Implementation of a New Condensation Heat Transfer Model into MARS-KS 1.3

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1. Introduction

From the lesson of the Fukushima accident, studies on passive cooling system have been actively performed. As a result of this trend, the PAFS (Passive Auxiliary Feedwater System) was developed for the APR+ (Advanced Power Reactor plus). The PAFS is designed to completely replace the conventional active auxiliary feedwater system [1]. It serves to cool-down the reactor coolant system using the secondary side of steam generators and eventually removes the decay heat from the reactor core under accident conditions (e.g. station black out). The heat exchanger of PAFS is composed of nearly horizontal tubes. To design the PAFS heat exchanger, the prediction of condensation heat transfer inside a nearly horizontal tube is very important.

Ahn et al. [2] suggested a new condensation heat transfer model for condensation of pure steam condition in a nearly horizontal tube. Then, Lee et al. [3] implemented the Ahn model to MARS-KS 1.3 and assessed the model using several experimental data. Recently, Ahn et al. added his model to consider the effect of noncondensable gases (NCGs).

In this work, the Ahn's condensation heat transfer model, which takes into account the effect of NCGs, was implemented to MARS-KS 1.3. Then, the MARS code was assessed using some experimental data for the condensation of pure vapor and vapor/air mixture.

2. Implementation of Ahn's condensation model

2.1. The Ahn's model

The Ahn's model consists of a film condensation correlation for upper side and a convective heat transfer correlation for bottom side to represent condensation inside a nearly horizontal tube:

$$h_{film} = 0.729\left(1 + 8.7\times10^{-4} Re_g^{\,0.47}\right)\times\left(\frac{g\rho_l(\rho_l-\rho_g)h_{fg}k_l^{\,3}}{\mu_l D(T_{sat}-T_w)}\right)^{1/4}, \quad (1)$$

$$h_{convective} = 0.023\,Re_l^{0.8}Pr_l^{0.4}\left(\frac{k_l}{D_{hl}}\right). \quad (2)$$

Eqs. (1) and (2) are the correlations for the film condensation HTC and convective HTC, respectively. Cross-section averaged HTC can be obtained using the HTCs and the wetted angle, γ_l, as follows:

$$h_{average} = \frac{h_{film}(2\pi-\gamma_l) + h_{convective}\gamma_l}{2\pi}. \quad (3)$$

Additionally, Ahn et al. applied a multiplier to Eq. (1) to consider the effect of NCGs on film condensation. The factor is

$$F_{NC} = \left\{exp\left[-17.6Re_{mixG}^{-0.22}\left(W_a/x_s^3\right)^{0.45}\right] + \frac{h_{mixG}}{h_{film}}\right\}, \quad (4)$$

where

$$h_{mixG} = 0.023\,Re_{mixG}^{0.8}Pr_{mixG}^{0.4}\left(\frac{k_{mixG}}{D}\right).$$

The subscript *mixG* means mixture of steam/air. W_a is air mass fraction(AMF) of the mixture. x_s is steam flow quality.

2.2. Modification of the Ahn's model for MARS-KS1.3

There are some modifications of the Ahn model for implementation into the MARS code as follows:

- Flow regime: The Ahn model considers annular-mist, stratified-wavy, stratified-smooth flow according to his flow regime determination method. But in the MARS flow regime, there is not a stratified-wavy flow regime. Thus, stratified wavy flow is not considered in this study.
- Hydraulic diameter: When void fraction is close to 1.0, Eqs. (1) and (2), which involve the equivalent diameter of each phase, show a drastic change according to void fraction. Thus, the tube inner diameter is used in Eqs. (1) and (2) instead of equivalent diameter of each phase.
- Condensation model in annular flow regime: We assume a condensation in the annular flow regime is a film condensation. Because film generated at the inner wall may be very thin. Thus, film condensation HTC model is applied in an annular flow regime unlike the original Ahn model using the convective HTC model.

3. Assessment of the Ahn's model

We selected the experimental data of PASCAL (PAFS condensing heat removal assessment loop) [4], Purdue-PCCS [5], and PICON (Inclined condensation with NCGs test loop) [6] tests. Ahn et al., designed the PICON facility and conducted several condensation experiments for pure vapor and vapor/air mixture to evaluate and improve his model. Test matrix of selected experiments is summarized in Table 1. In this assessment, only the test section of the experiments is modelled in order to reduce uncertainty which may occur during the calculation of the secondary side.

