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Development of MCCI module for Evaluating Ex-vessel Corium Coolability

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1. Introduction

In the event of a nuclear severe accident, the molten core (i.e. corium) is formed by mixing molten nuclear fuel with a various of structures inside the reactor core. Corium maintains a very hot temperature due to continuous decay heat. Therefore, a proper cooling of corium is required to maintain the integrity of the reactor system.

If corium remains at a high temperature due to the failure of cooling strategy, it will penetrate the reactor vessel and drop into the reactor cavity. During this process, Fuel Coolant Interaction (FCI), where the water inside the cavity reacts with the dropped corium, and Molten Core-Concrete Interaction (MCCI), where the corium and the concrete of the cavity react directly, can occur.

The MCCI phenomenon is a phenomenon in which the corium and the concrete cavity react directly, and the corium is cooled by transferring heat to the concrete and the upper atmosphere (or water). In the reaction between corium and concrete, the high temperature of corium causes the concrete to melt, which is called concrete ablation.

Various severe accident phenomena affect the integrity of the reactor, and therefore, the safety analysis is essential for predicting and mitigating a nuclear severe accident. In general, a nuclear severe accident safety analysis refers to a series of analysis that simulate the entire process from a serious damage to nuclear fuel in core to damage to containment building. With this respect, it is necessary to develop an integrated code that can analyze various severe accident phenomena. Integrated code for analysis of a nuclear severe accident is actively being developed in the world, and representative examples include MELCOR, MAAP, RELAB-SCD code in the United States and ASTEC code in Europe, and SAMSON code in Japan.

This study was carried out as part of a research project 'Development of Computational modules for Risk-Significant Severe Accident Phenomena in Reactor Containment Building'. The purpose of this research project is to develop a nuclear severe accident integrated analysis code, which can analyze a nuclear severe accident phenomenon that may occur in the reactor system.

Among a nuclear severe accident phenomenon, the MCCI analysis is the subject of this study. The proposed code has a lumped parameter approach that divides the MCCI geometry into several nodes. Between each node, the movement of the physical quantity is calculated through the governing equation: mass and energy conservation equation. The models for the upper heat transfer and concrete ablation were applied based on the empirical correlations. The detailed methodology of this work is described in the following section.

2. Methodology

In this section, an overall description of the proposed code is given. First, the development philosophy of the code is described, and the governing equation and the detailed heat transfer modeling used in code are described.

2.1 Code overview

In the proposed code, the corium and concrete are represented as 29 constituents (Table I). With this aspect, the corium composition can range from fully metallic to fully oxide, and stratification is not considered [1]

Table I: Treated 29 constituent in the proposed code

Index	Constituent	Index	Constituent
1	$Ca(OH)_2$	16	Fe_3O_4
2	$CaCO_3$	17	Fe
3	$MgCa(CO_3)_2$	18	Cr
4	$H_2O(l)$	19	Ni
5	$H_2O(v)$	20	Zr
6	$K_2O(s)$	21	ZrO_2
7	$K_2O(v)$	22	B_2O_3
8	Na_2O	23	U
9	TiO_2	24	B_4C
10	SiO_2	25	Si
11	CaO	26	SiC
12	MgO	27	Cr_2O_3
13	Al_2O_3	28	NiO
14	FeO	29	UO_2
15	Fe_2O_3		

The proposed code is the lumped parameter approach based code, which divides the MCCI geometry into five nodes: corium, top crust, bottom crust, sidewall crust, and concrete nodes. (Fig. 1.)

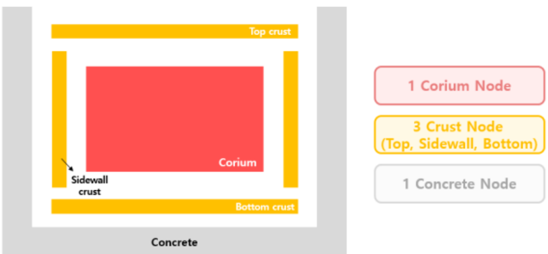

Fig. 1. The five nodes for the MCCI geometry in the proposed code

2.2 Governing equations

There are two governing equations calculated in the proposed code: mass and energy conservation equations. The mass conservation equation is calculated for four nodes: corium (1), top crust (2), sidewall crust (3), bottom crust (4). The mass conservation equation at each node is as follows.

