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

CFD Simulation for Prediction of Flow Characteristics in the Core Catcher by Upward Heat Transfer of Corium

Sangmin Kim [a*], Keun Sang Choi[a] and Jeahoon Jung[a]
[a]*Korea Atomic Energy Research Institute, 111, Daeduk-daero 989, Daejeon, Korea*
**Corresponding author: ksm0226@kaeri.re.kr*

1. Introduction

During a severe accident, insufficient cooling may lead to core melting, and in case of a reactor pressure vessel (RPV) failure, molten corium is ejected into the reactor cavity, causing concrete melting through molten core-concrete interaction (MCCI).

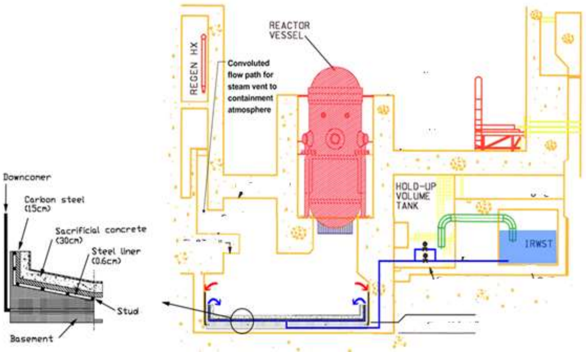

Figure. 1. PECS in EU-APR1400 [1]

The EU-APR features a Passive Ex-vessel Corium Retention and Cooling System (PECS) shown in Figure 1, which aims to prevent MCCI by utilizing an in-cavity coolant and a core catcher. The smooth flow of coolant within the PECS is crucial as it circulates naturally and continues to cool the corium.

We developed a CFD solver capable of predicting coolant flow during an accident, including natural convection and boiling due to heat flux on the core catcher. The solver's performance was verified by benchmarking with the CE-PECS test. However, the test only considered downward heat flux transferred to the core catcher, neglecting direct heat transfer from the top of the corium to the cooling water.

The stability of the core catcher can be risked if the boiling of the upper part of the corium affects the flow of cooling water into the cooling channel. To investigate this issue, this study conducted simulations to analyze the thermal characteristics of corium and the resulting coolant flow when the corium was situated on the core catcher.

2. CFD analysis

The openFOAM-based tryChtMultiRegionTwoPhase-EulerFoam solver was used for the two-phase flow model including wall heat transfer and boiling phenomena. The performance of the solver has been verified through the previous CE-PECS benchmark study, and a detailed explanation is in reference [2].

2.1 CFD computational domain

Figure 2 illustrates the geometry of the PECS system and the corresponding regions for CFD simulation. The computational domain is a bilaterally symmetrical section with a width of 1.3 m, including the down-comer. The total height of the domain is 4.95 m and the width is 3.885 m. The cross-section of the down-comer is square with an area of 15 cm × 15 cm. The computational mesh is fully hexahedral and consists of a total of 244,480 cells, as shown in Figure 2.

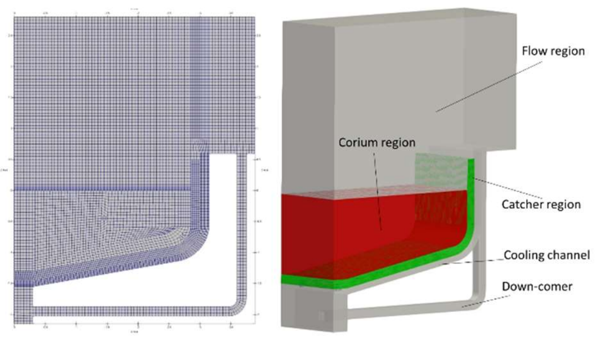

Figure. 2. Mesh and computational domain

2.2 W-ECM model

The W-ECM (Willschuetz - Effective Conductivity Model) was used to model the thermal properties of corium [3], which applied a new effective heat conduction model to enhance the analysis of temperature and heat transfer distribution in the lower hemisphere.

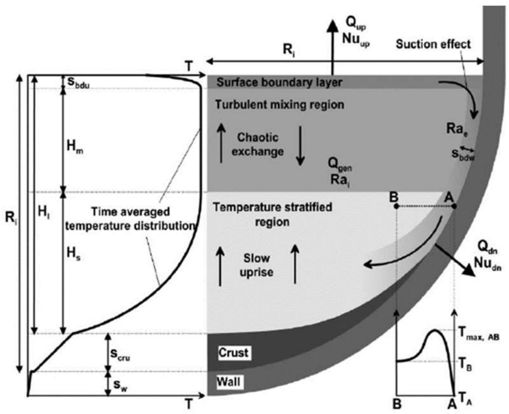

Fig. 3. Principle scheme of a hemispherical melt pool [3]

