Validation of SPACE Code for Condensation Heat Transfer of High-Pressure Pure Steam on Tube Outer Surface

Chang Won Lee*, Jong Hyuk Lee, Seung Wook Lee
Korea Atomic Energy Research Institute, 111 Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, Republic of Korea
**Corresponding author: cwlee94@kaeri.re.kr*

***Keywords :** iSMR, condensation, PCCS

1. Introduction

With the anticipated global growth in the Small Modular Reactor (SMR) market, various reactor designs such as NuScale[1], NUWARD[2], and BWRX-300[3] are actively under research and development. In South Korea, Korea Hydro & Nuclear Power (KHNP) is leading the development of an innovative Small Modular Reactor known as i-SMR[4]. The i-SMR incorporates advanced safety systems designed to enhance reactor safety, among which the Passive Containment Cooling System (PCCS) is particularly notable. The PCCS acts as an ultimate heat sink during accidents involving steam discharge due to coolant loss from breaks or steam release triggered by opening Emergency Depressurization Valves (EDV) to reduce reactor pressure. The PCCS effectively prevents excessive pressure increase within the containment vessel. Additionally, it supplies the condensed coolant back to the reactor core. Thus, the PCCS plays a critical role in ensuring reactor safety.

Previous studies in South Korea have examined PCCS performance, including experimental work by Bae et al [5]. However, these studies mainly focused on the iPOWER, addressing conditions with relatively high mass fractions of non-condensable gases and low pressure of gas mixture. In contrast, the i-SMR features a significantly smaller containment vessel than conventional commercial reactors, resulting in higher PCCS operating pressures. Additionally, the containment vessel of the i-SMR is maintained under near-vacuum conditions during normal operation, emphasizing the importance of condensation heat transfer involving pure steam. Therefore, this study aims to evaluate the applicability of the SPACE code to the i-SMR PCCS by performing validation analysis on condensation heat transfer phenomena for high-pressure pure steam. To achieve this, experiments involving pure steam condensation were selected, and validation analyses were conducted accordingly.

2. Validation analysis

2.1 Pure steam condensation tests

Recently, Pusan National University (PNU) conducted experimental studies on condensation heat transfer for a single tube. These experiments were performed under conditions with relatively low mass fractions of non-condensable gases [6]. The experimental setup at PNU is illustrated in Fig. 1(a). Steam is generated by boiling water in a heater located at the bottom. Cold cooling water flows through the condensation heat exchanger tube, which has a outer diameter of 21.5 mm and a height of 1.33 m, causing condensation on the tube surface. The condensed water flows back into the heater pool located below. This creates a balanced condition between the steam generated by the heater and the steam condensed on the tube surface. As a result, steady-state pressure is maintained. The experiments were conducted at pressures ranging from 2 to 6 bar.

In a related study, X. Ma from Zhengzhou University performed condensation heat transfer experiments on a single tube under various pressure conditions and mass fractions of non-condensable gases [7]. As shown in Fig. 1(b), the experimental setup resembles that used by PNU, with steam generated by heating water at the bottom. The heat exchanger tube has a height of 1.669 m and an outer diameter of 76 mm. Cold cooling water flowing inside the tube induces condensation on its surface. Similar to the PNU experiment, this setup achieves a balanced steady-state condition where the rates of evaporation and condensation remain equal, maintaining constant pressure.

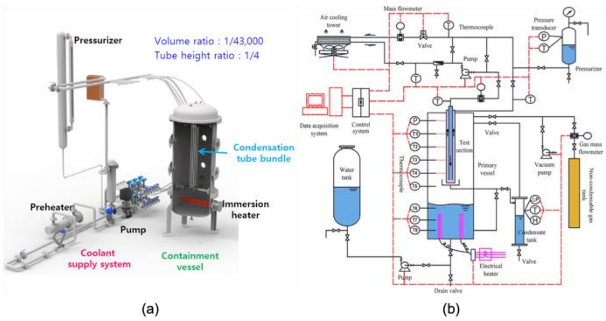

Fig. 1. Condensation test facilities
(a: PNU test, b: Ma's test)

