

## Assessment of the Boiling Heat Transfer Model for Horizontal Tube Bundles in the Passive Auxiliary Feedwater System of the SPACE code

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### 1. Introduction

The innovative small modular reactor (i-SMR), led by Korea Hydro & Nuclear Power (KHNP), is being developed with enhanced safety features to ensure safe shutdown under accident conditions without operator actions, external power, or additional cooling water injection. Various passive safety systems have been adopted as engineered safety features, including the Passive Auxiliary Feedwater System (PAFS).

The PAFS removes decay heat by transferring heat from main steam in steam generator to the Emergency Cooling Tank (ECT) water through horizontal U-tube bundles. During operation, condensation occurs inside the tubes, while pool boiling is a dominant heat transfer mechanism on the outer tube surfaces. Since the heat exchanger consists of multiple horizontal tubes arranged in a bundle, tube bundle effects may significantly influence the boiling heat transfer performance. Previous studies reported that boiling heat transfer on upper tubes can be enhanced by rising bubbles from lower tubes, while this enhancement decreases with increasing heat flux or external flow velocity [1].

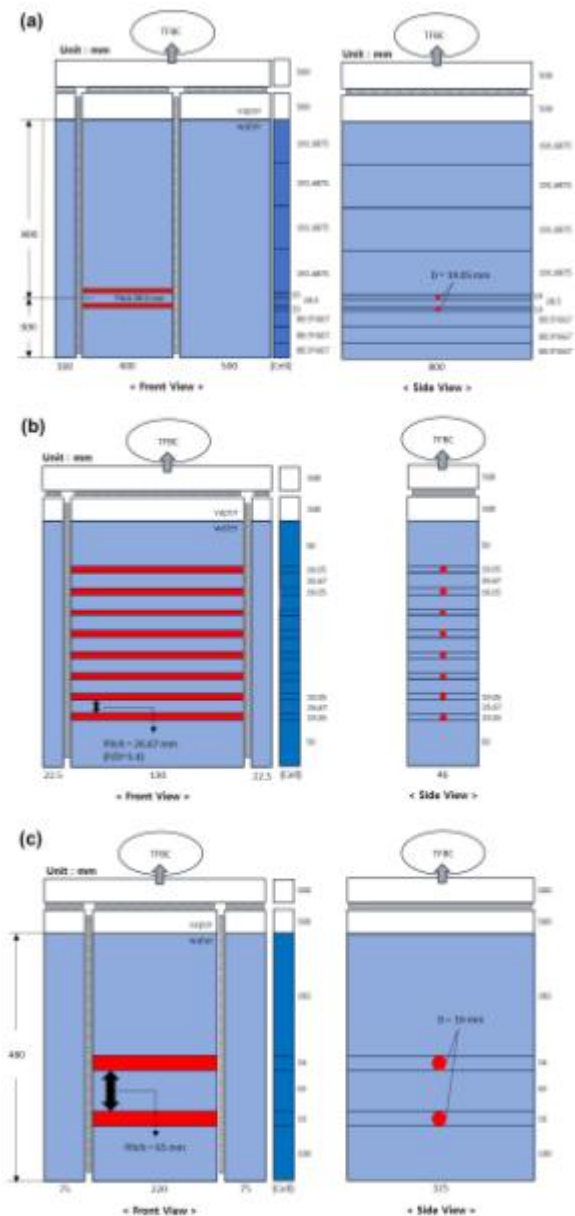
Therefore, it is necessary to assess whether the boiling heat transfer model for horizontal tube bundles in the PAFS implemented in the SPACE code appropriately accounts for tube bundle effects. In this study, SPACE code calculations were performed using previous pool boiling heat transfer experiments for horizontal tube bundles, and improvement options for the boiling heat transfer model were explored through model review and literature survey.