The model was applied to ANSYS to analyze the abnormal heat transfer phenomenon for the FOREVER experiment. Heat transfer analysis was also performed on the melt formed in the lower hemisphere of the PWR. The thicknesses of the boundary layers at the top and bottom walls were expressed as a function of 1/Nu, as defined by the Bernaz heat conduction relation (Nu).

$$s_{bdu} = \frac{H_l}{Nu_{up}} \quad (1)$$

$$s_{bdw} = \frac{R_i}{Nu_{down}} \quad (2)$$

$$Nu_{up} = 0.382\ Ra_i^{0.233} \quad (3)$$

$$Nu_{down} = 2.2\ Ra_i^{0.174} \quad (4)$$

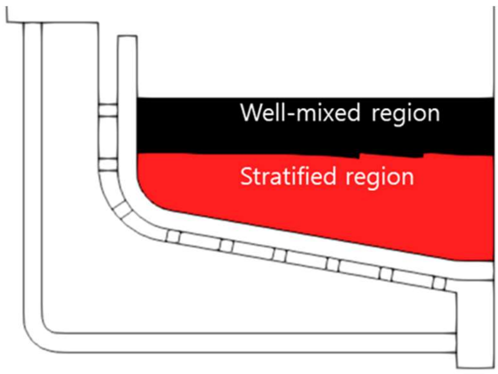

Fig. 4. Regions in corium for different thermal behavior

In the well-mixed region, corium materials, including molten fuel, control rod materials, structural materials, and coolant, form a homogeneous mixture. This thorough mixing of corium components results in a uniform temperature distribution and composition in this area.

On the other hand, the stratified region is quite different from the well-mixed region. In this region, various materials form distinct layers based on their density and melting temperature. Heavier materials, such as molten oxide fuel and control rod materials, settle at the bottom, while lighter metallic components like structural materials and coolant create layers above the heavier materials. Due to the separation of materials in the stratified region, heat transfer and cooling capabilities may be limited.

The heat conduction to the corium in the upper turbulent mixed(well-mixed) layer region has high heat conduction, formulated as follows.

$$k_m = k_0(T) \times Nu_{up} \quad (5)$$

In the stratified region below the melt, directional heat conduction is applied, using general thermal conductivity coefficient for vertical direction and effective thermal conductivity coefficient (eq. 6) for horizontal direction.

$$k_x = k_0(T) \times Nu_{down} \quad (6)$$

W-ECM model was successful in accurately predicting the thermal behavior in the FOREVER experiment.

2.3 CFD setting

The CFD simulations utilized the chtMultiRegionTwoPhaseEulerFoam solver in OpenFOAM [4], and the wall heat transfer and boiling model was validated through prior research [2]. The initial conditions applied in the simulations are presented in the following table.

Table I: Initial conditions

Initial temperature of corium	2000 K
Volumetric decay heat generation of corium	2500 kW/m^3
Initial temperature of coolant	363.15 K
Coolant level	4.65 m

3. Results

3.1 Thermal properties of corium

The upper part of the corium in contact with the cooling water exhibited a low temperature distribution, whereas the lower part in contact with the core catcher showed a significantly overheated temperature distribution. These results were obtained after analyzing the thermal behavior of the corium for 1500 seconds, with the initial temperature of the corium being uniformly set at 2000 K.

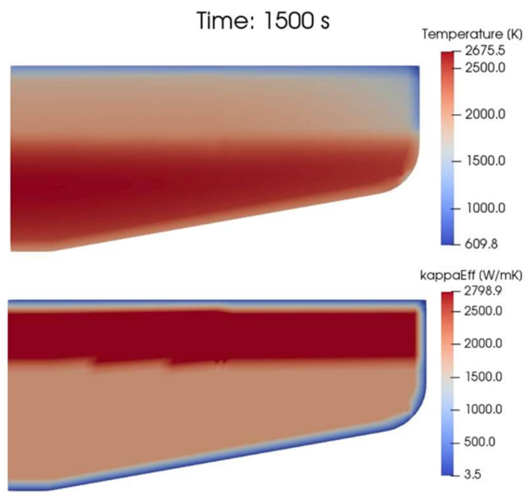

Fig. 5. Temperature and effective conductivity of corium

This is because the W-ECM model took into account the thermal conductivity distribution by considering the difference in mixing of corium at the upper and lower part, as well as the formation of a crust.

3.2 Flow pattern of coolant

Immediately after the start of the calculation, there is a rapid phase change at the interface between the corium and cooling water, which creates a flow above of the corium. Figure 6 shows the mass fraction of water vapor as a contour and the flow vector as an arrow.

