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Prediction of Heat Transfer Performance on Horizontal U-Shaped Heat Exchanger in Passive Safety System Using MARS

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1. Introduction

As a key equipment of a passive safety system such as a Passive Auxiliary Feedwater System (PAFS) as shown in Fig. 1, a horizontal U-shaped Heat Exchanger (HX) submerged in a pool is under development. For the successful design of the HX and the safety analysis of the Nuclear Power Plant (NPP), the reliable prediction of the heat transfer performance of the HX is important. At present, the design and the safety analysis of the passive safety systems are performed mainly using the best-estimate thermal-hydraulic analysis codes such as RELAP5 and MARS. However, those codes do not have the suitable models for both the condensation heat transfer in the horizontal tube and the natural convective and nucleate boiling heat transfer on the horizontal tube, both of which ultimately determining the heat transfer performance of the heat exchanger (see Fig. 2).

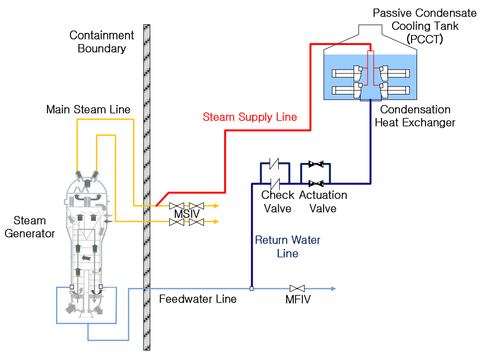

Fig. 1. Schematic diagram of APR+ PAFS [1]

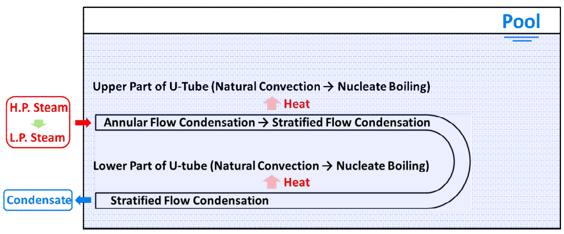

Fig. 2. Main heat transfer mode

This study developed the heat transfer model package for the horizontal U-shaped HX submerged in a pool by improving the horizontal in-tube condensation model and developing the outside-tube natural convective nucleate boiling model. This paper presents the HX model package and the validation results against the passive safety system-related experimental data of PASCAL [1, 2] and ATLAS-PAFS [3].

2. HX Model Package

2.1 Horizontal In-Tube Condensation Model

In a horizontal condenser tube, main flow regimes are the annular and stratified flows. As part of this research, Jeon et al. [4, 5] reviewed nineteen annular flow and eleven stratified flow condensation models and assessed the prediction capability of each model with various experimental data for the passive safety systems using MARS. They proposed that the condensation models by Dobson and Chato (1998) as shown in Eq. (1) for annular flow and Cavallini et al. (2006) as shown in Eq. (2) for the stratified flow were the most applicable models to the HX of the passive safety system. For the prediction of horizontal in-tube condensation heat transfer, the original MARS code employs Shah (1979) and Chato (1962) models for the annular and stratified flow regimes, respectively [6]. MARS code determines the condensation Heat Transfer Coefficient (HTC) from the maximum of the values predicted by Shah and Chato models. To improve the horizontal in-tube condensation model, this study replaced the models by Shah and Chato with the annular flow condensation model by Dobson and Chato and the stratified flow condensation model by Cavallini et al., respectively.

$$h = 0.023 Re_l^{0.8} Pr_l^{0.4} \left[1 + \frac{2.22}{X_{tt}^{0.89}} \right] \left(\frac{k_l}{D} \right) \tag{1}$$

$$h = 0.725 \left[\frac{k_l^3 \rho_l (\rho_l - \rho_v) h_{fg} g}{\mu_l D (T_{sat} - T_w)} \right]^{1/4} \times \left[1 + 0.82 \left(\frac{1-x}{x} \right)^{0.268} \right]^{-1} + h_{lo} (1-x)^{0.8} \left(1 - \frac{\theta_{strat}}{\pi} \right) \tag{2}$$

