

Thermal Stratification Analysis of the ECT in i-SMR Using the SPACE Code

HYEON-GYEONG CHOI^{a*}, YU-JUNG CHOI^a, HYUK-JIN SONG^a

¹Korea Hydro & Nuclear Power co. (KHNP), Ltd., Central Research Institute, Daejeon, Republic of Korea

*Corresponding author: choihg418@khnp.co.kr

*** Keywords : i-SMR, Emergency Cooling Tank, Thermal Stratification, Passive Safety System, SPACE Code**

1. Introduction

The innovative Small Modular Reactor (i-SMR) employs Passive Safety Systems (PSS) that remove decay heat through natural circulation without off-site power or active equipment. Since natural circulation is governed by temperature-dependent density differences, accurate prediction of buoyancy-driven thermal-hydraulic behavior is essential for evaluating passive safety performance.

The Emergency Cooling Tank (ECT) supplies cooling water to the Passive Auxiliary Feedwater System (PAFS) and the Passive Containment Cooling System (PCCS). Temperature differences inside the ECT may result in thermal stratification, which affects the thermal-hydraulic characteristics of the PSSs.

This study analyzes thermal stratification in the ECT using the Safety and Performance Analysis Code (SPACE). Rather than simulating a Loss-of-Coolant Accident (LOCA), the analysis conditions were established based on LOCA results to promote thermal stratification. The objective is to evaluate the capability of SPACE to predict thermal stratification and to support its current application to the thermal-hydraulic performance evaluation of the ECT.

2. Analysis Model and Method

2.1 ECT Modeling

The thermal-hydraulic model of the ECT with exchangers connecting PAFS and PCCS pipelines was developed using the SPACE, as shown in Figure 1. SPACE is a best-estimate system thermal-hydraulic code developed for the analysis of steady-state and transient behaviors in nuclear power plants. The code employs a three-field formulation that separately solves the conservation equations of mass, momentum, and energy for the continuous liquid, continuous vapor, and dispersed droplet fields. Based on these governing equations, SPACE can simulate complex two-phase flow phenomena, including natural circulation and buoyancy-driven thermal-hydraulic behavior [1]. Thermal stratification is a representative buoyancy-driven phenomenon caused by density variations resulting from temperature differences within a fluid. When a temperature gradient exists, the corresponding density difference generates buoyancy forces. If momentum-driven mixing is sufficiently strong, the fluid remains nearly homogeneous. However, as the circulation weakens and mixing decreases, buoyancy

becomes the dominant mechanism, allowing warmer and less dense fluid to remain in the upper region while colder and denser fluid settles in the lower region, thereby forming a stable thermal stratification layer.

To improve the prediction of stratified flow, Lee et al. refined the horizontal stratification criteria implemented in SPACE, demonstrating improved capability for representing buoyancy-driven flow behavior [2]. Based on these developments, SPACE has been widely applied to analyses involving natural circulation and thermal stratification in nuclear thermal-hydraulic systems.

Based on this capability, the ECT was modeled using two large vertically discretized PIPE components to resolve the axial temperature distribution and development of thermal stratification. The two PIPE components were interconnected by FLOW junctions, allowing lateral mass and energy exchange while maintaining independent vertical temperature profiles. The dual-PIPE configuration enables the one-dimensional system code to effectively represent the dominant flow characteristics within the ECT. The PAFS heat exchanger tubes were explicitly modeled within the ECT to account for heat transfer between the secondary coolant (circulating auxiliary feedwater) the tank water. Furthermore, the PCCS was modeled as an independent flow path directly connected to the ECT, through which hot coolant enters the upper region of the tank and returns from the lower region, thereby reproducing the natural circulation path during the transient. Consequently, this modeling strategy enables the coupled prediction of circulation flow, heat transfer, and buoyancy-driven thermal stratification in the ECT. The complete SPACE nodalization adopted in this study is shown in Figure 1.

