Preliminary study of high-pressure steam condensation model in SPACE code for iSMR PCCS

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*

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1. Introduction

Small Modular Reactors (SMRs) have gained significant attention as a viable alternative to conventional large-scale nuclear power plants, primarily due to their reduced capital costs, enhanced site selection flexibility, and superior safety, security, and nonproliferation features. One of the leading developments in this field is the NuScale SMR, a 50 MWe reactor, which received design certification approval from the U.S. Nuclear Regulatory Commission (NRC) in September 2020.

Korea Hydro and Nuclear Power Company (KHNP) has also embarked on developing an innovative SMR (iSMR) since 2020, with the objective of achieving economic benefits while ensuring safety standards comparable to other SMR designs [1]. One of the safety system iSMR is the Passive Containment Cooling System (PCCS), which serves as the final heat sink by condensing high-temperature, high-pressure steam within the containment vessel. Thus the accurate prediction of PCCS performance is essential, necessitating the use of a properly validated model within system analysis codes.

However, a gap in research concerning the validation of high-pressure steam condensation phenomena, particularly under conditions relevant to SMRs, has been identified. To address this, extended Shah model was implemented into the SPACE code, as NRELAP5, and validation analyses were performed against to the KAIST high-pressure steam condensation experiments. This study focuses on validating the condensation model and its implementation in the SPACE code to ensure the reliable prediction of condensation heat transfer accident conditions of iSMR. Through this research, an effort has been made to fill the existing gap in the understanding of high-pressure steam condensation and to provide a robust analytical foundation for the safety of iSMR.

2. Methods and Results

Recently, NuScale Power utilized the NRELAP5 code, a modified version of RELAP5-3D, to analyze condensation heat transfer within the tubes of the Decay Heat Removal Heat Exchanger (DHRHX). Due to the condensation of high-pressure steam under accident conditions within the DHRHX, Shah's 2009 condensation model was implemented in NRELAP5 [2]. Unlike NuScale's DHRHX, condensation in the iSMR PCCS occurs on the outer surface of the heat exchanger tubes. However, both systems share the common challenge of under high-pressure conditions. Therefore, in this study, Shah's 2009 condensation model was implemented into the SPACE code, and validation was performed using the KAIST high-pressure condensation experiments[3].

2.1 Shah's condensation model

In the extended Shah model, condensation heat transfer regimes are classified into three categories using two key parameters: the correlating parameter (Z) introduced by Shah and the dimensionless vapor velocity (J_g) as defined follows.

$$Z = \left(\frac{1}{x} - 1\right)^{0.8} p_r^{0.4}$$

$$J_g = \frac{xG}{(gD\rho_G \Delta\rho)^{0.5}}$$

The different condensation heat transfer regimes are bounded by these parameters. In each regime, the condensation heat transfer coefficient was provided as follows:

In Regime I, $h_I = h_{LS}\left(1 + \frac{3.8}{Z^{0.95}}\right)$
In Regime II, $h_{II} = h_I + h_{III}$
In Regime III, $h_{III} = 1.32 Re_{LS}^{-\frac{1}{3}} \left[\frac{\rho_L \Delta\rho g k_L^3}{\mu_L^2}\right]^{\frac{1}{3}}$

The details of the model are explained in studies of Shah [4,5].

2.2 High pressure condensation analysis by using SPACE

The KAIST high-pressure condensation tests were calculated using the SPACE code, where the aforementioned Shah model was implemented. The test facility, computational domain, and SPACE nodalization are illustrated in Fig. 1. The cooling pool in Fig. 1(a) was not simulated as shown in Fig. 1(b), and the calculations were performed by using the outer wall temperature as the boundary condition. For ease of inputting the boundary conditions, the nodalization was set so that the measurement points of the outer wall temperature were as close as possible to the center of the PIPE volume (Fig.

1(b) and Fig. 1(c)). The computational conditions are provided in Table 1. The calculation results showed that the local heat transfer coefficient was underestimated by the default SPACE code (Fig. 2). Although the calculation results are improved with the implementation of the extended Shah model in SPACE, it still underestimated the heat transfer coefficient. Furthermore, there was a tendency for the predicted heat transfer coefficient to be lower than that predicted by NRELAP5. This tendency is believed to be due to the fact that the KSP multiplier applied in NRELAP5 was not utilized in SPACE. The KSP multiplier is expected to double the heat transfer coefficients suggested by the model for the heat transfer between the gas-phase interface and the liquid-wall, specifically in film-wise condensation. This adjustment ensures that the overall heat transfer resistance achieves the intended value as prescribed by the model. The local heat transfer coefficients for all analyzed conditions are shown in Fig. 3. Overall, it was observed that the local heat transfer coefficients were better predicted by the modified SPACE compared to the default SPACE. However, even with the use of the modified SPACE, the condensation heat transfer coefficient was still underestimated by an average of approximately 15%.