$$\dot{m}_i = \dot{m}^{Oxidation}_{concrete\to corium} - \dot{m}^{Crust\ Forming}_{corium\to crust} + \dot{m}^{Ablation}_{concrete\to corium} + \dot{m}^{Vessel}_{vessel\to corium} \quad (1)$$

$$\dot{m}_i = \dot{m}^{Crust\ Forming}_{corium\to crust} \quad (2)$$

$$\dot{m}_i = \dot{m}^{Crust\ Forming}_{corium\to crust} \quad (3)$$

$$\dot{m}_i = \dot{m}^{Crust\ Forming}_{corium\to crust} \quad (4)$$

$$\dot{m} = \sum_{i}^{22} \dot{m}_i \quad (5)$$

The mass conservation equation is calculated for each constituent (Table. I), and each term of the equation refers to the movement of mass according to various physical phenomena in the MCCI. On the other hand, the energy conservation equation is calculated only for the corium node to obtain the enthalpy of the corium. The equation is as follows:

$$\dot{e} = -\dot{e}^{MassChange}_{corium\to corium} + \dot{e}^{DecayHeat}_{corium} - \dot{e}^{HeatTransfer}_{corium\to con} + \dot{e}^{Oxidation}_{concrete\to corium} + \dot{e}^{Ablation}_{concrete\to corium} - \dot{e}^{Crust\ Forming}_{corium\to crust} + \dot{e}^{Vessel}_{vessel\to corium} \quad (6)$$

2.3 Upper heat transfer Model

The heat transfer mechanism between the corium in the cavity and the upper atmosphere is calculated through an appropriate model. The upper heat transfer model aim to obtain the upper corium temperature (T_t) through the balance of the convective heat transfer from corium and the radiation heat transfer to the atmosphere (Fig. 2.). The variables calculated in this model are used to calculate the governing equation, which is as follows:

$$h_t(T_m - T_t) = h_r(T_t - T_{bound}) \quad (7)$$

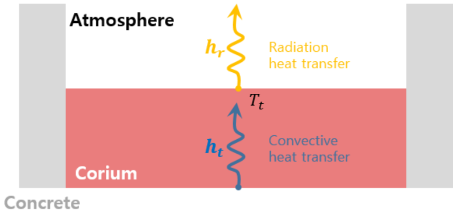

Fig. 2. The heat transfer balance between the corium and the atmosphere

where h_t and h_r are the convective and radiation heat transfer coefficient, T_m and T_{bound} are the temperature of the corium and surrounding cavity. [2] Another model's goal is to calculate the thickness change rate of top crust ($\dot{\delta}_t$) through the energy balance equation. However, the current version of the code does not consider the creation of crusts, so the crust thickness change rate is calculated as zero.

2.4 Concrete ablation Model

In the MCCI process, concrete is melted by corium, and it is necessary to calculate ablation depth rate ($\dot{\eta}_{b,s}$), which means the degree of melting of concrete. The concrete ablation depth rate is calculated through the Quasi-Steady model, which means that all thermal energy from the corium is used for concrete ablation (Fig. 3.). The bottom and sidewall results are in an analogous relationship, and the balance equation is as follows:

$$\rho_{con} e_{con,d} \dot{\eta} = h_m(T_m - T_{dc}) \quad (8)$$

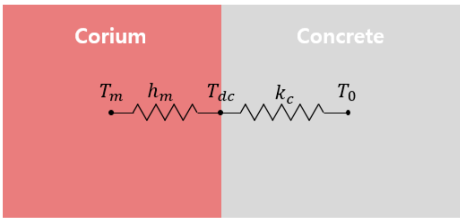

Fig. 3. The heat transfer balance between the corium and concrete

Where ρ_{con} is the density of concrete, and $e_{con,d}$ is the specific enthalpy at decomposition temperature (T_{dc}), and h_m is the convective heat transfer coefficient. [3] As with the upper heat transfer model, the bottom and sidewall crusts are not considered, so crust thickness ($\dot{\delta}_{b,s}$) rate is calculated as zero.

3. Conclusions and Future works

In this paper, we proposed a lumped parameter approach based MCCI analysis code. The proposed code was developed as a module of a nuclear severe accident integrated code, which is the goal of of a research project 'Development of Computational modules for Risk-

Significant Severe Accident Phenomena in Reactor Containment Building'.

We considered the MCCI geometry by dividing five nodes, and calculated the movement of the physical quantity between each node through the governing equation. The governing equation is the mass and energy conservation equation, which takes into account various physical phenomena in MCCI.

The heat transfer mechanism between the corium and its surrounding were simulated through detailed modeling. The upper heat transfer model calculates the energy balance equation between the corium and the atmosphere to obtain the upper corium temperature (T_t) and top crust thickness rate ($\dot{\delta}_t$). Concrete ablation model calculates the concrete ablation depth ($\dot{\eta}_{b,s}$) rate and crust thickness rate ($\dot{\delta}_{b,s}$) using the Quasi-steady model.

Currently, the proposed code can be implemented only for dry cavity situations (corium-atmosphere), and it will be developed to simulate wet cavity situations (corium-water) as the future works. In addition, the validation with the CCI series experiment, an MCCI experiment carried out at the Argon Laboratory, will be conducted. Finally, the heat transfer models of corium used in the proposed code can be replaced with models that further physical models for the accurate results.

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