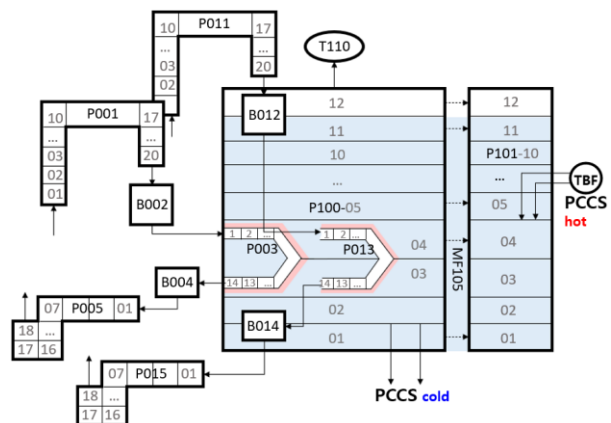


Fig. 1 ECT Modeling

2.2 Thermal Stratification Analysis Conditions

The analysis conditions were established with reference to LOCA analysis results. However, the objective was not to reproduce an actual LOCA transient but to generate thermal-hydraulic conditions favorable for the development of thermal stratification. Initially, a flow rate of 22 kg/s (vapor of approximately 300°C) was imposed through each PAFS heat exchanger to maintain a well-mixed condition inside the ECT. The circulation flow rate was subsequently reduced to weaken momentum-driven mixing while maintaining the temperature difference required for buoyancy generation. Therefore, PAFS flow rate was intentionally reduced to 0.8 kg/s and temperature of PAFS fluid also gradually decreases until it runs parallel to the ECT temperature. Additionally, to promote the development of thermal stratification, the PCCS flow was intentionally terminated after 10 min. Unlike an actual LOCA, this artificial boundary condition suppresses continuous natural circulation and momentum-driven mixing, thereby establishing a buoyancy-dominated condition for evaluating thermal stratification.

As circulation weakened, the relative influence of buoyancy gradually increased, allowing warmer water to remain in the upper region and colder water in the lower region. These conditions enabled the transition from a mixing-dominated state to a buoyancy-dominated stratified state to be clearly observed.

3. Results and Discussion

Fig. 2 presents the heat-transfer rate of the PAFS heat exchanger. During the initial stage, the relatively high PAFS flow maintained a large heat-transfer rate. Under this condition, sufficient momentum was available to circulate the fluid inside the ECT, resulting in strong mixing. Therefore, the initial PAFS flow rate of 22 kg/s was maintained for only 10 sec, followed by a rapid reduction in both temperature and flow rate to minimize thermal mixing within the ECT. As shown in the figure, the PAFS heat transfer rate decreases to approximately 1 MW ($0.5 \text{ MW} \times 2$) after 3 min, and continues to decline thereafter. After 30 min, the PAFS heat-transfer rate remains very low, at less than 1 kW. The reduction in heat transfer reflects the decreasing circulation intensity inside the ECT, leading to weaker momentum-driven mixing. Consequently, the ability of the circulation flow to homogenize the tank temperature progressively diminished. The decrease in the heat-transfer rate therefore represents more than a reduction in thermal energy transfer. It also indicates a transition in the dominant thermal-hydraulic mechanism governing the ECT. While momentum-driven mixing controlled the flow during the early stage, buoyancy became increasingly dominant as circulation weakened.