2.2 SPACE code modeling

SPACE code nodalization was performed for validation analysis based on the PNU and Ma experiments. Due to similarities in the geometries of the two experimental setups, identical nodalization was adopted. Only geometric parameters, such as area and length, were modified accordingly. As depicted in Fig. 2, the nodalization consists of a pipe component representing the steam supply pool at the bottom, with a heat structure connected to one of its cells to simulate the heater. Above the water pool, another pipe component, consisting of five cells, represents the condensation region, and a heat structure connected to this component simulates the condensation heat exchanger tube. This nodalization forms a closed system where differences between experimental and calculated condensation heat transfer coefficients could lead to pressure variations due to imbalance in evaporation and condensation rates. To ensure thermal-hydraulic conditions comparable to the experiments, heater power was adjusted through trial and error. This iterative procedure allowed maintaining a constant pressure, consistent with experimental conditions. Thus, accurate assessment of condensation heat transfer coefficients could be achieved.

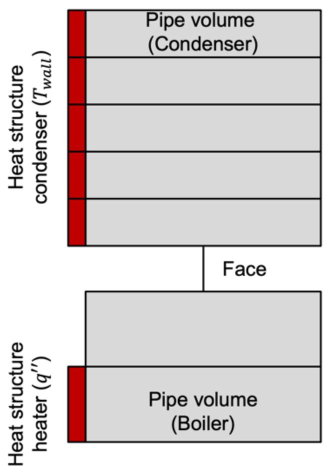

Fig. 2. SPACE code nodalization

2.3 Calculation results

The analysis results for the PNU experiments, depicting heat transfer coefficient (HTC) behavior along the wall subcooling, are presented in Fig. 3. Initially, SPACE calculations significantly underestimated HTC under conditions involving non-condensable gases. This discrepancy was attributed to the three-step heat transfer model used in the presence of non-condensable gases, where the condensation film heat transfer coefficient was significantly underestimated due to an overly thick minimum film thickness prediction. By correcting this minimum film thickness limit, HTC predictions were improved, with most results within ±20%. Conditions showing overprediction beyond 20% were identified when non-condensable gas mass fractions exceeded 5%. Thus the sensitivity analyses on non-condensable gas effects should be conducted.

The results of SPACE calculation for Ma's experiments are presented in Fig. 4. The SPACE results indicate overprediction of HTC at lower pressures and underprediction at higher pressures. Ma noted in their study that even slight residual non-condensable gases could significantly affect HTC at low pressures. Indeed, the current study's SPACE calculation, assuming pure steam, suggest significant overestimation of HTC at the lowest pressure conditions. Future sensitivity analyses regarding this phenomenon are recommended. Additionally, at high pressures, HTC was underpredicted by SPACE simulations. This underprediction seems related to increased condensation rates associated with turbulent film condensation. Currently, the SPACE code lacks a suitable turbulent film condensation model for external tube condensation. Therefore, it is expected that the Nusselt film model in default SPACE code underestimates the condensation HTC in the turbulent film region where the film thickness becomes relatively large.

The condensation HTC obtained from experimental data were compared with those predicted by SPACE calculations (Fig. 5). As illustrated, the SPACE code generally overpredicts HTC in the laminar film region, whereas in the wavy film and turbulent film regions, HTC is either well predicted or underpredicted. This behavior highlights the current limitation of the SPACE code, which lacks specific heat transfer models based on film flow regimes for condensation on the external surface of vertical tubes. Thus, additional model improvements addressing these film flow regimes are recommended to enhance the predictive accuracy of the SPACE code.

