Assessment and Improvement of the Horizontal In-Tube Condensation Model of the MARS-KS 1.3

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1. Introduction

In-tube condensation heat transfer model for a horizontal tube is very important for the safety analysis of nuclear power plant because the phenomenon has been adopted in many safety-related systems. To improve the condensation heat transfer model, many researches have been conducted. Ahn et al. suggested a new condensation heat transfer model for horizontal or slightly inclined tubes [1].

In this work, we firstly implemented the Ahn's condensation heat transfer model into the MARS-KS1.3 code and assessed it using the PASCAL experimental data. Based on the results of the assessment, we identified the limitations of the Ahn`s model and suggested a modified Ahn`s model. Finally, the modified model was evaluated using various experimental data, which cover the pressure ranging from 0.1 MPa to 7.81 MPa and the mass flow rates ranging from 0.09 kg/s to 1.01 kg/s.

2. Assessment of the Ahn condensation model

Ahn et al. proposed a new in-tube condensation heat transfer correlation for horizontal or slightly inclined tubes, of which flow regime is horizontally stratified. They assumed the film condensation of saturated steam at the upper part of the tube and convective heat transfer of the condensate water at the bottom of the tube[1].

For the film condensation, Dhir and Lienhard(1971) changed the coefficient of the original Nusselt model[2] into 0.729 to consider the film condensation at the outer wall of a horizontal cylinder. But this model can't take into account the turbulent flow well because it was developed in the laminar flow. Ahn et al. added the Reynolds number of steam into the correlation to consider the shear effect of phase boundary layer by vapor flow as follow:

$$h_{film} = 0.729(1+8.7\times10^{-4}\,\mathrm{Re}_g^{0.57})\times\left(\frac{g\rho_l(\rho_l-\rho_g)h_{fg}k_l^3}{\mu_l D(T_{sat}-T_w)}\right)^{1/4} \quad (1)$$

Then, Ahn et al. assumed that the heat transfer at the bottom side has same principle with single-phase convective heat transfer and used the Dittus and Boelter correlation[3].

$$h_{convective} = 0.023\,\mathrm{Re}_l^{0.8}\,\mathrm{Pr}^{0.4}\left(\frac{k_l}{D_{hl}}\right) \quad (2)$$

Then, the mean heat transfer coefficient is defined in the way of weighted average with wetted angle[1].

$$h = \frac{h_{film}(2\pi-\gamma_1)+h_{convective}\gamma_1}{2\pi}, \quad (3)$$

where $\gamma_1 = 2\pi$ for annular flow,
$\gamma_1 = 2\pi(0.52(1-\alpha)^{0.374}+0.26Fr^{0.58})$ for stratified wavy flow,
$\gamma_1 = \gamma_s$ for stratified flow.

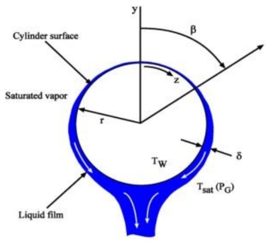

Fig. 1 Film condensation modeling at the outer wall of horizontal cylinder[1]

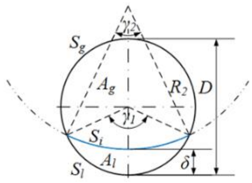

Fig. 2 Condensation at the inner wall of horizontal cylinder[1]

Six quasi-steady state cases of PASCAL test[4] are selected to assess the Ahn model. Boundary conditions of selected cases are in Table 1[4]. The MARS calculations are carried out twice using the original and the modified MARS codes. Fig. 3 shows the comparison of the calculated heat fluxes and experimental data. It is clear that the Ahn model predicts more accurately than the default model of MARS-KS 1.3. However, Ahn model still under-predicts the heat flux under high-pressure conditions. Thus, the improvement of the Ahn model is needed for a wide range of applications. It is noted that, when the Ahn model calculates the condensation heat transfer coefficient, it doesn't use the void fraction predicted by the MARS code but the value calculated by its own model [1]. Also, as shown in Fig. 4, abrupt increase or decrease occurred in the calculations using the Ahn model.