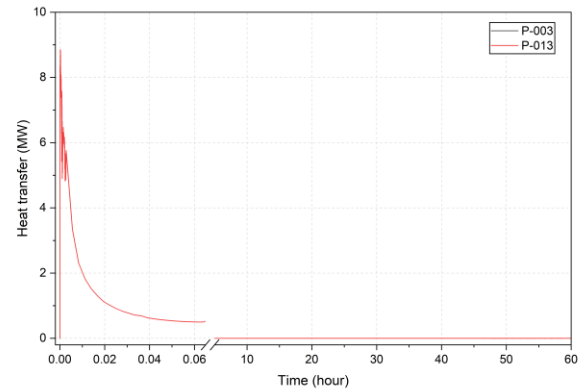


Fig. 2 Heat transfer from PAFS to ECT

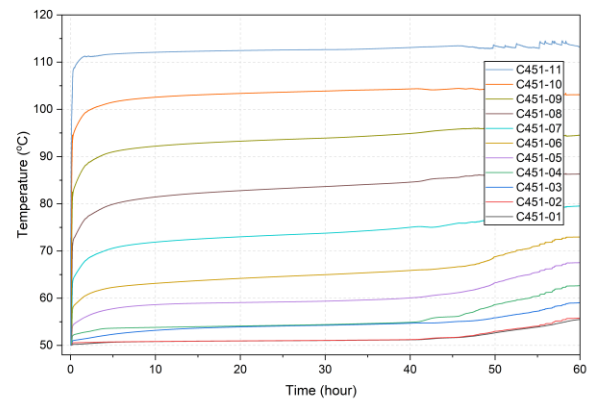


Fig. 3 The axial temperature distribution in ECT

Fig. 3 shows the axial temperature distribution inside the ECT at different times. During the initial stage, the ECT temperature increases rapidly due to the high input from the PAFS and PCCS, momentum-driven mixing is significantly reduced after 10 sec, and a distinct thermal stratification develops within the ECT. During this period, the overall tank temperature increases gradually while the stratified temperature distribution is maintained.

After approximately 40 hrs, however, the temperature of the stratified water begins to increase again rapidly than before, particularly in the region adjacent to PAFS heat exchanger, due to the low-level heat transfer from the PAFS. As the thermal energy is gradually transferred to the upper region (PIPE 100-11) of the ECT, boiling eventually occurs. The subsequent vapor generation causes a gradual decrease in the ECT water level and enhances mixing within the tank. Consequently, the previously established thermal stratification begins to deteriorate and is no longer maintained after approximately 60 hrs. Since the present study focuses on the formation and evolution of thermal stratification, the results are presented only up to 60 hrs, beyond which the stratified structure begins to deteriorate due to boiling and the associated reduction in the ECT water level. These results demonstrate that SPACE can capture the long-term evolution of the ECT

from the formation and maintenance of thermal stratification to its eventual degradation under sustained low-level heat input.

The results in Fig. 2 and 3 collectively show that the reduction in heat-transfer rate weakens circulation and momentum-driven mixing, thereby increasing the relative importance of buoyancy and promoting the development and stabilization of thermal stratification. The calculated results demonstrate that SPACE successfully reproduces this sequence of thermal-hydraulic phenomena, including the transition from and to a well-mixed condition to a buoyancy-dominated stratified condition. Since thermal stratification is one of the representative buoyancy-driven phenomena in passive safety systems, these results provide additional confidence in the capability of SPACE to analyze the thermal-hydraulic behavior of the ECT.

4. Conclusions

Thermal stratification in the ECT of i-SMR was analyzed using the SPACE code under buoyancy-dominated conditions established from intentionally imposed boundary conditions.

The reduction in the PAFS heat-transfer rate weakened momentum-driven mixing inside the ECT, allowing buoyancy to become the dominant flow mechanism. Consequently, stable thermal stratification characterized by a warm upper layer and a cold lower layer developed. Although the thermal stratification eventually degraded due to boiling caused by continuous heat input without heat loss, the results demonstrate that SPACE can reasonably capture the transition of thermal-hydraulic phenomena from stratification to boiling and subsequent mixing. This study provides additional confidence in the applicability of SPACE to the current thermal-hydraulic performance evaluation of the ECT in the i-SMR beyond accident simulation.

ACKNOWLEDGEMENTS

This work was supported by the Innovative Small Modular Reactor Development Agency grant funded by the Korea government (MSIT) (No.RS-2023-00257680).

REFERENCES

- [1] Y. Ahn et al., "Development of Innovative Small Modular Reactor (i-SMR)," Transactions of the Korean Nuclear Society Autumn Meeting, 2023.
- [2] Korea Atomic Energy Research Institute, SPACE Code Manual, KAERI, Daejeon, Republic of Korea, 2021.

- [3] H. G. Lee et al., "Improvement of Horizontal Stratification Criteria in the SPACE Code," Annals of Nuclear Energy, Vol. 132, pp. 176–188, 2019.

- [4] M. Ishii and T. Hibiki, Thermo-Fluid Dynamics of Two-Phase Flow, 2nd ed., Springer, New York, 2011.