Table 1 Test matrix of selected experiments

	Pure steam		Steam/air mixture	
Experiment	PASCAL	PICON	PICON	Purdue-PCCS
Length [m]	8.4	3	3	3
Inner diameter [mm]	44.8	40	40	27.5
Inclined angle [°]	3	3	3	0
AMF [%]	0	0	1-35	1-20
Pressure [MPa]	0.8-6.7	0.1	0.1	0.1
Steam flow rate [kg/s]	0.09-0.43	0.03-0.06	0.025	0.011

3.1 Condensation of pure steam

The results of PASCAL and PICON are compared in Figs. 1 and 2, respectively. Both experiments are conducted for pure steam. The Ahn model predicts the HTC higher than the condensation model of the MARS.

Fig. 3 compares the measured and calculated HTCS of the original MARS model and the Ahn model for pure steam. As shown in Fig. 3, the Ahn model tends to slightly over-predict HTC. However, it shows improved result than MARS generally.

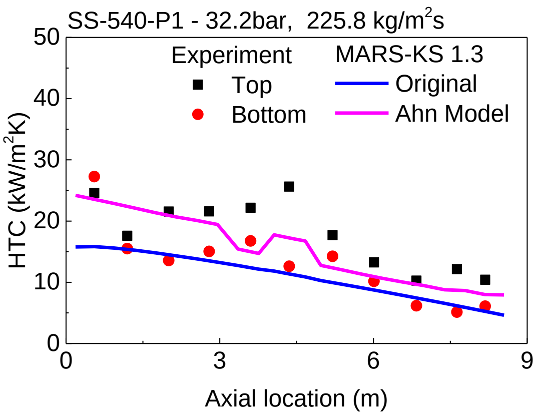

Fig. 1 Calculation result of PASCAL

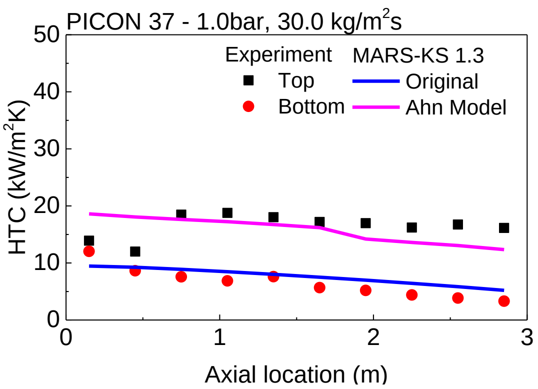

Fig. 2 Calculation result of PICON for pure steam

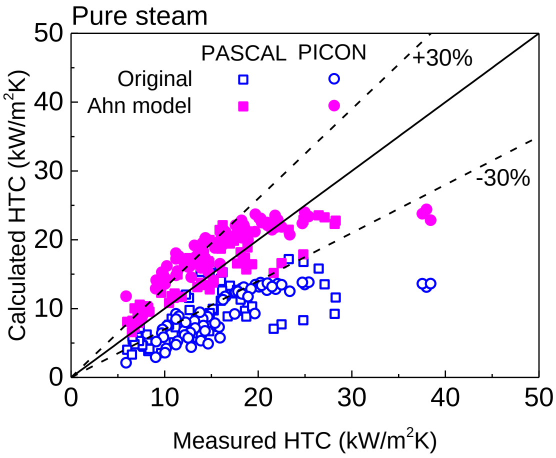

Fig. 3 Comparison of measured and calculated HTC (Pure steam)

3.2 Condensation of steam/air mixture

Figs. 4 and 5 show the results of PICON and Purdue-PCCS vapor/air mixture tests, respectively.

The Ahn model shows improved calculation result when inlet AMF is low in both experiments. On the other hand, the result of Purdue-PCCS test, which has high inlet AMF, seems that the Ahn model under-predicts the HTC. However, it shows more similar trend to experimental data than the original MARS model.