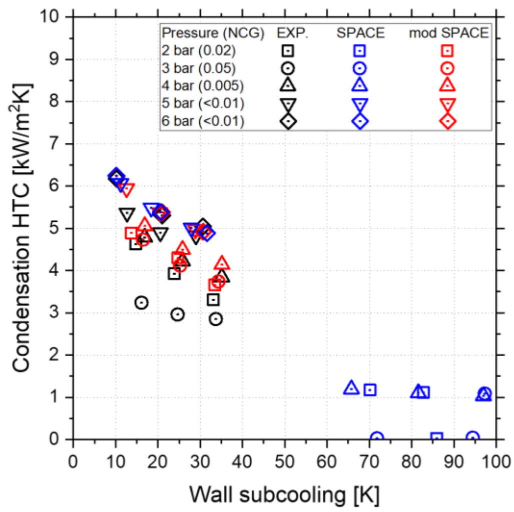

Fig. 3. PNU tests calculation results

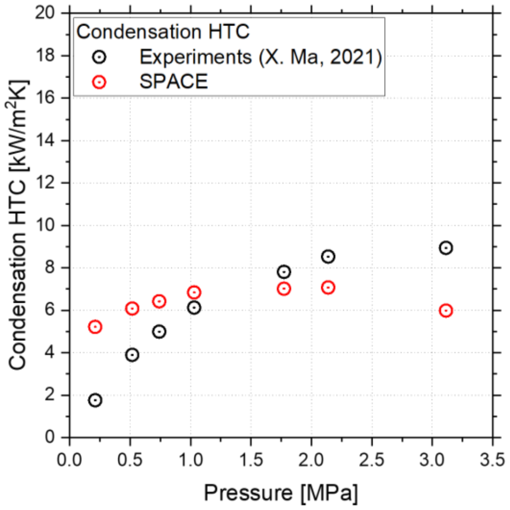

Fig. 4. Ma's tests calculation results

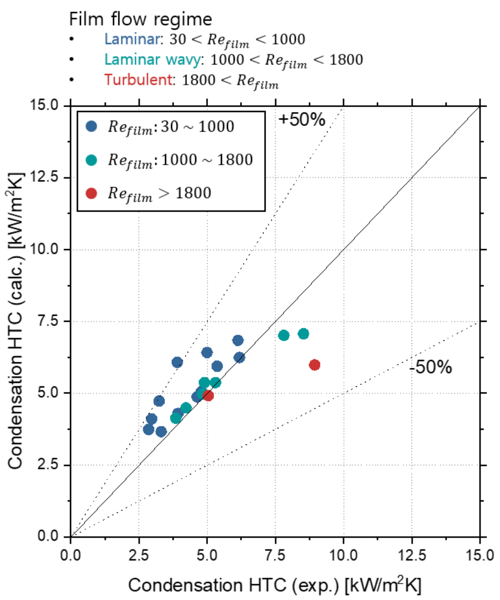

Fig. 5. Comparison between pure steam condensation test results and SPACE calculation results

Acknowledgements

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

3. Conclusions

In conclusion, this study demonstrates that the SPACE code can be effectively utilized for predicting condensation heat transfer phenomena under high-pressure pure steam conditions relevant to i-SMR's PCCS. However, the SPACE model currently lacks capabilities for accurately predicting turbulent film condensation at higher pressures. Additionally, it is suspected that the SPACE code tends to overpredict HTC at low-pressure conditions due to the possible presence of residual non-condensable gases. Future improvements should include adding and validating a turbulent film condensation model for external tube conditions and conducting sensitivity analyses on non-condensable gas effects to enhance the predictive capability of the SPACE code for advanced SMR applications.

REFERENCES

[1] NuScale Power, "The NuScale Design," U.S. Nuclear Regulatory Commission, Presentation, 2016. https://www.nrc.gov/docs/ML1616/ML16161A723.pdf.
[2] Francis, D., and S. Beils, " NUWARD SMR safety approach and licensing objectives for international deployment," Nuclear Engineering and Technology 56.3, 2024.
[3] GE Hitachi Nuclear Energy, " BWRX-300 General Description," 005N9751, Revision F, December 2023.
[4] H. O. Kang, B. J. Lee, & S. G. Lim, " Light water SMR development status in Korea," Nuclear Engineering and Design, 419, 112966, 2024.
[5] B. U. Bae, S. Kim, Y. S. Park, K. H. Kang, "Experimental investigation on condensation heat transfer for bundle tube heat exchanger of the PCCS (Passive Containment Cooling System)," Annals of Nuclear Energy, Vol. 139, p. 107285, 2020. https://doi.org/10.1016/j.anucene.2019.107285.
[6] X. Ma, X. Xiao, H. Jia, J. Li, Y. Ji, Z. Lian, Y. Guo, Experimental research on steam condensation in presence of non-condensable gas under high pressure, Annals of Nuclear Energy, Vol.158, p.108282, 2021.
[7] J. Kang, Y. Ko, L. D. Manh, J. J. Jeong, B. Yun, Development of filmwise condensation model for steam–air mixture on vertical plates and tubes under free convection, International Communications in Heat and Mass Transfer, Vol.157, p.107782,