Comparative analysis of CCI-4 test simulation using COCCI and CORQUENCH

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1. Introduction

Recently, various innovative nuclear power plants such as a small modular reactor which reduce the possibility of severe accident are being developed. However even the probability is extremely low, the plant response on Molten Core Concrete Interaction (MCCI) should be estimated because the molten core finally falls down to the cavity under the reactor vessel regardless of the type of the nuclear power plant if the residual heat removal is insufficient.

Code Of Corium-Concrete Interaction (COCCI) is being developed by KAERI for MCCI analysis with C++ focused on wider usability and improved applicability [1]. The code is also being connected with Code Of Corium Coolability Analysis (COCCA) which covers ex-vessel corium behaviors such as jet breakup, spreading, and cooling in the cavity. Under the wet cavity condition, simulation using the connected code would be mainly focused on the corium coolability, which is covered by COCCA. On the other hand, the simulation would be mainly focused on MCCI, which is covered by COCCI under the dry cavity condition. Therefore, verification of MCCI analysis under the dry cavity condition is the most significant for COCCI in terms of code connection with COCCA.

In this research, CCI-4 test simulation was performed using COCCI. The result was comparatively analyzed with the simulation using CORQUENCH.

2. Method

There are several codes to simulate MCCI such as CORCON, CORQUENCH, COSACO, MEDICIS, TOLBIAC-ICB, WECHSL, COCO, MAAP, and so on. All codes can currently analyze the case in which the corium is assumed to be instantaneously spread over the entire floor of the reactor pit under dry cavity conditions [2]. Generally the melt/concrete interfacial heat transfer coefficient, the concrete ablation model, and the concrete ablation temperature are the most important variables for the dry cavity condition MCCI analysis.

CORQUENCH has been developed based on the MACE and OECD/MCCI experiments by ANL since the early 1990's [3]. The code is capable of performing either a 1-D or simplified 2-D ablation calculation. MCCI conservation of energy equation includes the following energy source/sink terms: i) decay heat, ii) mass flux of melt from the failed reactor pressure vessel, iii) chemical reactions between metallic melt constituents Zr, Si, Cr, Fe (in sequence) and concrete decomposition gases H_2O and CO_2, iv) condensed phase chemical reactions between Zr and SiO2, v) downward (and sideward for 2-D case) heat transfer to concrete, including slag ingression into the melt, and vi) heat transfer to overlying atmosphere (wet or dry). The melt composition can range from fully metallic to fully oxidic; in all cases, the two phases are assumed to be well mixed (i.e., phase stratification is not modeled). In terms of heat transfer at the melt/concrete interface, CORQUENCH incorporates a transient concrete ablation/decomposition model based on integral thermal boundary layer theory. This model has been upgraded as a part of this work to account for the effects of transient concrete heat-up with simultaneous crust growth following initial melt contact with the concrete. The inclusion of a concrete dryout model is considered to be important in evaluating both the early and late phases of core-concrete interaction. CORQUENCH provides the following options for melt/concrete interfacial heat transfer coefficient calculation: i) Bradley's modification to Malenkov-Kutateladze correlation, ii) CORCON gas film model, iii) CORCON gas film model with a transition to the Bradley model if the gas velocity falls below the Berenson modified gas sparging limit for film collapse, iv) Sevon heat transfer correlation. For the concrete ablation calculation, the following options are provided: i) quasi-steady concrete decomposition model, ii) concrete dry-out model that is initiated with a fully developed thermal boundary layer with no surface crust present and the surface temperature is initially at the concrete decomposition temperature, iii) concrete dry-out model that considers formation of a surface crust and the surface temperature is initially at a specific temperature by user input. The constant concrete ablation temperature by user input is used in the analysis.

