Preliminary Modification of the SPACE Code Condensation Model for Superheated Steam Condensation in the i-SMR Containment Vessel

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

***Keywords :** i-SMR, Condensation, PCCS, Superheated steam

1. Introduction

Superheated steam can be formed in the containment vessel (CV) through various mechanisms during an accident. A representative source is the once-through steam generator adopted in the innovative small modular reactor (i-SMR). The main steam is produced in a superheated state, not in a saturated state, during normal operation. This differs fundamentally from conventional PWRs, whose recirculation-type steam generators produce saturated steam. Therefore, when the secondary-side steam is discharged directly into the CV, as in a main steam line break (MSLB), the CV remains in a superheated condition rather than a saturated condition. Moreover, the free volume of the i-SMR CV is much smaller than that of the containment of conventional plants. The same mass and energy release thus produces a much higher degree of superheat [1]. Consequently, wall condensation under superheated conditions must be predicted accurately to evaluate the pressure and temperature behavior of the i-SMR CV.

However, existing system analysis codes such as SPACE were developed mainly for the thermal-hydraulic analysis of the reactor coolant system. They were not developed to analyze the containment of conventional PWRs or the CV of small modular reactors. Accordingly, their condensation models were mostly developed under the assumption of saturated steam [1]. The containment analysis code CAP corrects the reduced condensation under superheated steam conditions only through a user-input coefficient called the re-vaporization rate [2]. In other words, the system analysis codes do not yet have a mechanistic model for superheated steam condensation. In the i-SMR CV, however, an inaccurate prediction of the condensation rate under superheated conditions leads to an inaccurate evaluation of not only the pressure and temperature but also the passive heat removal performance itself. As described above, the CV maintains a high degree of superheat during an accident. These conditions differ somewhat from the range over which the existing condensation models have been developed and validated. The condensation model of the system analysis code needs to be improved to properly simulate superheated steam condensation.

In this study, the condensation model of the SPACE code was modified for this purpose. The modified model sets the gas-liquid interface temperature to the saturation temperature corresponding to the pressure. Based on this, the latent heat transfer by condensation and the sensible heat transfer due to the superheat are calculated separately. A conceptual problem was then analyzed with the modified SPACE code. The results confirmed that the modified code can reproduce the physical behavior of superheated steam condensation.

2. Superheated Steam Condensation on a Vertical Wall

2.1 Heat Transfer Contribution in Superheated Steam Condensation

The mechanism of superheated steam condensation has been identified through the theoretical work of Minkowycz and Sparrow [3] and subsequent experiments [4,5]. The steam temperature decreases toward the wall. The temperature at the gas-liquid interface reaches the saturation temperature corresponding to the pressure. Condensation therefore occurs when the wall temperature is below the saturation temperature. Meanwhile, the bulk gas remains superheated. In addition, the sensible heat transfer due to the superheat accounts for a non-negligible portion of the total heat transfer [4]. The same trend was confirmed in the steam-air mixture experiment of Murase et al. [5]. The contribution of the sensible heat transfer should therefore be considered in superheated steam condensation analysis.

Consider a vertical heat transfer surface such as a passive containment cooling system (PCCS) tube or the CV inner wall. The wall temperature is maintained below the saturation temperature. The superheated steam near the wall is cooled and forms a thermal boundary layer. Inside the boundary layer, the gas temperature decreases toward the wall. The gas temperature reaches the saturation temperature at the gas-liquid interface. Condensation occurs at this point, and the condensate forms a liquid film along the wall. The film flows downward by gravity and gradually thickens. The overall heat transfer path is thus divided into two resistances. One is the convective heat transfer on the gas side. The other is the conduction across the liquid film. Accurate analysis of superheated steam condensation therefore requires proper modeling of these two resistances. This heat transfer partition can be expressed as Eq. (1) [4].

$$h_{sh}(T_b - T_{sat}) + h_{cond}(T_{sat} - T_w) = h_{tot}(T_b - T_w) \quad (1)$$

Here, h is the heat transfer coefficient. The subscripts sh, cond, and tot denote the gas-side sensible heat transfer, the condensation latent heat transfer, and the total heat transfer, respectively. The key point is that the two components have different driving temperature differences.