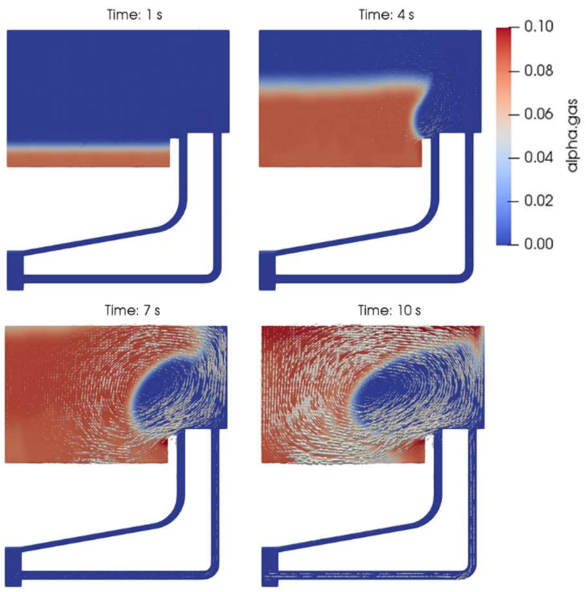

Fig. 6. Flow pattern of coolant in the initial stage of calculation

As time progresses, heat transfer from the corium to the core catcher results in boiling at the contact surface between the core catcher and the cooling water, creating a flow. The lower part of the corium has a higher thermal conductivity and temperature than the upper part, resulting in active phase change in the cooling channel as time passes. At 1500 s, the circulation pattern in the upper region of the PECS weakens somewhat, and the flow through the down-comer and cooling channel becomes more active.

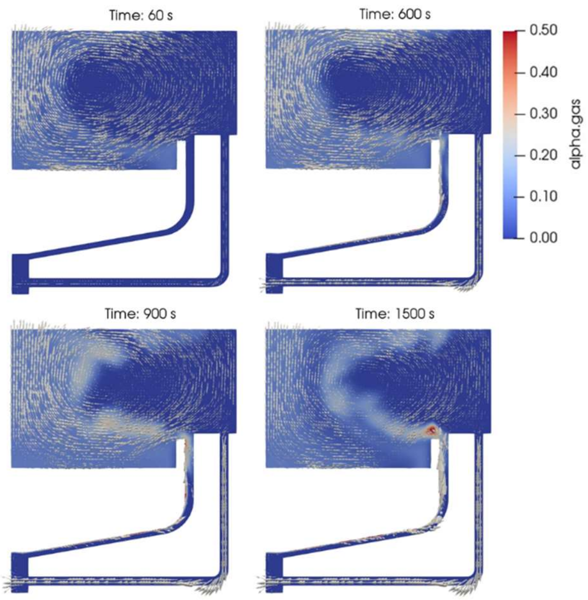

Fig. 7. Flow pattern of coolant over time

3.3 Coolant mass flow rate in down-comer

Figure 8 shows the variation in time of the mass flow rate of the coolant passing through the cross-section of the down-comer. At the start of the calculation, it appears that the strong flow in the upper part of PECS affected the inside of the down-comer. Boiling started in the cooling channel at 400 s, and the flow rate increased rapidly, converging to 30 kg/s and stabilizing.

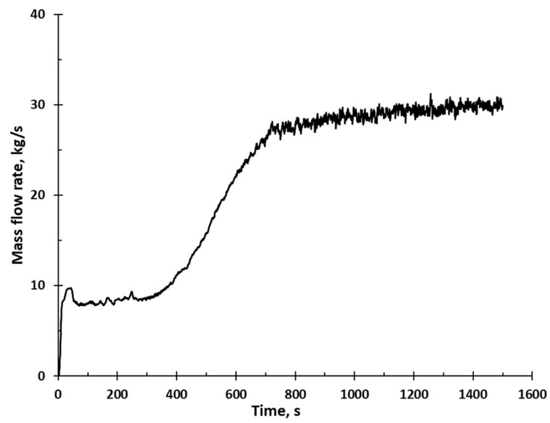

Fig. 8. Coolant mass flow rate in down-comer cross-section

4. Conclusions

We simulated the coolant flow pattern of PECS using the W-ECM model to analyze the thermal characteristics of corium. The implementation of corium's volumetric heating and the thermal conductivity distribution considering the differences in crust formation and convection characteristics were successful.

The flow inside the cooling channel remained stable, while a strong flow occurred in the upper region of the corium without any disturbance. In our next study, we plan to increase the calculation time to determine the conditions under which the temperature of the corium stabilizes or decreases. Additionally, we aim to calculate the heat flux generated by the corium and improve the W-ECM model.

REFERENCES

[1] J. H. Song, et al., A core catcher design for advanced light water reactors. ICAPP2011, Nice, France, 2011.
[2] S. Kim, K. Choi, & J. Jung, CFD simulation of Boiling Two-Phase Flows with Different Thermophysical Properties for Core-Catcher Cooling System. Korean Nuclear Society Spring Meeting, 2022
[3] H. G. Willschütz, E. Altstadt, B. R. Sehgal, & F. P. Weiss, Recursively coupled thermal and mechanical FEM-analysis of lower plenum creep failure experiments. Annals of Nuclear Energy, 33(2), 126-148, 2006
[4] OpenFOAM Web site, https://openfoam.org.