2.2 Natural Convective Nucleate Boiling Model on Horizontal U-Shaped HX Submerged in a Pool

Nucleate boiling model

As part of this research, Jeon et al. [7] reported the heat transfer analysis with the BE code for the nucleate boiling heat transfer on the horizontal U-shaped HX submerged in a pool of water with the multi-dimensional flow. To obtain a reliable prediction of the nucleate boiling heat transfer on the horizontal parts of the U-shaped tubes, Jeon et al. [7] reviewed seven pool boiling correlations and eight forced convective boiling correlations on the horizontal tubes and assessed the prediction capability of the previous nucleate boiling correlations. According to the research by Jeon et al. [7], as a default model in MARS, the nucleate boiling model by Chen (1966) is not physically valid to be applied to the prediction of the nucleate boiling heat transfer on the horizontal tubes. Furthermore, there was no single correlation which could be universally applied to the prediction of the local HTCs on the U-tube. Jeon et al. analyzed the heat transfer mechanisms and developed the nucleate boiling model on the horizontal U-shaped tube. The proposed nucleate boiling model showed good agreement with the experimental data by applying new subcooled pool boiling correlation as shown in Eq. (3) and new forced convective boiling correlation as shown in Eq. (4) to the lower and upper parts of the U-tube, respectively. Therefore, authors determined the nucleate boiling model by Jeon et al. [7] as the most applicable model to the HX of the passive safety system.

$$h_{nb} = 9.7 \cdot P_c^{0.5} \cdot \frac{k_l}{D} \cdot F_p \cdot \left(\frac{\dot{q}'' D}{\mu_l h_{fg}} \right)^{0.67} \times Pr_l^{0.4} \cdot \left(1 + \frac{\Delta T_{sub}}{\Delta T_{sat}} \right)^{-0.167} \quad (3)$$

$$h = h_{nb} + h_{cv} \quad (4)$$

$$h_{cv} = \left(\frac{1}{1-\alpha_v} \right)^{0.744} \times \left(\left(\left(0.4 Re_l^{1/2} + 0.06 Re_l^{2/3} \right) \left(Pr_l \right)^{0.36} \left(\frac{\mu_l}{\mu_v} \right)^{0.25} \left(\frac{k_l}{D} \right) \right)^2 + \left(0.023 Re_l^{0.8} Pr_l^{0.4} \left(\frac{k_l}{D} \right) \right)^2 \right)^{0.5} \quad (5)$$

Natural convection model

The nucleate boiling model proposed by Jeon et al. [7] was validated at low subcooling conditions (up to around 30 K); however, when the passive safety system starts to operate, the water temperature in the HX pool is low at the room temperature, ~300 K, and the subcooling is significantly high. In order to complete the modeling of the heat transfer outside the horizontal HX tube, it is required to secure the heat transfer model to be applicable to a full time operation of the passive safety system including the high subcooling conditions. Jeon et al. [8] assessed the prediction capability of the nucleate boiling models and the MARS default natural convection model at high subcooling conditions in the PASCAL and developed the natural convection model on the horizontal U-shaped HX submerged in a pool suitable for high subcooling conditions. The proposed boiling model showed good agreement with the experimental data by applying Eq. (6) and Eq. (7) to the upper and lower parts of the U-tube, respectively.

$$h_{upper} = 0.0405 Ra_D^{0.471} \frac{k_l}{D} \quad (6)$$

$$h_{lower} = 0.0117 Ra_D^{0.514} \frac{k_l}{D} \quad (7)$$

Natural convective nucleate boiling model

For the smooth transition, authors determined the HTCs from the maximum of the values predicted by the proposed natural convection model and the proposed nucleate boiling model and finally developed the natural convective nucleate boiling model for the horizontal U-shaped HX submerged in a pool.

3. Validation of HX Model Package

The proposed HX heat transfer model is implemented to the MARS. This modified version of MARS is renamed as MARS/PAFS in this study. This section describes the validation results of the MARS/PAFS against passive safety system-related experimental data of PASCAL [1, 2] and ATLAS-PAFS [3].

2.1 Simulation Results of PASCAL

Figures 3 and 4 show the comparison between the experimental data and MARS predictions for local HTCs of the horizontal in-tube condensation along the tube axial length under the SS-540-P1 test as a representative condition. While the original MARS code under-predicted the local HTCs, the predictions by MARS/PAFS were well located between experimental top and bottom HTCs. Figure 5 shows the comparison between the experimental data and MARS predictions the SG pressure at the quasi-steady state condition, according to a variation of the SG thermal power. The original MARS code generally over-predicted the system pressure; however, the MARS/PAFS well traced the increase of the system pressure with the SG power.