COCCI is being developed to simulate the molten corium and concrete interaction in condition with or without coolant at the top. The code has the following representative characteristics: (i) modeling the physical transient phenomena, (ii) various geometry coordinate options, (iii) various physical model options [1]. By COCCA analysis, the state of the corium which is discharged to the cavity initially can be determined as a liquid or the particle debris. The particle debris can be turned into the liquid by the re-melting in the cavity. Based on geometry coordinate options, simulations on various experiments and realistic analysis of plant response to MCCI in the cavity can be performed. COCCI provides the following model options for melt/concrete interfacial heat transfer coefficient calculation: i) Kutateladze, ii) modified Kutateladze, iii) Bali, iv) Kutateladze and Malenkov. For the concrete ablation calculation, the following options are provided: i) quasi-steady ablation model, ii) fully-developed concrete dry-out model. Currently, two concrete ablation models are available in COCCI, the transient concrete dry-out model which considers heat-up phase of melt/concrete surface temperature and crust formation is developing [4]. The constant concrete ablation temperature by user input is used in the analysis same as CORQUENCH.

CCI tests were performed in ANL by OECD from 2002 to 2010 after the end of MACE tests. There were total 6 tests, the purpose was obtaining the MCCI data such as ablation rate and temperature to build the simulation code. 100% oxide corium was used in CCI-1, 2, and 3 tests, however, about 8 w/o metal was included in the corium in CCI-4 test to verify the effect of the metal on the concrete ablation and corium coolability. From CCI-4 test, corium temperature and ablation depth under the dry cavity condition were mainly obtained. The facility for the test was used as 2-D notch-geometry with two opposing, ablating walls. The summary of CCI-4 test is shown in table I [5].

Table I: Summary of CCI-4 test

Variable	Contents
Initial corium composition	UO_2 (63.91), ZrO_2 (22.27), Concrete (8.51: SiO_2 / MgO / CaO / Al_2O_3), chromium (5.31)
Concrete type	Limestone/common sand
Floor size [cm × cm]	50 × 40
Initial corium mass (depth) [kg (cm)]	300 (25)
Side ablation limit [cm]	45
Axial ablation limit [cm]	42.5
System pressure [bar]	1.0
Initial melt temperature [K]	2123.15
Power [kW] (before water injection)	95
Water injection condition ("OR" condition)	1) 7 hours since test initiation 2) Ablation depth margin < 5 cm
Injected water temperature [K]	293.15
Water injection rate [L/s]	2
Controlled water level [cm]	50 ± 5
Test termination condition ("OR" condition)	1) Corium temp. ≤ Solidus temp. 2) Ablation rate = 0 cm/s 3) Ablation depth margin = 0 cm

3. Result

The simulation of CCI-4 test was performed only for the dry cavity condition, in other words, the simulation was terminated before the water injection. Simulation inputs for the COCCI and CORQUENCH was built based on the CORQUENCH manual [1] and the analysis report from KAERI [5]. To compare the performance of codes, same models and values were used for the inputs. Quasi-steady model was used for the concrete ablation, and Kutateladze and Malenkov model was used for the melt/concrete interfacial heat transfer coefficient calculation.

The experiment and simulation results of ablation depth is shown in Fig. 1. The axial and radial ablation depths were resulted as same in simulation results because the same melt/concrete heat transfer coefficients are used to axial and radial interface. The ablation depth results analyzed by CORQUENCH and COCCI are higher than the experiment result. It is because the most conservative model for calculating concrete ablation depth, quasi-steady model, was used for simulations. The model assumes the total heat from the corium to concrete is used for ablation. COCCI predicts the ablation depth higher than the prediction of CORQUENCH, because the prediction of the bulk melt temperature was higher in COCCI as shown in Fig. 2. When the heat removal from the corium gets low, the bulk melt temperature gets high. However, the prediction of the upper heat flux in COCCI is also higher as shown in Fig 3. It means the calculated heat removed by another way except interfacial heat transfer is higher in CORQUENCH. The another way is the ablation gas release through the melt. The assumed ratio of the ablation gas release is lower in COCCI so that the predicted corium mass is higher at 330 minutes that predicted ablation depths of COCCI and CORQUENCH are almost same.