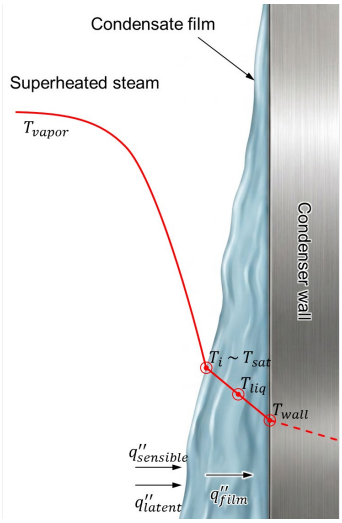


Fig. 1. Concept of superheated steam condensation on a vertical wall

The liquid film side is not a major problem. The film is a subcooled liquid placed between the interface at the saturation temperature and the colder wall. The temperature boundary condition of the film is identical whether the bulk is saturated or superheated. The existing model based on the Nusselt film analysis can therefore be used as it is. The difficult part is the convective heat transfer on the gas side. The convection of the superheated gas mixture and the condensation at the interface are coupled with each other. A rigorous solution requires a sophisticated model for the boundary layer. However, the system analysis codes already have single-phase convective heat transfer models validated over a long period. Applying these models to the gas-side sensible heat transfer would not produce severely unphysical results. Based on this judgment, a PCCS-oriented model was added to the condensation and interfacial heat transfer model options of the SPACE code.

2.2 Modifications to the SPACE Code

The original code treats superheated steam condensation as follows. When the gas is superheated, the superheat is first removed by the sensible heat transfer to the wall. Condensation starts only after the gas temperature falls below the saturation temperature. This treatment works without difficulty when saturated steam enters. Under superheated conditions, however, condensation is delayed until the superheat is consumed. In this process, the sensible heat transfer is overestimated, and the superheat is exhausted unphysically fast. This contradicts the actual mechanism, in which condensation starts once the wall temperature is below the saturation temperature regardless of the bulk superheat. In addition, the heat transfer coefficients between the gas and the interface and between the interface and the liquid were excessively large under some conditions.

These two problems were corrected in this study. First, the interface temperature is set to the saturation temperature corresponding to the pressure. Condensation then starts whenever the wall temperature is below the saturation temperature, regardless of the bulk superheat. The interface-to-liquid heat transfer is practically identical to that of saturated condensation. The interface-to-liquid heat transfer coefficient is therefore set equal to the calculated condensation heat transfer coefficient. The gas-to-interface heat transfer uses the existing single-phase convective heat transfer model.

3. Conceptual Problem Analysis

A conceptual problem was set up to examine the effect of the modified model. The geometry and boundary conditions except the inlet vapor temperature and velocity were taken from the UCB-Kuhn condensation test 1.1-4R1 [6]. This experiment targets steam condensation in a vertical tube and has been widely used for condensation model validation. In this analysis, the inlet condition was changed to superheated steam. Calculations were performed with the default SPACE and the modified SPACE under the same conditions. The effect of the superheat treatment on the condensation heat transfer prediction was compared through the difference between the two results.

The SPACE nodalization is shown in Fig. 2. Superheated steam is supplied through the inlet boundary condition (TFBC 105). The test section, where condensation occurs, is modeled by PIPE 110 with the heat structure HST 110. The outlet of the condenser is connected to the outlet boundary condition (TFBC 125) through PIPE 120.

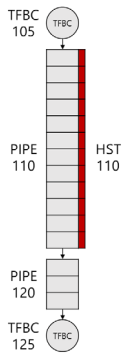


Fig. 2. SPACE nodalization for the conceptual problem

The main analysis conditions are summarized in Table I. Fig. 3 compares the temperatures calculated at the first node right after the superheated steam enters. In the default SPACE code, the gas temperature drops to the saturation temperature immediately (first time step). The heat of the superheated steam is excessively removed by

the sensible heat transfer, or the superheat is consumed immediately by evaporation at the interface. The liquid temperature is also calculated excessively low, close to the wall temperature. In the modified code, on the other hand, the condensate forms while the gas remains superheated. The liquid temperature is calculated at an intermediate level between the wall temperature and the saturation temperature. This behavior is consistent with the condensation mechanism described in Section 2.

Fig. 4 shows the calculated temperature profiles after steady state was reached, from the condenser inlet to the lower part of the test section. Although this is not central to the present discussion, the wall temperature downstream of 1.5 m was not measured in the experiment. Therefore, the wall temperature at the lowermost measurement location was imposed as the boundary condition, resulting in a flat wall-temperature profile in this region. As shown in the figure, with the default SPACE code, the vapor temperature is equal to the saturation temperature at every node. In contrast, the modified SPACE code preserves the superheat, which gradually decreases toward the lower part of the test section. These results suggest that a system code can properly represent superheated steam condensation without explicitly resolving the boundary layer.

