Improvement of Heat Transfer Model of SPACE Code for Heat Exchanger Tube in LAPLACE Test Facility

Hae Min Park, Jong Hyuk Lee*
Reactor System Safety Research Division, Korea Atomic Energy Research Institute,
111 Daedeok-daero 989 been-gil, Yuseong-gu, Daejeon, 34057, Republic of Korea
Corresponding author: leejonghyuk@kaeri.re.kr

***Keywords :** SPACE, LAPLACE, in-tube condensation, bundle heat transfer

1. Introduction

The passive type heat removal system was utilized in the advanced reactor design in Korea, such as the passive auxiliary feedwater system (PAFS) of APR+ and the passive residual heat removal system (PRHRS) of SMART. The innovative Small Modular Reactor (i-SMR), which is the new SMR design developed in Korea, also adopt the PAFS as the safety system. The PAFS in the i-SMR consists of a two-phase natural circulation loop and heat exchanger tubes which are submerged in the emergency cooling tank (ECT). In the PAFS, the saturated steam generated in the steam generator flows into the heat exchanger tubes, and the steam is condensed into liquid.

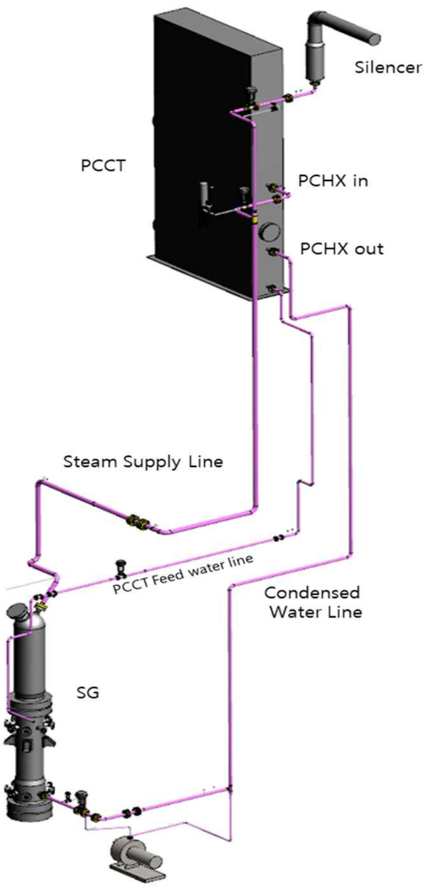

Fig. 1. Schematic diagram of LAPLACE test facility

To evaluate the cooling performance of PAFS, the Large Scale PAFS Loop for Assessment of Condensation Effectiveness (LAPLACE) has been constructed. The LAPLACE test facility simulated a natural circulation loop of PAFS with the volume ratio of 1/12 for PAFS of APR1000, as shown in Fig. 1 [1]. In the LAPLACE test facility, the PCHX has a bundle geometry having 3 × 5 nearly horizontal tubes. The objectives of this study are to evaluate the SPACE code and to improve the heat transfer model for validating the quasi-steady state tests of the LAPLACE experiments. Specifically, the predictabilities of models for the in-tube condensation and boiling heat transfer in ECT were investigated.

2. Heat transfer model in SPACE code

2.1 Condensation model in tube [2]

As a default model for a horizontal tube, the SPACE code uses Shah (1979) correlation [3]. In the SPACE code, Bae et al. (2017) [4] applied the PAFS model based on the condensation model developed by Ahn et al. (2014) [5]. Recently, the PAFS model was improved via adopting the interpolation method between Shah correlation and PAFS model and an improved identification method for a horizontal stratified flow suggested by Lee et al. (2019) [6].