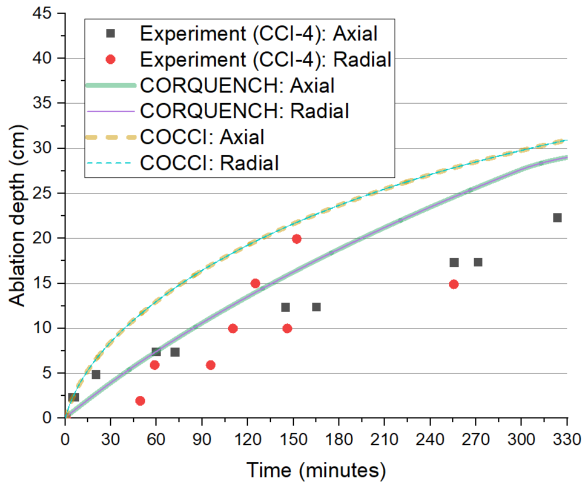

Fig. 1. Comparison of ablation depth

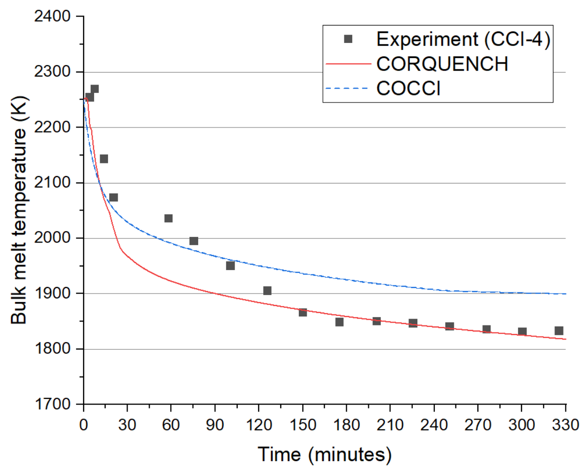

Fig. 2. Comparison of bulk melt temperature

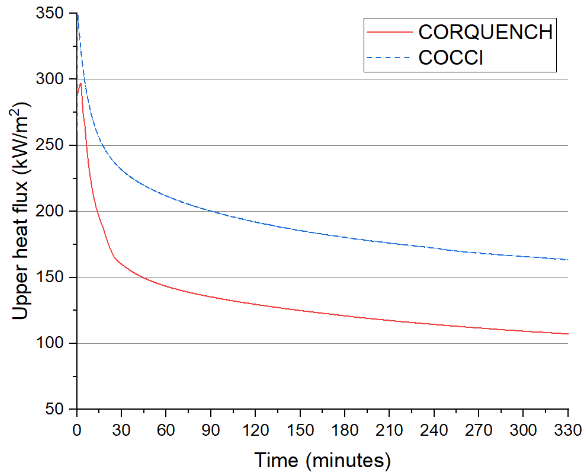

Fig. 3. Comparison of upper heat flux

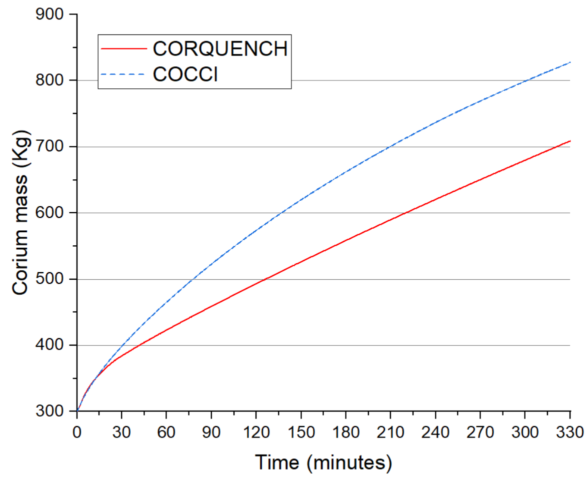

Fig. 4. Comparison of corium mass

4. Conclusion

In this research, comparative analysis of CCI-4 test simulation results that were performed using COCCI and CORQUENCH was done. The dry cavity condition was only covered in the simulation. The simulation result of CORQUENCH was well fitted with the experiment result, but COCCI result was slightly over-predict the ablation depth and bulk melt temperature. It is because the ratio of the gas release from the upper surface of the melt was lower in COCCI so that the prediction of the corium mass was higher when the predicted ablation depth of COCCI and CORQUENCH are almost same. COCCI is developing on the gas flow model in the melt. In addition, the transient dry-out model for concrete ablation and chemical reaction model are developing. It is expected that the code can simulate the dry cavity condition better with developing model options so that the analysis following the options using COCCI will be performed for the further study.

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