

Crust Formation and Growth in Analysis of Molten Corium and Concrete Interaction

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1. Introduction

Molten corium and concrete interaction (MCCI) is one of the important issues in a severe accident of a nuclear power plant. That is because it can cause the failure of containment. It has to be proven that the molten corium is fully cooled in a severe accident management of a nuclear power plant.

In order to prove the molten corium is fully cooled in a reactor cavity, the thermal analysis has to be performed. The specific analysis systems for mass and temperature variations, mass and heat transfer, material properties of layers in MCCI configuration have to be set and operated in a MCCI code.

When a molten corium is fell into a reactor cavity, it can be a liquid, or mushy lump containing solid parts. The decay heat and heat from chemical reactions are continuously generated inside a corium lump. When there is a water in a reactor cavity, the corium lump is cooled and the interface solidifies.

The heat from the inside of a corium liquid pool is transferred relatively well to the interface due to the natural convection and gas barbotage inside a corium pool. On the other hand, when the interface solidifies, the solid crust plays a role of thermal resistance as a solid layer. As a heat transfer inside a solid crust is dependent on conduction, the conductivity of mixture material is a main variable. Exceptionally for the upper crust of corium, various additional cooling mechanisms such as melt eruption, water ingress and crust breach are developed when there is water on the top of the upper crust.

The purpose of this paper is to review and characterize the analysis methodologies in the existing and developing MCCI analysis codes. Improvements on analysis for formation and growth of crust are proposed.

2. Review of Analysis Models in Existing MCCI Codes

In this section, the analysis methodologies for formation and growth of crust in MCCI configuration are summarized and reviewed.

2.1 MELCOR

The modeling for the MCCI in MELCOR code is based on the CORCON-Mod3 code [1]. In the MELCOR version 1.8.5, the conservative assumption that water cannot penetrate crust was applied. It was revised by promoting quenching by increasing the

thermal conductivities. The current version includes the model on water ingress.

The approach for the crust formation is to construct a steady-state solution to the heat-transfer equations in a right circular cylinder whose average temperature, boundary temperatures, thickness, and volume all match those of the actual layer [2]. The steady-state conduction leads to quadratic temperature profiles inside the crust. Newton's iteration is utilized for calculating the thickness and temperature of the sub-layer. And then, the heat fluxes are calculated and used for the heat transfer to the corresponding boundaries.

2.2 MAAP5

MAAP is a modular accident analysis program that simulates various severe accident sequences [3]. In the MAAP5 code, the interface of the molten debris and its crust is at the debris melting point. Due to the internal heating, three independent crusts, the lower, side, and upper crust, are assumed to have parabolic temperature profiles. Based on the temperature profiles, the interface temperatures between the crust and the concrete are calculated. The temperature profile in concrete is one-dimensional in the direction of ablation. In the case of the upper crust, the heat transfer is calculated based on the convection and radiation to the surroundings.

2.3 ASTEC-V2

In an ASTEC code, the crust that can grow up at the corium-atmosphere interface can be simulated by two different methods [4]. First, the crust is regarded as a fictive layer. It is calculated under the assumption of the heat flux continuity at the interface. Second, the crust is regarded as an independent layer with a liquid or mushy corium layer. The solidification or melting of the crust is determined by the difference between the convection heat flux and conduction heat flux. The mass flow rate from or to the crust also comes from the heat flux difference. Based on the two estimated heat fluxes, the interface temperature is calculated.

2.4 CORQUENCH-4.1

In a CORQUENCH code, when the top interface temperature of a corium layer is smaller than the freezing temperature, the potential exists for crust formation to occur at the melt-atmosphere interface depending upon the thermal-hydraulic conditions [5]. The crust growth depends on whether the incipient crust

is stable in the presence of the sparging concrete decomposition gases. During the incipient growth phase, the crust will remain thin and decay heat within the crust is negligible. Under the condition, the crust growth rate is calculated by the heat flux difference between the convection and conduction. The force balance about the buoyancy force of a rising bubble to the load is calculated to determine whether the crust segment is in a stable state.