### 2. SPACE code calculations

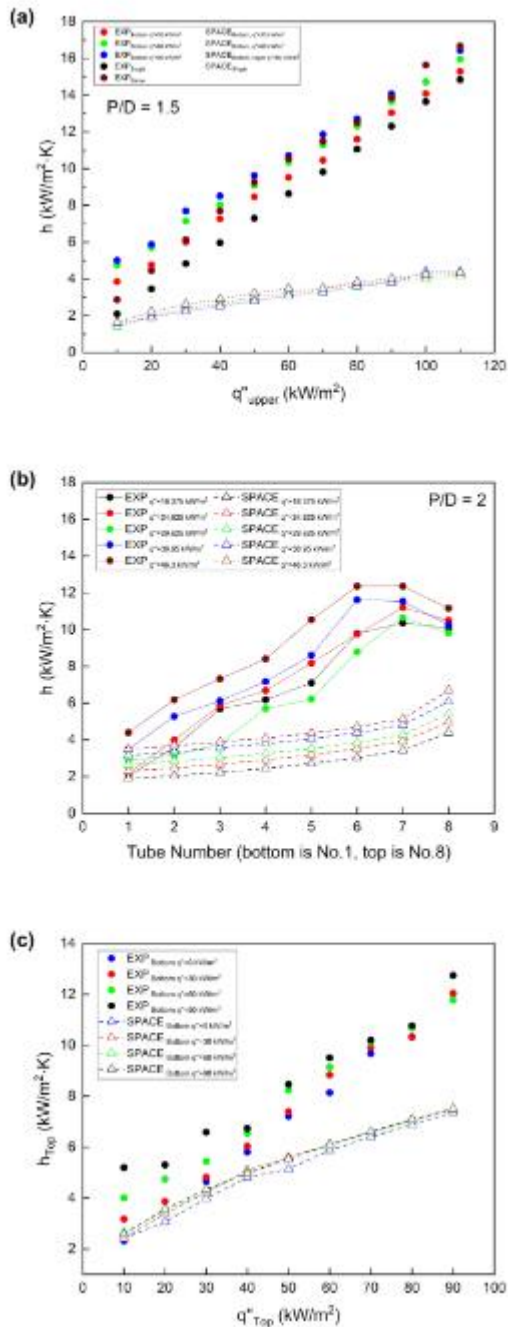
In this study, validation calculations were performed using the SPACE code (SPACE 3.3) for three pool boiling heat transfer experiments of horizontal tube bundles reported in previous studies (Table 1) [2–4], in order to investigate whether the horizontal tube boiling heat transfer model in SPACE appropriately accounts for the tube bundle effect.

For each experimental facility, the pool was modeled using the PIPE component in SPACE. The water level in the pool was represented by assigning an appropriate

void fraction to the upper cells. In addition, the Time-Dependent Flow Boundary Condition (TFBC) was imposed at the top of the pool to maintain atmospheric saturated conditions.



**Figure. 1** Nodalization for SPACE validation calculation of previous experiments. (a) Kang et al. (2015) [2]. (b) Lakhera et al. (2014) [3], (c) Wang et al. (2023) [4]



**Figure. 2** Results of SPACE validation calculation of previous experiments. (a) Kang et al. (2015) [2], (b) Lakhera et al. (2014) [3] ( $q'' = 18.375 \text{ kW/m}^2$  case), (c) Wang et al. (2023) [4] ( $\theta = 0^\circ$  case)

The horizontal tubes, on which external boiling occurs, were modeled as heat structures. For the experiment of Lakhera *et al.* [3], which consists of an  $8 \times 3$  horizontal tube array, it is difficult to explicitly represent the tube geometry in the width direction of the pool in SPACE. Therefore, the experiment was modeled

as an  $8 \times 1$  tube array, and the heat transfer area of each tube was multiplied by a factor of three so that the total heat transfer from the tube bundle could be preserved in the calculation. Figure 1 shows the nodalization used for each experiment.

Figure 2 presents the SPACE validation results for the pool boiling heat transfer experiments of horizontal tube bundles. As shown in the figure, the boiling heat transfer coefficients for the lower tubes, where the bundle effect is negligible, were predicted well by SPACE. However, for the upper tubes, where the bundle effect becomes significant, the experimental data showed a remarkable increase in the boiling heat transfer coefficient compared to the lower tubes, whereas the SPACE results predicted values close to those of the lower tubes. These results indicate that the current SPACE code does not properly reflect the enhancement of boiling heat transfer due to tube bundle effects.

Table. 1 Previous pool boiling heat transfer experiments of horizontal tube bundles

Contents	Kang (2015) <sup>[2]</sup>	Lakhera <i>et al.</i> (2014) <sup>[3]</sup>	Wang <i>et al.</i> (2023) <sup>[4]</sup>
Tube diameter [mm]	19	19.05	16
Tube length [mm]	400	130	220
Pitch/Diameter [-]	1.5-6.0	1.4-2.0	4.06
Number of tubes [EA]	2	$8 \times 3$ arrays	2
Heat flux [kW/m <sup>2</sup> ]	(upper)10-110 (bottom)0-90	10-110	(upper)10-90 (bottom)0-90
Conditions	Atmospheric Saturated	Atmospheric Saturated	Atmospheric Saturated

### 3. Review and assessment of the boiling heat transfer models for horizontal tube bundles

The SPACE code employs the Chen's correlation for boiling heat transfer, as expressed in Eq. (1), and the same model is also applied to the external boiling conditions of horizontal tubes in a pool [5]. The Chen's correlation was originally developed for forced convective boiling inside tubes. As shown in Eq. (1), the model combines a nucleate boiling correlation for pool boiling (Eq. (2)) and a convective heat transfer correlation (Eq. (3)), where a boiling suppression factor and a convective enhancement factor are introduced. These two factors are expressed as functions of the Martinelli parameter (or quality). Therefore, Chen's correlation has inherent physical limitations in applying to external pool boiling on horizontal tubes. In addition, SPACE code does not include a dedicated model to represent the boiling heat transfer enhancement on the upper tubes induced by tube bundle effects. As a result, as shown as Figure 2, only the increased convective term associated with the flow induced by boiling on the

lower tubes is reflected in the upper-tube prediction, leading to a negligible bundle effect in the SPACE validation results.