Table I: Analysis conditions of the conceptual problem

Parameters	Values
Tube inner diameter	47.5 mm
Length	2.4 m
Pressure	0.4 MPa
Saturation temperature	416.7 K
Inlet steam temperature	450.0 K (superheat 33.3 K)
Mean wall temperature	402 K
Inlet velocity	5 m/s

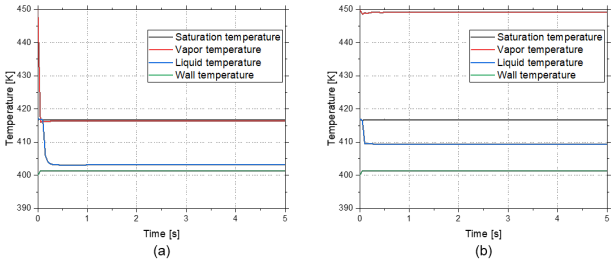


Fig. 3. Calculated temperatures at 1st node (a: default SPACE, b: modified SPACE)

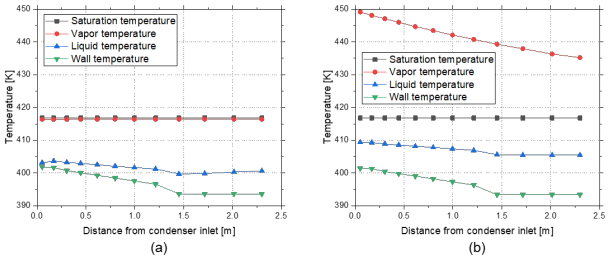


Fig. 4. Calculated temperatures along distance from condenser inlet (a: default SPACE, b: modified SPACE)

4. Conclusions

Superheated steam condensation may occur during postulated accident scenarios in the i-SMR CV. However, this condition has not been a major issue in conventional containment analysis. The existing condensation models were developed under the assumption of saturated steam, and they have worked without difficulty so far. In this study, the condensation model of the SPACE code was modified to analyze the sensible and latent heat transfer separately based on the interface saturation condition. The existing single-phase convective heat transfer model was applied to the gas-side sensible heat transfer. The difference before and after the modification was confirmed through a conceptual problem based on the geometry of the UCB-Kuhn experiment. It should be noted that condensation itself occurs in both the default and the modified calculations. The modification changes the bulk gas temperature behavior so that it follows the expected trend, and it was implemented as one of the model options in the SPACE code. This approach is expected to contribute to predicting the gas behavior in the i-SMR CV and the condensation performance of the PCCS. Separate effect tests (SETs) on superheated steam condensation are planned at KAERI. The modified model will be validated against the test results and further improved if necessary.

Acknowledgements

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] J. Lee, S. J. Hong, Y. J. Choo, K. H. Han, Analysis the Effect of Sensible Heat Transfer on Condensation Rate during Wall Condensation of Superheated Steam in Containment Building, NTHAS12, Miyazaki, Japan, October 30-November 2, 2022.

[2] S. H. Jee, et al., Development of Advanced Containment Thermal-Hydraulic Analysis Methodology Based on Three-Field Model Codes for APR1400, Nuclear Engineering and Technology, Vol.57, 103616, 2025.

[3] W. J. Minkowycz, E. M. Sparrow, The Effect of Superheating on Condensation Heat Transfer in a Forced Convection Boundary Layer Flow, International Journal of Heat and Mass Transfer, Vol.12, pp.147-154, 1969.

[4] C. Kondou, P. Hrnjak, Condensation from Superheated Vapor Flow of R744 and R410A at Subcritical Pressures in a Horizontal Smooth Tube, International Journal of Heat and Mass Transfer, Vol.55, pp.2779-2791, 2012.
[5] M. Murase, et al., Condensation Heat Transfer for Downward Flows of Superheated Steam-Air Mixture in a Circular Pipe, Nuclear Engineering and Design, Vol.371, 110948, 2021.
[6] S. Z. Kuhn, V. E. Schrock, P. F. Peterson, An Investigation of Condensation from Steam-Gas Mixtures Flowing Downward inside a Vertical Tube, Nuclear Engineering and Design, Vol.177, pp.53-69, 1997.