2.5 WECHSL

The WECHSL-Mod3 code is a mechanistic computer code developed by FZK in Germany for the analysis of the thermal and chemical interaction of initially molten reactor materials with concrete in a cavity [6]. In the WECHSL code, the crust formation is governed by the following mechanisms:

- The temperature at the crust internal side is freezing temperature. And heat is transferred by the temperature difference with the bulk temperature of melt pool.
- Heat is transferred by the heat conduction through the crust.
- Heat is transferred at the crust external side by the temperature difference between interface and surroundings.

In case that the crust is thin, the steady state heat conduction is solved. Otherwise, the transient heat conduction is applied.

3. Methodology in Developing MCCI Code

A domestic computer code for the analysis of MCCI named Code of Corium-Concrete Interaction (COCCI) is under development. The analysis system and general characteristics of COCCI were presented in the previous paper [7].

In the COCCI, independent mass and energy transfer rates are calculated in every time step. Based on the values, each mass or energy equation is solved.

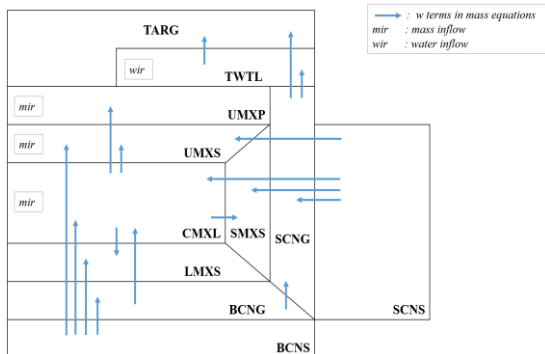


Fig. 1. Mass Flow of Representative Control Volumes in COCCI Code

Independent control volumes were basically defined in the code. In the definition of the control volume, the meaning of the relative position and representative material properties is indicated. Each mass flow between the control volumes is illustrated in Fig. 1.

Crusts in the COCCI consists of UMXS, SMXS, and LMXS according to the locations, upper, side, and lower. MXS means a mixture solid. The crust is formed when the interface temperature of CMXL (Center Mixture Liquid) is lower than the solidus temperature of the corium mixture. According to the location of the crust formation, one of the three control volumes is determined. The solidification of the liquid layer or melting of the solid layer is wholly dependent on the governing energy equation. Based on the calculated temperatures in the configuration of layers, heat fluxes at the interfaces are calculated. Surplus of energy in the crust layer causes the melting of the layer, and lack of energy in the liquid layer causes the solidification of the layer.

Fig. 2 shows the simulation result of the simple problem using the COCCI code. The mass of the CMXL increased due to the inflow of the concrete ablated by the heat transfer from CMXL to the concrete layers. After that, the surface temperature of the CMXL decreased to the solidus temperature of the corium mixture layer. The mass of the crust on each direction gradually increased as the CMXL was cooled.

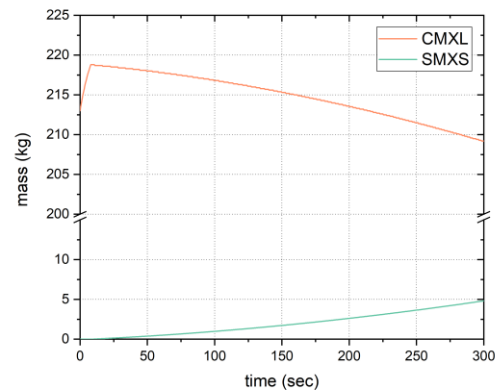


Fig. 2. Mass Variations of Control Volumes in COCCI Code

4. Conclusions

The analysis methodologies for the crust formation and growth are reviewed in the existing MCCI analysis codes. The analytic characteristics of the developing COCCI were explained.

Acknowledgement

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