$$h = S \cdot h_{PB} + F \cdot h_{FC} \quad (1)$$

$$h_{PB} = 0.00122 \frac{k_l^{0.79} C_{\rho,l}^{0.45} \rho_l^{0.45}}{\sigma_l^{0.5} \mu_l^{0.29} i_{fg}^{0.24} \rho_g^{0.24}} (\Delta T_w)^{0.24} (\Delta P_{sat})^{0.75} \quad (2)$$

$$h_{FC} = 0.023 \text{Re}_{TP}^{0.8} \text{Pr}_{TP}^{-0.94} \frac{k_l}{d} \quad (3)$$

Various models for external pool boiling on horizontal tube bundles have been reported in the literature. Among them, Polley *et al.* (1980) [6] (Eq. (4)-(6)) and Gupta *et al.* (1992) [1] (Eq. (4), (8)-(10)) proposed modified forms of the Chen's correlation in which tube bundle effects are incorporated. In these models, the boiling suppression factor (S) is fixed to unity, while the convective enhancement factor is modified as a function of void fraction and/or bundle geometric parameters such as the pitch-to-diameter ratio and the number of tubes, so that the bundle effect on the upper tubes can be reflected within the Chen framework. Hwang *et al.* (1986) [7] (Eq. (6)) also proposed a Chen-type model in which both the boiling suppression factor (S) and the convective enhancement factor (F) are expressed as functions of quality and void fraction to account for bundle effects on the upper tubes.

$$h = h_{PB} + F \cdot h_{FC} \quad (4)$$

$$h_{FC} = 0.211 \text{Re}_i^{0.651} \text{Pr}_i^{0.34} \frac{k_l}{D} \quad (5)$$

$$F = \left( \frac{1}{1-\alpha} \right)^{0.744} \quad (6)$$

$$h_i = h_{FC} (1-x_{LOC})^{0.6} \quad (8)$$

$$S = \frac{h_i}{F h_i} \left[ 1 - \exp\left(-\frac{F h_i}{k_l}\right) \right] \quad (9)$$

$$F = \left( \frac{1}{1-\alpha_w} \right)^{0.744}, \quad \alpha_w = \frac{0.833 x_{LOC}}{x_{LOC} + (1-x_{LOC})(\rho_g/\rho_l)} \quad (10)$$

In contrast, Lakhera *et al.* (2014) [3] (Eq. (11)), Kang (2015) [2] (Eq. (12)), and Wang *et al.* (2023) [4] (Eq. (13)-(14)) developed non-dimensional functions incorporating parameters such as the pitch-to-diameter ratio, the heat flux of the lower tubes, and the effective wall superheat, to predict the enhancement ratio of boiling heat transfer on the upper tubes relative to the lower tubes.

$$\frac{h_{PB\_local}}{h_{PB\_bottom}} = 2.288 \left[ \frac{1}{1-\alpha} \right]^{0.275} \left( \frac{P}{d} \right)^{-0.297} \quad (11)$$

$$\frac{h_{PB\_local}}{h_{PB\_bottom}} = \left[ 0.847 + \frac{0.397}{(P/d)^2} \right] q_l^{1.279} \frac{\ln(2.424 + P/d)}{q_l} \quad (12)$$

$$h_{PB\_local} = -0.001 \gamma C q_l^{0.67} M_r^{-0.5} P_r^m (-\log_{10} P_r)^{-0.55} \quad (13)$$

$$\gamma = \frac{(0.88963 + 0.00267 q_l - 0.0032 \theta) \left( \frac{\Delta T_{ql}}{\Delta T_{ql=0}} \right)}{\Delta T_{ql=0}} \quad (14)$$

Considering that many nuclear system codes adopt the Chen's correlation as the base boiling heat transfer model, and that it is difficult for SPACE to obtain wall temperature and heat flux without iterative procedures, the models proposed by Polley *et al.* [6] and Hwang *et al.* [7] are considered to be practically suitable for implementation in the SPACE code among the available external pool boiling models for horizontal tube bundles.

#### 4. Conclusion

In this study, the applicability of the horizontal tube boiling heat transfer model in the SPACE code (version 3.3) to tube bundle effects was investigated through validation calculations and literature review. Validation analyses were performed for three pool boiling experiments of horizontal tube bundles. The results showed that SPACE reasonably predicted the boiling heat transfer coefficients for lower tubes where bundle effects are negligible. However, for upper tubes, the significant enhancement observed in the experiments was not properly reproduced by the code.

The review of existing boiling heat transfer models revealed that the Chen's correlation currently implemented in SPACE has inherent limitations when applied to external pool boiling on horizontal tube bundles. In particular, the current model does not explicitly account for bundle-induced enhancement effects. Among the reviewed correlations, the models proposed by Polley *et al.* [6] and Hwang *et al.* [7] were identified as practically suitable candidates for implementation within the Chen-based framework of the SPACE code.

The present results indicate that improvement of the horizontal tube boiling heat transfer model is necessary for more accurate prediction of PAFS heat removal performance in the i-SMR. Further work will focus on the implementation and validation of modified bundle-effect models in SPACE.

#### ACKNOWLEDGEMENT

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