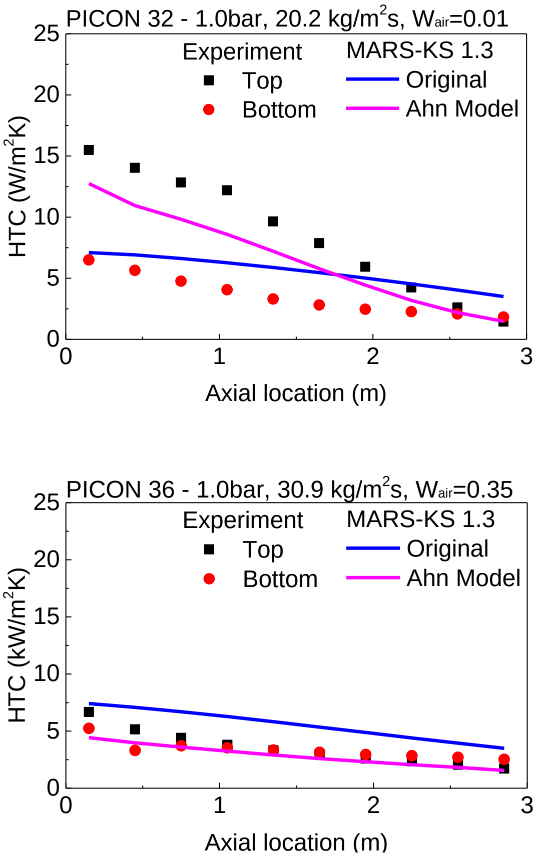

Fig. 4 Calculation result of PICON for steam/air mixture

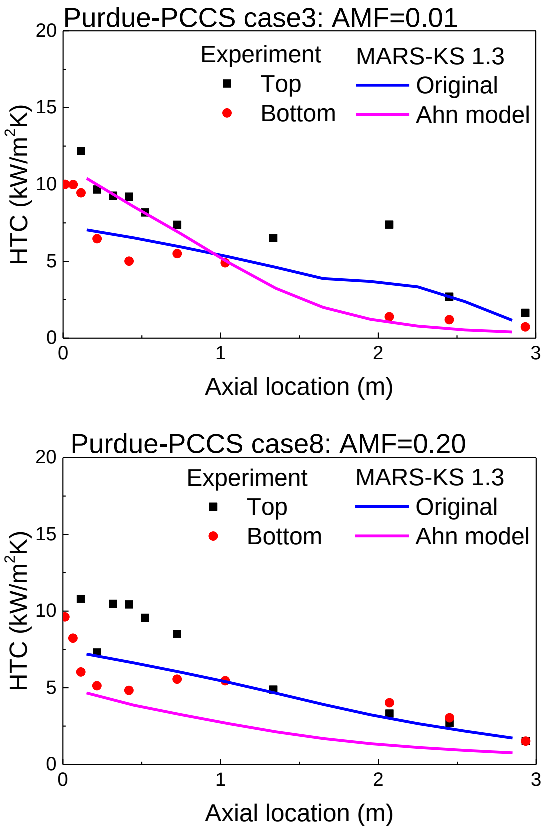

Fig. 5 Calculation result of Purdue-PCCS for steam/air mixture

Fig. 6 shows the comparison of the measured and the calculated HTCs by the Ahn model and the original MARS model. For the comparison, experimental data are needed for the top side and the bottom side of the tube. However, some data of the Purdue-PCCS tests have only top-side data or bottom-side data. Thus, only the PICON data are used for the comparison. As shown in Fig. 6, the Ahn model predicts condensation heat transfer coefficient in a horizontal tube better than the condensation model of MARS.

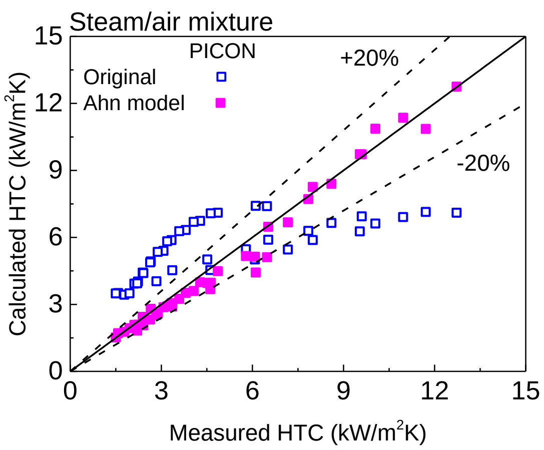

Fig. 6 Comparison of measured and calculated HTC (Steam/air mixture)

4. Conclusions

In this work, the Ahn's condensation heat transfer model, which has been developed to take into account the effect of NCGs on condensation in a nearly horizontal tube, was implemented to MARS-KS 1.3 with some additional assumptions and, then, the code was assessed using the experimental data of PASCAL, Purdue-PCCS, and PICON facilities.

The result of the assessment shows that the Ahn's model predicts condensation heat transfer in a slightly inclined tube better than the original MARS model. However, because the experimental data for assessment are limited to very low pressure conditions, a more systematic assessment is needed so that a wide range of thermal-hydraulic conditions can be covered.

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