Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 26-27, 2023

Preliminary Analysis Results of IVR-ERVC in a 3-layer Molten Pool using the Lagrangian CFD

Tae Hoon Lee [a], Kukhee Lim [b], Byung Jo Kim [c], Yun-Jae Kim [d], Eung Soo Kim [a*]
[a]*Department of Nuclear Engineering, Seoul National University, 1 Gwank-ro, Gwanak-gu, Seoul, Korea*
[b]*Department of Nuclear Safety Research, Korea Institute of Nuclear Safety, 62 Gwahak-ro, Yuseong-gu, Daejeon 34142, Korea*
[c]*Department of Nuclear Engineering, KEPCO E&C,269 Hyeoksin-ro, Gimcheon-si, 39660, Korea*
[d]*Mechanical Engineering, Korea University, Seoul, 02841, Korea*
[*]*Corresponding author: kes7741@snu.ac.kr*

Keywords: Severe accident, IVR-ERVC, 3-layer molten pool, Numerical analysis, Lagrangian method

1. Introduction

When a severe accident occurs, the nuclear fuel melts and is relocated to the reactor vessel lower head. At this time, if the decay heat is not properly removed, the integrity of the reactor vessel is threatened by thermal load. The IVR-ERVC (In-Vessel Retention External Reactor Vessel Cooling) is a severe accident mitigation strategy in order to maintain integrity of the reactor vessel by holding the molten corium in the reactor vessel and the decay heat is removed through external wall cooling. The molten corium within reactor vessel typically comprises two layers: a metal layer and an oxide layer due to material property differences and exhibits complex physical phenomena (natural convection, turbulence, crust formation, stratification, radiative heat transfer, thermal ablation, etc.). It is important to accurately interpret the behavior of the molten corium because it affects the distribution of thermal loads that decay heat exerts on the reactor vessel wall. In particular, high-power reactor such as APR-1400 should be interpreted more accurately because the thermal margin is small.

Recently, it has been confirmed in the OECD MASCA experiment that molten corium may exhibit a 3-layer configuration, comprising a Light Metal Layer, an Oxide Layer, and a Heavy Metal Layer [1]. Uranium inside the oxide layer may react with the metal layer while the molten corium is in the 2-layer configuration. As a result, a heavy metal with a higher density than the oxide layer is formed, and a density inversion phenomenon occurs, causing the heavy metal to move downward beneath the oxide layer. When molten corium is composed of 3-layer, the thickness of the light metal layer becomes thinner, leading to an increased focusing effect. As a result, the thermal load on the reactor vessel intensifies. [2]. Consequently, a precise analysis of the thermal load on the reactor vessel becomes even more crucial, necessitating an accurate understanding of the behavior of this 3-layer molten corium.

In this study, the Smoothed Particle Hydrodynamics (SPH), which is well known as a particle-based analysis method, is used to simulate the behavior of the molten corium. In addition, the MARS-KS, a system code, is coupled to the SPH code to simulate external wall cooling. The preliminary analysis is performed at 3-layer molten corium for the APR-1400 reactor.

2. Methodology

In this study, The SOPHIA code, developed by Seoul National University, is utilized to interpret the IVR-ERVC strategy. The code is developed to analyze phenomena related to nuclear safety and is a multi-physics/multi-fluid analysis code accelerated using GPUs [3]. It is based on the SPH method, which is the representative Lagrangian method-based numerical analysis techniques. This method expresses the fluid as a collection of particles, and each particle interacts with the surrounding particles with physical properties (mass, velocity, temperature, etc.). The interaction is calculated through conservation equations (mass, momentum, energy, etc.) based on the fundamental principles of physics [4].

The SOPHIA code is used to analyze the behavior of molten corium inside the reactor vessel. The code uses the improved mass conservation equation (Eq. (1)) to accurately account for the density variation present in molten corium [5]. The pressure force, viscous force, and gravity are calculated through the momentum conservation equation (Eq. (2)-(4)). Thanks to the characteristics of the Lagrangian method, the energy conservation equation is exclusively calculated using the conduction equation (Eq. (5)). The Non-Boussinesq model is used to simulate the natural convection of the molten corium (Eq. (7)-(8)). The radiative heat transfer model is applied to analyze the heat transfer with air at the upper part of the Light metal layer (Eq. (9)). For modeling the thermal ablation of the reactor vessel and the oxide layer crust, a simplified phase change model is implemented. This model induces changes in the material properties in response to temperature variations.

