Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18-19, 2023

Preliminary 1-D Analysis Model on Ex-vessel Corium Coolability in Pre-flooded Reactor Cavity

Seokgyu Jeong [a*], Jaehoon Jung [a], Sang Ho Kim [a], Jaehyun Ham [a]
[a]*Korea Atomic Energy Research Institute(KAERI), 989-111 Daedeok-daero, Yuseong-gu, Daejeon, Korea*
[*]*Corresponding author: jsk1201@kaeri.re.kr*

1. Introduction

In the event of a severe accident in a Pressurized-Water Reactor (PWR), the corium melt is released from the reactor vessel into the pre-flooded cavity. As a result of Fuel Coolant Interaction (FCI), particulate debris accumulates at the bottom of the cavity. If the corium jet is not completely fragmented or sufficiently cooled, molten corium can be formed at the bottom of the debris bed. The molten corium can then interact with the concrete structure (MCCI: Molten Corium Concrete Interaction), leading to concrete ablation. In the absence of effective cooling of the debris bed and molten corium within a certain time, the containment may fail and release nuclear material into the environment. To prevent such catastrophic outcomes, it is necessary to predict the long-term coolability of the corium with accuracy. In this study, we have developed a preliminary one-dimensional analysis model to predict the coolability of ex-vessel corium in a pre-flooded reactor cavity based on previous models [1-3].

2. Methods

This section describes the condition of the coolability model and the modeling methods used in this study.

2.1 Modeling Condition

To simplify the analysis, the model considers the coolability of released corium only after its settlement. Consequently, melt jet break-up or FCI are not taken into account. Additionally, it is assumed that the debris bed and molten corium at the bottom have a cylindrical geometry, and no mass or heat transfer occurs in the radial direction. The detailed bed condition is as follows: corium layer diameter = 0.56 m, total mass of corium = 400 kg, particulate debris bed porosity = 0.4, particle diameter of debris bed = 3 mm, and the ratio of particulate debris bed to molten corium = 8:2. The initial temperatures of corium and bed are 2500 K. After validating this 1-D code, cases will be extended. The model was developed based on C++. The model's layers are divided into TARG (top air gas), TWTL (top water liquid), UMXP (upper mixture particle bed), UMXS (upper mixture solid), CMXL (center mixture liquid), LMXS (lower mixture solid), BCNS (bottom concrete solid). The decay heat is set similarly to the CCI-2 experiment.

2.2 Modeling Methods

Mass and heat transfer between each layer after a unit time from the previous condition was calculated for a period of six hours. The properties of each layer over time were determined by satisfying the mass and energy equilibrium of the entire system. The corium coolability model from the previous COCCA code was utilized to calculate heat transfer inside the particle bed [1], while the concrete ablation model from the previous COCCI code was employed for the MCCI phenomenon [2,3]. Various heat transfer methods, such as pool boiling, solid-liquid convection, and solid-solid conduction, were employed between layers with respect to corium conditions (particle bed layer only, particle bed/molten corium layer, and particle bed/solid/melt layer) in this model. Heat transfer at the contact surface between the particle layer and the underlying layer was calculated by subdividing heat transfers, as illustrated in Fig. 1.

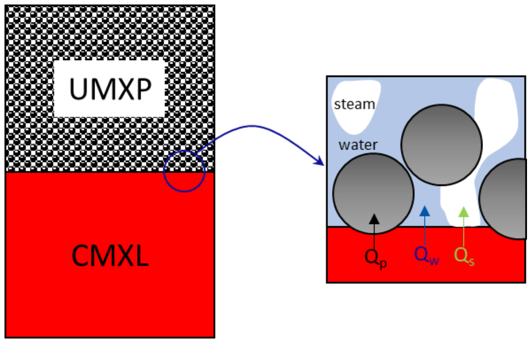

Fig. 1. Heat transfer from CMXL to upward layers

The direct contact area of UMXP and CMXL is equal to $(1-\varepsilon)A$ when the porous volume is taken into account, while the direct contact area of CMXL and water is equal to $(1 - \alpha)\varepsilon A$ when the void fraction is considered. The remaining area $\alpha\varepsilon A$ represents the contact area with steam, where α, ε, and A denote void fraction, porosity of the debris bed, and cross-sectional area, respectively. The amount of upward heat from the CMXL is calculated as follows based on the area and heat transfer between each layer.

$$Q_p=h_{CMXL}(1-\varepsilon)A(T_{CMXL}-T_{UMXP,btm}),$$
$$Q_w=h_{water}(1-\alpha)\varepsilon A(T_{CMXL}-T_{sat}),$$
$$Q_s=h_{steam}\alpha\varepsilon A(T_{CMXL}-T_{sat}),$$

where, Q_p, Q_w, Q_s are heat transfer from CMXL to UMXP, TWTL, TARG, respectively.

3. Results and Discussions

This section presents the modeling results obtained from the initial condition described in Section 2.1 to after 6 hours.

3.1 Mass and Temperature of Each Layer

Figures 2 and 3 shows the mass and temperature of each layer obtained from the model, respectively. Initially, due to the high temperature and decay heat, re-melting of the particulate debris bed occurred, resulting in rapid mass transfer from the UMXP to CMXL layer, as shown in Fig. 2. However, this mass transfer decreased as the coolant completely cooled the debris bed, which is evident from the debris bed temperature change in Fig. 3. Even after the mass inflow from the debris bed vanished, the CMXL mass continued to rise due to the mass inflow from the concrete layer caused by MCCI. However, crust formation due to cooling of the CMXL did not occur within 6 hours. Since the solidification temperature of the corium is around 1500K, the phenomenon of crust formation can be confirmed in the future by extending the analysis period or carrying out the analysis under low decay heat conditions.

