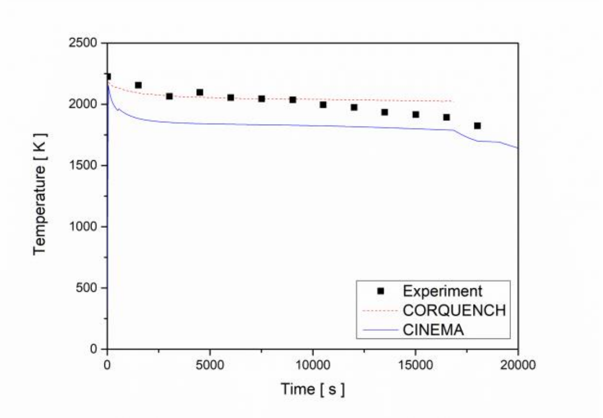

Fig. 5. Melt temperature prediction for CCI-5 test

3. Conclusions

CINEMA, an integrated severe accident analysis code, can evaluate the scenarios of severe accident, and in this study, CCI-5, an MCCI validation test, is analyzed and the results are compared. Further in the validation test, analysis can be performed on NPPs with complex geometries and more extreme conditions.

ACKNOWLEDGMENTS

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning(KETEP) and the Ministry of Trade, Industry & Energy(MOTIE) of the Republic of Korea (No. 20193110100050).

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