2.2 Nucleate boiling heat transfer model in pool

As a default model for nucleate boiling, the SPACE code uses Chen (1966) correlation. In a horizontal tube bundle geometry, the boiling heat transfer rate can be enhanced by convective heat transfer. Reflecting this enhancement mechanism, the MARS-KS code already adopted the heat transfer model package for a horizontal tube bundle [7]. Among that heat transfer model package in the MARS-KS code, the nucleate boiling heat transfer model was implemented in the SPACE code, as given by;

$$\begin{aligned} & h = h_{pb} + h_f \left(\frac{1}{1-\alpha}\right)^{0.744} \\ & h_{pb} : \textit{Forster and Zuber}\,(1955) \\ & Nu_f = \frac{h_f D_h}{k} = 0.211 \mathrm{Re}_f^{0.651} \mathrm{Pr}_f^{0.34} F_4 \\ & (\textit{horizontal bundle crossflow}, \textit{ESDU}\,1973) \end{aligned} \quad (1)$$

3. SPACE code analysis for LAPLACE

The SPACE code analyses were conducted for the LAPLACE experiments via using input model. As shown in Fig. 2. The node configuration of the SPACE code input model is the same with the MARS input model [8], except for PCCT nodes. In the SPACE code input model, the PCCT nodes consists of vertical PIPE components and horizontal junctions connecting each PIPE components.

The six test cases among the LAPLACE experimental results were selected for validation of the SPACE code. Those test cases had the experimental conditions, which are the SG power ranging from 1.7 to 8.1 MW, saturated coolant conditions in PCCT and initial SG pressure ranging from 0.1 to 0.3 MPa.

The cooling performance of the PAFS is determined by the condensation heat transfer inside tube and the boiling heat transfer outside tube in the PCCT pool. The sensitivity analysis of the SPACE code was conducted for three cases;

- Case 0: default model for inside (Shah) and outside (Chen) tube
- Case 1: (in-tube) PAFS condensation model and (pool) default boiling model
- Case 2: (in-tube) PAFS condensation model and (pool) bundle heat transfer model.

The LAPLACE experiments simulated a natural circulation and obtained quasi-steady-state conditions. Therefore, the steam pressure is a comprehensive performance indicator for condensation and boiling heat transfers. If the heat transfer rates for in-tube condensation and nucleate boiling in PCCT pool are underpredicted, the steam pressure of quasi-steady state condition tends to be higher, whereas if those are overpredicted, the steam pressure of quasi-steady state condition tends to be lower.

The predicted steam pressures for three sensitivity cases were compared with the LAPLACE experimental results, as shown in Fig. 3. From the SPACE code analysis results, the default model (case 0) of the SPACE code overpredicted the steam pressure compared with that of the experimental results. Although the analysis results for case 1 also showed overprediction of the steam pressure, the case 1 showed the better predictability than the default model (case 0). The analysis results for the case 2 were well agreed with the experimental results.

For the analysis results for the PASCAL experiments using a single tube, the analysis case of the same model application with case 2 showed a good agreement for the steam pressure with the experimental results [2]. The analysis results of the case 2 in this study demonstrated that the bundle heat transfer model is also necessary and effective in improving the predictability of the SPACE code for the evaluation of PAFS cooling performance.

