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Effects of Thermal Conductivity of Corium on Molten Core Concrete Interaction

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1. Introduction

A nuclear power plants is designed based on the concept of a defense-in-depth. There are various physical barriers and tools to mitigate and prevent accidents. Containment is a final physical barrier to prevent the release of radioactive materials to the environment. In case that a reactor vessel is broken due to a certain reason, the integrity of containment has to be maintained. Accordingly, the state of a corium on the cavity has to be exactly identified and grasped with the coolability of the corium.

In this research on the simulation of molten core concrete interaction (MCCI), thermal conductivity of corium and heat transfer models were selected as independent variables.

The material properties and heat transfer models were reviewed firstly. The effects of the variables on the temperature variation in each part and the concrete ablation were derived and analyzed as a result.

2. Thermal Conductivity of Corium

In order to calculate the heat transfer from corium pool to the others, the thermal properties of corium has to be exactly defined for the wide range of temperature. The thermal conductivity is a basic value for most of the models in the MCCI simulation.

The thermal conductivity of solid oxide decreases from room temperature to specific value and increases from it to the melting temperature. The thermal conductivity of UO_2 increases from 2.0 W/m·K at 2100 K to 4.0 W/m·K in a liquid state in itself [1]. That of ZrO_2 increases from 1 to 3 W/m·K in a solid state. Most metals have much higher thermal conductivity in the solid phase than that in the molten phase. The thermal conductivity of molten metal is normally higher than that of oxide. In CORCON code, mixture values are computed from the species values by mole-fraction averaging. Even though the calculation for the thermal conductivity of the mixture is disputable, the content ratio of the metallic materials is crucial for a mixed corium pool geometry in MCCI simulation. In a stratified condition for oxide and metal layers, the thermal conductivity of each oxide material must be carefully defined for a molten oxide pool.

3. Calculation of Heat Transfer in MCCI

In this chapter, the temperature of each layer between a corium pool and concrete was calculated as the thermal conductivity and heat transfer models were varied. Fig. 1 shows the overall geometry of various zones between concrete and corium pool considered in this paper.

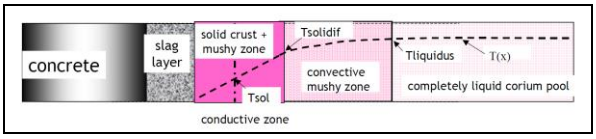

Fig. 1. Build-up of Various Zones between Concrete and Corium Pool

3.1 Corium Pool and Mushy Zone

The molten pool where the decay heat is generated transfers the heat to the crust, concrete, upper air or water. Convective heat transfer coefficient is calculated according to the direction of the heat transfer.

As shown in Fig. 1, the boundary temperature of corium pool and convective mushy zone can be assumed to be liquidus temperature of corium. Then, the boundary temperature of convective mushy zone and solid crust is solidus temperature of corium. In this calculation, it was assumed that convective mushy zone was included in the corium pool as there was a convective flow inside.

There are various models for convective heat transfer at the boundary of corium pool in the MCCI codes. In order to model convection coefficient between corium layer and boundary, Kutateladze or Bali model was directly used or modified to be used. Otherwise, it was calculated by the user provided coefficient. It actually depends on the natural convection and gas flow inside a corium pool.

The heat transfer coefficients were estimated for 3100 K of corium. The averaged thermal conductivity having a range of 2 to 10 W/m·K was set based on the recent code revision of the MELCOR code [2]. Limestone common sand concrete known as the concrete generating much gases in the MCCI condition was selected.

As shown in Fig. 2, the results from BALI model were much larger than those from Standard Kutateladze model. As the Kutateladze model was arranged for the function of thermal conductivity, the function was ordered by the power of 1/3 of the thermal conductivity. Otherwise, the function of the BALI model was ordered by the power of 1.25 of the thermal conductivity.

In comparison with the convection heat transfer between the oxide and metal layers modeled by the Greene, the heat transfer coefficient was higher than that of the BALI model when the thermal conductivity of the mixed pool was lower than 5 W/m·K. The result also means the heat is efficiently transferred from the oxide layer to the metal layer even when the amount of the heat transfer from the corium pool to the concrete is limited due to the result of the Kutateladze model.