Table I: Computational conditions

Case no.	Pressure [MPa]	Outer wall temp. [K]	Vapor velocity [m/s]	Gas temp. [K]
1	1.071	386.1	3.144	456.65
2	1.479	368.0	3.194	471.15
3	1.749	373.3	3.008	473.50
4	2.100	375.3	2.735	488.55
5	2.621	384.8	2.320	500.25
6	3.045	387.6	1.708	508.65
7	3.490	386.3	2.083	515.95
8	4.053	389.4	1.397	524.45
9	4.559	388.9	1.911	531.25
10	5.260	389.3	1.762	540.05
11	2.452	388.4	2.549	540.95
12	6.021	389.1	1.715	548.85
13	6.656	390.0	1.502	555.45
14	7.155	390.0	1.403	560.05
15	7.305	384.8	1.621	562.15

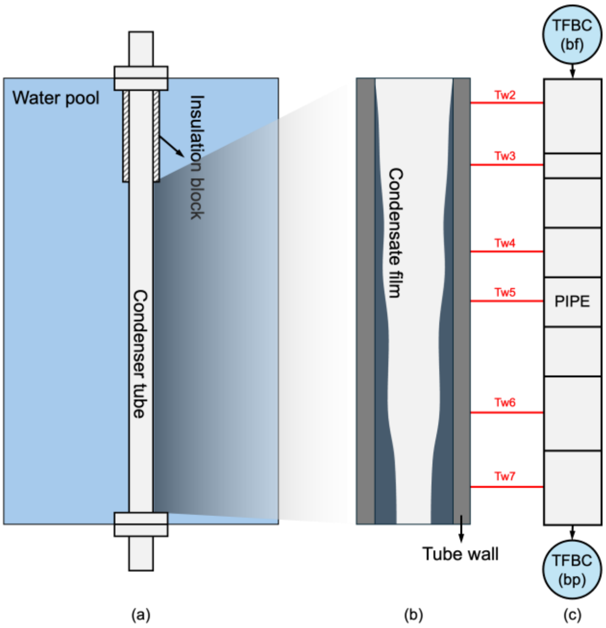

Fig. 1. Schematics of test section and computational domain (a: test section, b: computational domain, c: SPACE nodalization)

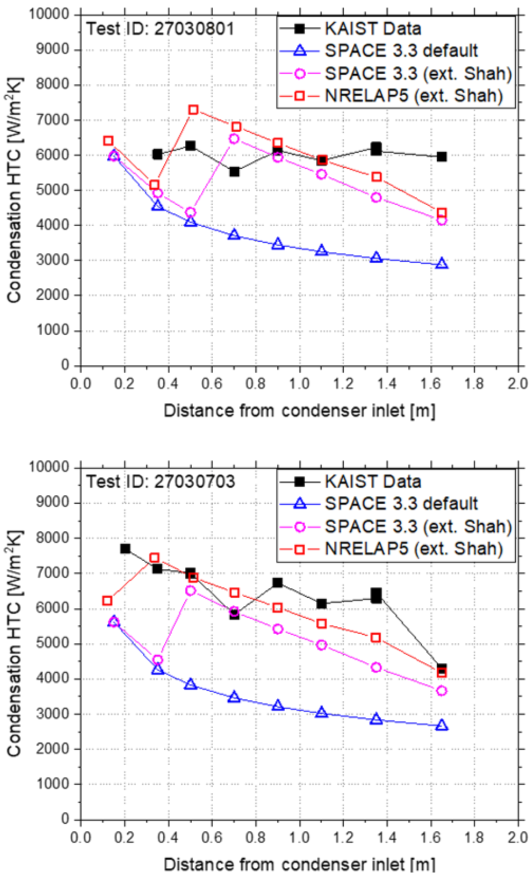

Fig. 2. Comparison between measured local condensation HTC and calculated local condenstion HTC

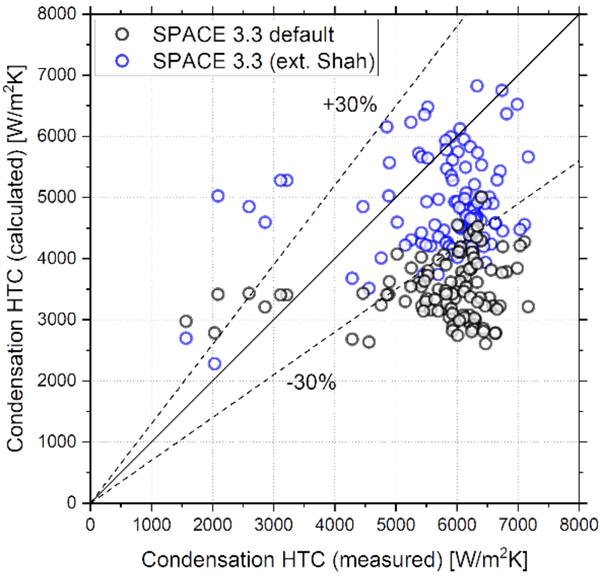

Fig. 3. Comparison between measured local condensation HTC and calculated local condenstion HTC in all computed cases

3. Conclusions

In this study, the extended Shah model was implemented into the SPACE code to analyze high-pressure steam condensation expected in the PCCS of the iSMR. The modified SPACE code was validated against the KAIST condensation tests. The validation results indicated that while the modified SPACE predicted the heat transfer coefficient more accurately than the default SPACE, there was still a tendency to underestimate the heat transfer coefficient compared to the experimental results.

This preliminary research builds upon the advancements made in the NRELAP5 code, establishing a baseline for enhancing high-pressure condensation analysis capabilities of SPACE code. Future studies will concentrate on developing models for high-pressure condensation on outer walls, such as those found in the PCCS. The improved SPACE code will then be employed in the safety analysis of iSMRs.

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