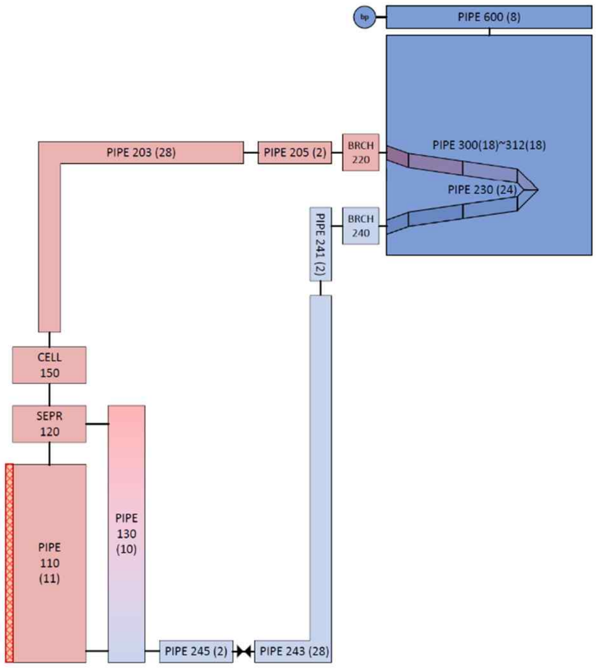

Fig. 2. Nodalization of SPACE code input model for LAPLACE test facility

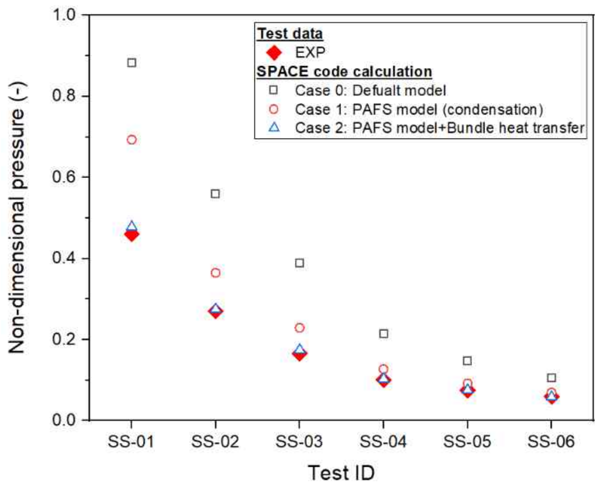

Fig. 3. Steam pressure of SPACE code calculation for LAPLACE experiments

4. Conclusion

In this study, the SPACE code analyses were performed for the LAPLACE experiments, which is a large-scale experimental facility simulating PAFS with a tube bundle. To validate the quasi-steady state tests of the LAPLACE experiments, the improved PAFS condensation model and bundle heat transfer model adopted in MARS-KS code were utilized and the predictabilities of those model were investigated though the model sensitivity study. The sensitivity analysis result showed that the PAFS condensation model enhanced the performance of the SPACE code prediction for PAFS coolability, in comparison with the existing default model. In addition to that, those analysis results showed that the bundle heat transfer model is also effective in improving the predictability of the SPACE code.

ACKNOWLEDGEMENT

This work was supported by the Innovative Small Modular Reactor Development Agency grant funded by the Korea Government(MSIT) (No. RS-2024-00403548).

REFERENCES

[1] S. Kim, "LAPLACE Test Report", PAFS-TR-22-01, KAERI, 2022.
[2] J.H. Lee et al., SPACE Code Applicability Report on Safety Analysis of i-SMR, KAERI, 2024 (classified).
[3] KHNP, KEPCO E&C, KEPCO NF, KAERI, SPACE 3.3 manual Volume 5. Model and correlation, Korea, 2022.
[4] B.U. Bae, S. Kim, Y.S. Park, K.H. Kang, T.H. Ahn, and B.J. Yun, Evaluation of mechanistic wall condensation models for horizontal heat exchanger in PAFS (Passive Auxiliary Feedwater System), Annals of Nuclear Energy, Vol. 107, p. 53, 2017.
[5] T.H. Ahn, B.J. Yun, J.J. Jeong, K.H. Kang, Y.S. Park, J. Cheon, and D.W. Jerng, Development of a new condensation model for the nearly-horizontal heat exchanger tube under the steam flowing conditions, International Journal of Heat and Mass Transfer, Vol. 79, p. 876, 2014.
[6] J.H. Lee, B.J. Kim, and K.D. Kim, Improvement of horizontal stratification criteria in the SPACE code, Annals of Nuclear Energy, Vol. 133, p. 122, 2019.
[7] KINS, MARS-KS Code Manual Volume V: Models and Correlations Manual, KINS/RR-1822, 2021.
[8] B.U. Bae, S. Kim, Y.S. Choi, S. Cho, Y.S. Park, S.K. Moon, S.H. Lee, S.G. Lim, J. Cheon, and S.W. Lee, "Assessment of MARS-KS Heat Transfer Model for the PAFS Heat Exchanger in the LAPLACE Test Facility", Transactions of the Korean Nuclear Society Autumn Meeting, Changwon, Korea, Oct. 20 – 21, 2022.