2.2 Simulation Results of ATLAS-PAFS

For the ATLAS-PAFS, this study simulated the FLB accident scenario. Figure 6 shows the comparison between the experimental data and MARS predictions for the SG pressure as the most important parameter. Initially, an oscillating behavior of the SG pressure is caused by the opening and closing of the main steam safety valve (MSSV). After the PAFS actuation, the SG pressure decreased rapidly owing to the SG secondary-side cooling by the PAFS. The original MARS code significantly over-predicted the SG pressure. On the other hand, MARS/PAFS considerably well predicted the system pressure with the natural convection flow rate similar to the experimental data.

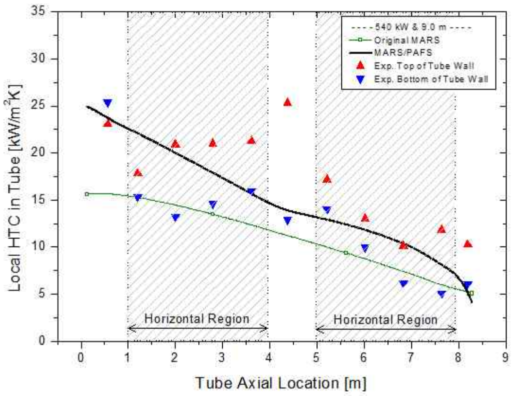

Fig. 3. Local HTCs in tube - condensation

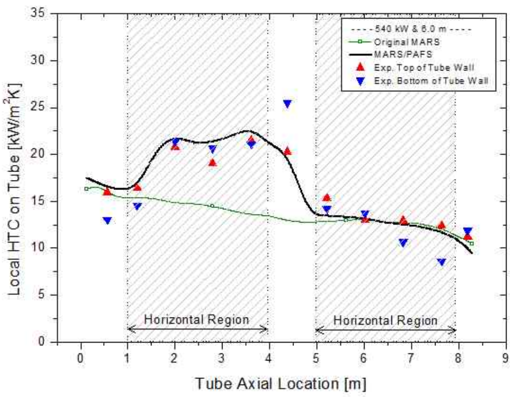

Fig. 4. Local HTCs on tube - boiling

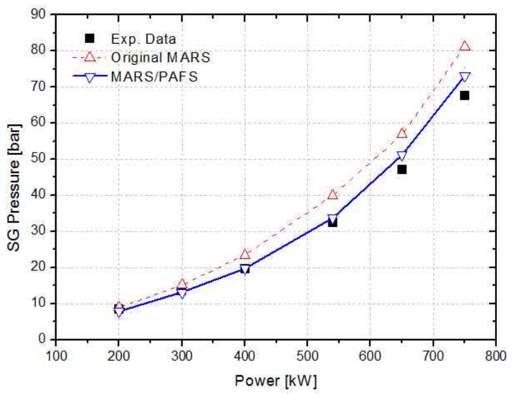

Fig. 5. SG pressure of PASCAL

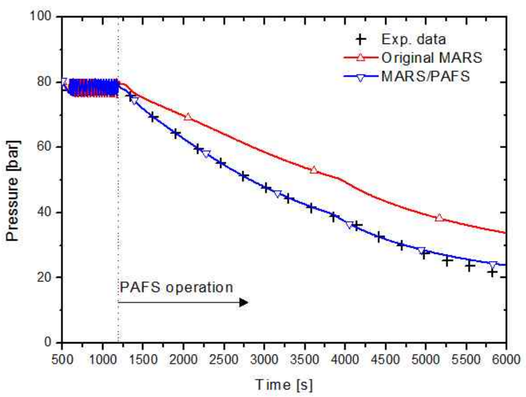

Fig. 6. SG pressure of ATLAS

3. Conclusions

This study developed the heat transfer model package of the horizontal U-shaped HX submerged in a pool in order to obtain a reliable prediction of the HX heat removal performance of the passive safety system, especially PAFS, using MARS. From the validation results, the proposed model package provided the improved prediction of HX performance (condensation, natural convective nucleate boiling, and heat removal rate of the HX) compared to the default model in MARS. It is expected that the proposed new HX model is helpful to the reliable design of the HX and the safety analysis of the NPP with the passive safety system.

ACKNOWLEDGMENTS

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