Table I: The governing equation applied to SOPHIA code

Mass conservation	
$\left(\frac{\rho}{\rho_{ref}}\right)_i = \sum_j \frac{m_j}{\rho_{ref,j}} W_{ij}$	(1)

Momentum conservation

$$\left(\frac{d\boldsymbol{u}}{dt}\right)_i = \left(\frac{d\boldsymbol{u}}{dt}\right)_i^{fp} + \left(\frac{d\boldsymbol{u}}{dt}\right)_i^{fv} + \boldsymbol{g} + f_{ext} \qquad (2)$$

$$\left(\frac{d\boldsymbol{u}}{dt}\right)_i^{fp} = -\sum_j m_j \left(\frac{p_i+p_j}{\rho_i\rho_j}\right)\nabla W_{ij} \qquad (3)$$

$$\left(\frac{d\boldsymbol{u}}{dt}\right)_i^{fv} = \sum_j \frac{4m_j}{\rho_i\rho_j}\frac{\mu_i\mu_j}{(\mu_i+\mu_j)}\left(\boldsymbol{u}_i-\boldsymbol{u}_j\right)\frac{\boldsymbol{r}_{ij}\cdot\nabla W_{ij}}{\left(\left|\boldsymbol{r}_{ij}\right|^2+\eta^2\right)} \qquad (4)$$

Energy conservation

$$\left(\frac{dh}{dt}\right)_i = \sum_j \frac{4m_j}{\rho_i\rho_j}\frac{k_ik_j}{(k_i+k_j)}\left(T_i-T_j\right)\frac{\boldsymbol{r}_{ij}\cdot\nabla W_{ij}}{\left(\left|\boldsymbol{r}_{ij}\right|^2+\eta^2\right)} + \dot{q}_i \qquad (5)$$

Equation of State

$$\mathrm{p} = \frac{c_0^2\rho_{ref,i}}{\gamma}\left[\left(\frac{\rho}{\rho_{ref,i}}\right)^{\gamma} - 1\right] \qquad (6)$$

Non-Boussinesq model

$$\rho_{ref,i} = \rho_{0,i}\left(1-\alpha_T\left(T_i - T_{ref,i}\right)\right) \qquad (7)$$

$$m_i = \rho_{ref,i}\cdot V_{0,i} \qquad (8)$$

Radiative heat transfer model

$$\frac{\mathrm{dh_i}}{dt} = \varepsilon\sigma\frac{A_i}{m_i}\left(T_i^4 - T_o^4\right) \qquad (9)$$

The coupling of the system code MARS-KS is utilized to calculate the external wall cooling of IVR-ERVC through two-phase water natural circulation. The coupling process involves the reciprocal exchange of temperature determined by external wall cooling and heat flux computed by the SOPHIA code at each time step. Coupling of the two codes is performed through a socket programming.

For the preliminary analysis, the APR-1400 reactor was chosen as the benchmark reactor. The severe accident scenario is SBO (Station Black Out), and the composition and physical properties of the molten corium were referred to the MAAP5 analysis results performed by Dr. Byung-jo Kim of KEPCO E&C. The molten corium exhibits a 3-layer structure consisting of a light metal layer, an oxide layer, and a heavy metal layer. Decay heat generation occurs within the oxide and heavy metal layers, respectively. It is cooled through heat exchange with the reactor vessel wall and radiative heat transfer from the light metal layer.

Based on the MAAP5 analysis results, a state in which the temperature of all molten corium converges was selected as the initial condition. Notably, the MAAP5 state selected as the initial condition has ablation of the reactor vessel wall, but the SOPHIA code is difficult to reflect ablation in the initial shape. To reflect this, the initial shape was constructed except for the ablation mass from the light metal mass. The initial shape of the analysis is shown in Fig. 1, and the initial conditions are shown in Table II. Considering the analysis time and calculation cost, the analysis shape was composed of a 1/4 hemispherical shape, and a symmetric boundary condition was applied.

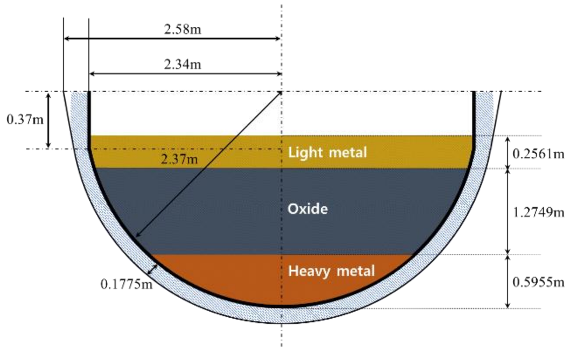

Fig. 1. Simulation geometry and configuration

Table II: Initial simulation properties and conditions

Parameter		Value
Light metal	Density (kg/m^3)	6657.05
	Dynamic viscosity (Pa·s)	0.006
	Thermal exp. coeff. (K^{-1})	0.0001
	Conductivity (W/m·K)	28.42
	Specific heat (J/kg·K)	664.19
	Initial Temperature (K)	1915.65
Molten oxide	Density (kg/m^3)	8230.08
	Dynamic viscosity (Pa·s)	0.0093
	Thermal exp. coeff. (K^{-1})	0.0001
	Conductivity (W/m·K)	5.88
	Specific heat (J/kg·K)	585.93
	Initial Temperature (K)	2736.71
	Decay heat (MW)	17.56
Heavy metal	Density (kg/m^3)	8949.68
	Dynamic viscosity (Pa·s)	0.00436
	Thermal exp. coeff. (K^{-1})	0.0001
	Conductivity (W/m·K)	22.25
	Specific heat (J/kg·K)	367.31
	Initial Temperature (K)	2512.57
	Decay heat (MW)	2.2