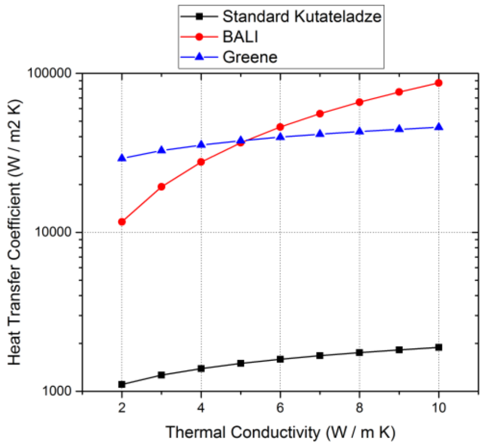

Fig. 2. Convection Coefficient of Corium Pool

3.2 Crust Inside

The boundary temperature of solid crust and concrete slag (or gas) layer is unknown. This temperature is higher than the decomposition temperature of the concrete and lower than the solidus temperature of the corium. In MAAP code, molten slag or gas layer is not considered to be modeled. In the solid crust, as the heat is only transferred by the conduction, the thermal conductivity must be set correctly. As it is assumed that there is no porosity in the crust, the heat transfer inside the crust is the function proportional to the thermal conductivity in itself. In the calculation with the models described above, as the convection heat transfer rate was large, the net heat transfer from the corium to the outside was limited in the heat transfer inside the crust.

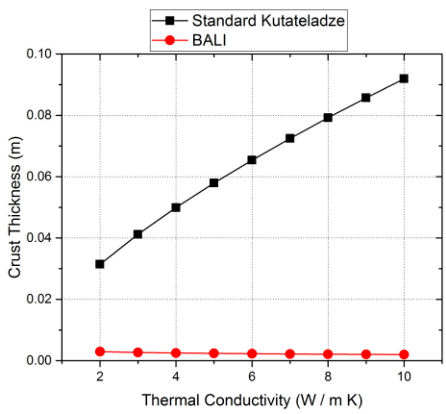

Fig. 3. Maximum Crust Thickness for the Equilibrium of Heat Transfer from Corium Pool to Concrete (at Tmelt = 2900 K)

As discussed above, the range of thermal conductivity of the mixed corium is wide due to the inclusion ratio of metal materials. When the metal inclusion ratio is low, the thermal conductivity is low due to those of the oxide materials.

Under the assumption that the corium temperature decreased from 3100 K to 2900K, the heat flux from each model was calculated. Fig. 3 shows the maximum thickness of the crust between the slag layer of concrete and the corium pool when there is no upper water. It means the overall heat transfer from the corium pool to the concrete would be limited to the heat transfer inside the crust by conduction. It was also calculated to estimate the effect of the variation of the thermal conductivity. As the convection heat transfer by the BALI model is so high, the crust of the melt even thinner than 1 cm limits the heat transfer and causes the temperature increase of the melt.

3.3 Slag and Solid Concrete

The heat transfer at the interface between the solid crust and the concrete slag layer is generally modeled depending on the type of the gas release. The boundary temperature of solid concrete and slag concrete layer can be assumed to be solidus or decomposition temperature of concrete. However, as the concrete is a mixture made by mixing various materials not chemically coupled, there is a series of decomposition for substance in concrete through each temperature range.

4. Conclusions

The heat transfer mechanisms between each layer in the condition of molten core concrete interaction was reviewed. Convective heat transfer models were estimated by varying the thermal conductivity of mixed corium. Even though the thermal conductivity of the mixed corium is a key value for the corium pool modeling, the selection of a specific model has the larger effect on the result. Otherwise, in the total geometry of the molten core concrete interaction, the maximum crust thickness for the equilibrium heat transfer from corium pool to concrete was estimated to be lower than 0.1 m even when the thermal conductivity was 10 W/m·K. This is the result without the upper water. To simulate the progress of the stable cooling of the corium, the thermal conductivity and the water ingression of the crust layer have to be exactly modeled. In addition, the transient concrete decomposition modeling is needed.

Acknowledgement

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