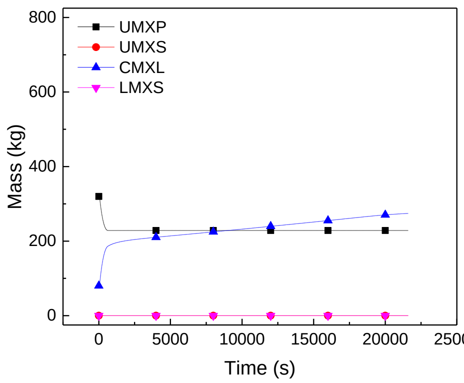

Fig. 2. Mass of layers with time

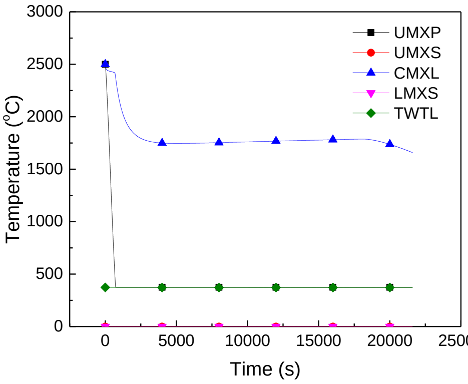

Fig. 3. Temperature of layers with time

3.2 Heat Transfer from CMXL to Each Layer

Figure 4 shows the heat transfer characteristics from the CMXL layer to the other layers. Since the crust was not formed, the heat transfer to the UMXS and LMXS layers was zero. Initially, the coolant could not penetrate the bottom of the debris bed layer due to its high temperature. Therefore, only a small amount of heat was transferred upward via steam, and most of the heat was transferred to the concrete below. As the cooling of the debris bed layer progressed, heat transfer to the upper debris bed layer and coolant layer progressed rapidly due to coolant penetration to the bottom of the debris bed, and gradually reached a stable state. After about 18000s, heat transfer gradually decreased as the temperature of the melt layer decreased due to the decay heat decreasing, as shown in Fig. 3.

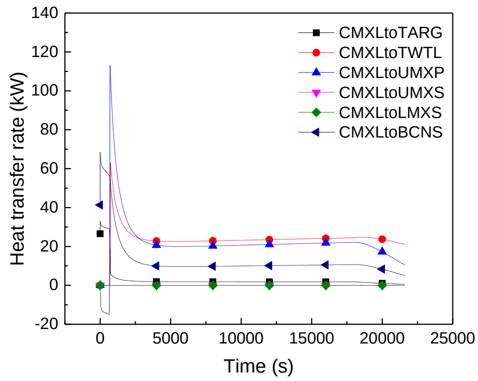

Fig. 4. Heat transfer from CMXL to other layers with time

3.3 Top Position of Each Layer

Figure 5 displays the top position of each layer with time. Top positions of UMXP and CMXL were changed at an early time due to the re-melting of UMXP. After re-melting of the debris bed was complete, the top position of UMXP and CMXL remained constant with time. The top position of BCNS shows the concrete ablation depth by MCCI. Initially, ablation occurred rapidly because most of the heat was transferred to the concrete due to poor cooling of the melt layer by the coolant. Then, as the amount of heat removed by top cooling increased, the ablation gradient decreased. The final concrete ablation depth after 6 hours was about 0.2 m.

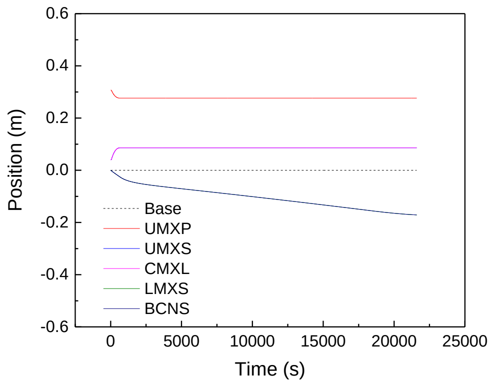

Fig. 5. Top position of layers with time

4. Conclusions

In the prediction of severe accident scenarios, long-term coolability with respect to corium conditions plays a crucial role. Particularly, there is a need for a tool that can quickly and accurately analyze severe accident cases given the wide range of postulated accident conditions. Therefore, this study has developed a 1-D analysis code. Through testing, the coolability model produced reasonable results. Moving forward, further analysis will be conducted to assess the long-term coolability of molten corium, by varying melt conditions and extending analysis periods.

ACKNOWLEDGMENTS

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korean government (Ministry of Trade, Industry, and Energy) (No. 20193110100090).

REFERENCES

[1] J. Jung, D. Son, and S. H. Kim, Coolability Analysis of Ex-vessel Corium in OPR1000 pre-flooded reactor cavity, Transactions of the Korean Nuclear Society Spring Meeting, May 19-20, 2022, Jeju, Korea.

[2] S. H. Kim, J. Ham, H. Y. Kim, R. J. Park, and J. Jung, COCCI for a simulation of molten core and concrete interaction during a severe accident, Transactions of the Korean Nuclear Society Spring Meeting, May 19-20, 2022, Jeju, Korea.

[3] J. Ham, S. H. Kim, and J. Jung, Comparative analysis of CCI-4 test simulation using COCCI and CORQUENCH, Transactions of the Korean Nuclear Society Spring Meeting, May 19-20, 2022, Jeju, Korea.