3. Results and Discussions

Fig. 2 depicts the temperature distribution of the molten corium in the preliminary analysis at 300 seconds, and Fig. 3 is a diagram showing the material distribution of molten corium. Each molten corium layer was classified without mixing by the density difference. The light metal layer was heated by heat transferred from the oxide layer and cooled by radiative heat transfer and heat exchange with the wall. The oxide layer and heavy metal layer were heated by decay heat and cooled by heat exchange with the wall. In the oxide layer, a downward flow appeared near the reactor vessel wall, and crust was generated by cooling at the bottom. In the heavy metal layer, stratification occurred at the bottom, and the shape was changed. At the reactor vessel wall, thermal ablation occurred by heating to a temperature above the melting point.

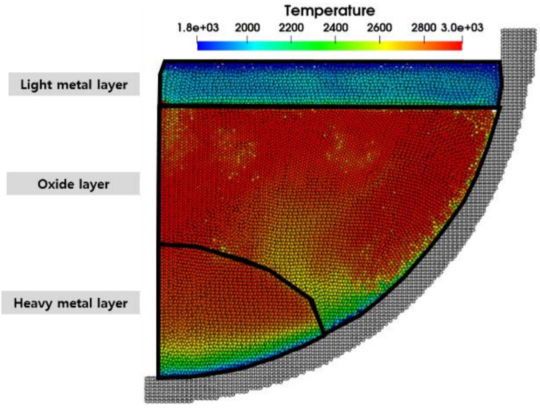

Fig. 2. Temperature distribution of molten corium at 300s

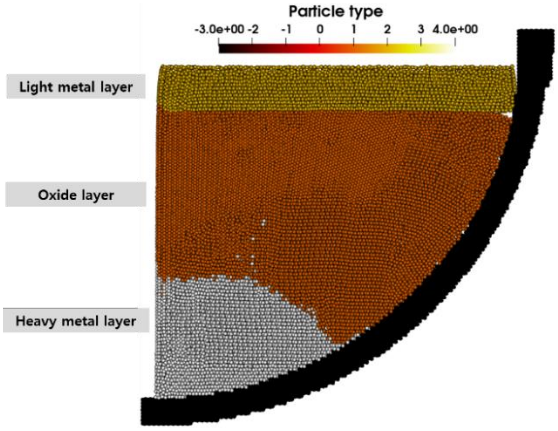

Fig. 3. Material distribution of molten corium at 300s

The above results were slightly different from the general 3-layer structure of previous studies [2, 6]. The first is the shape of the heavy metal layer. As shown in Fig. 4, in previous studies [6], the heavy metal layer appeared parallel to the oxide layer, but in this study, the shape of the heavy metal layer was deformed by the downward flow of the oxide layer. This is inferred to be due to the characteristics of SPH method. This method allows boundaries to deform under the influence of descending flows, and it inherently accommodates tracking these deformed boundaries during multi-fluid flow analysis without necessitating supplementary techniques. The second is the location of crust formation. In previous studies, crust was created under the heavy metal layer, but not in this study. This is a difference caused by the initial shape set in this study. In previous studies, after it is first formed as a 2-layer, a heavy metal is generated and moves under the oxide layer. Therefore, a crust is already created at the bottom, and then a heavy metal is created and moved. However, in this study, since it starts with a 3-layer state from the beginning, no crust was generated at the bottom.

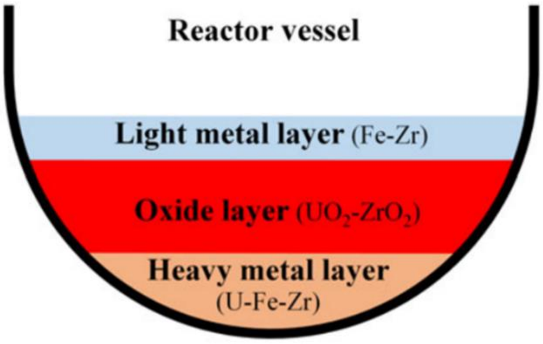

Fig. 4. Molten corium 3-layer configuration of previous study [6]

4. Conclusions

In this study, a preliminary analysis of the IVR-ERVC strategy was conducted, focusing on a 3-layer configuration of the molten corium. The transient behavior of the molten corium (natural convection, turbulence, crust formation, stratification, radiative heat transfer, thermal ablation, etc.) was calculated using the SOPHIA code. The external wall cooling was calculated through the MARS-KS code, and the connection between the two codes was made using a socket programming. As a result of the preliminary analysis, the natural convection and crust formation of the molten corium and the thermal ablation of the reactor vessel wall were calculated. However, the shape of the heavy metal layer and the location of crust generation were slightly different from those of previous studies. Further investigations are needed to clarify it.

ACKNOWLEDGEMENT

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea. (No. 2103079)

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