Table 1 Boundary conditions of the PASCAL quasi-steady state[4]

	SS-200-P1	SS-300-P1	SS-400-P1	SS-540-P1	SS-650-P1	SS-750-P1
Heat Power (kW)	199.8	299.8	399.9	540.0	650.1	750.2
PCCT Water Level (m)	9.3	9.3	9.3	9.3	9.3	9.3
Inlet Pressure (MPa)	0.845	1.342	1.971	3.220	4.698	6.736
Inlet Temperature (℃)	175.2	194.6	213.0	239.1	261.3	284.4
Inlet Flowrate (kg/s)	0.094	0.147	0.204	0.295	0.365	0.430

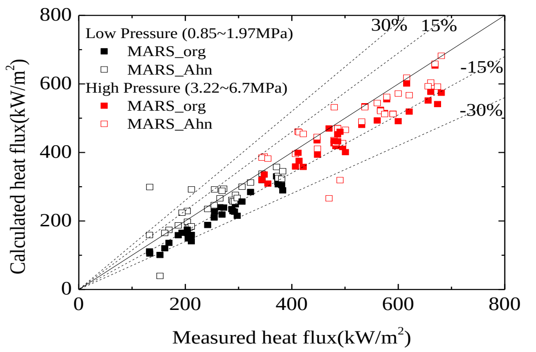

Fig. 3 Comparison of heat flux with PASCAL in same location (Ahn model)

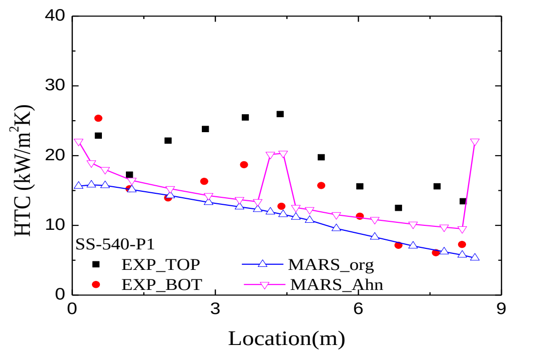

Fig. 4 Discontinuity in HTC calculation result

3. Modification of the Ahn condensation model

To overcome some drawbacks of the Ahn model, we modified it; First, we adopted the void fraction predicted by the MARS code to calculate the condensation heat transfer model and this leads to a new fitting of the coefficient and exponent in Eq. (1), resulting in

$$h_{film} = 0.7734(1+3.72\times10^{-3}\,\mathrm{Re}_g^{\,0.4538})\times\left(\frac{g\rho_l(\rho_l-\rho_g)h_{fg}k_l^3}{\mu_l D(T_{sat}-T_w)}\right)^{1/4} \qquad (4)$$

Second, the Dittus-Boelter correlation [3] for the convective condensation at the bottom of the tube was very sensitive with void fraction range of 0.9 to 1.0. It leads to abrupt increase or decrease as mentioned earlier. Thus, it was replaced with the Shah correlation[5] which has no dependence of the void fraction.

$$h_{convective} = 0.023\,\mathrm{Re}_{ls}^{0.8}\,\mathrm{Pr}_l^{0.4}\times\left[1+\frac{3.8}{\mathrm{Pr}_{red}^{0.38}}\left(\frac{x}{1-x}\right)^{0.76}\right]\left(\frac{k_l}{D}\right) \qquad (5)$$

4. Assessment of the modified Ahn model

The assessment of the modified Ahn model was carried out using the various experimental data. Experiments are selected considering a wide range of pressure and mass flow rate and noncondensable gas effects. Condensate tubes of test facilities are horizontal or slightly inclined between 0°~3.2°. Detailed experiment conditions are summarized in Table 2.

Table 2 Horizontal in-tube steam condensation experiments

	PASCAL [4]	ATLAS -PAFS [6]	KAIST -SCOP [7]	JAEA -PCCS [8]	Purdue -PCCS [9]
Length [m]	8.4	4.77	8.4	9	3
Inner Diameter [mm]	44.8	30.8	44.8	29	27.5
Inclined angle [°]	3	3	3	0	0
Air Mass Fraction [%]	0	0	0	1	1, 20
Steam mass flow rate [kg/s]	0.09-0.43	0.4277	0.15-0.18	0.048	0.006-0.035
Pressure [MPa]	0.8-6.7	7.81	1.2-1.88	0.7	0.1-0.4

PASCAL tests are simulated two ways according to presence or absence of steam generator modeling. Fig. 5 shows the comparison result of heat flux between PASCAL[4] experimental data and calculation results of the default MARS-KS1.3 and the modified Ahn model without steam generator modeling. It seems that the modified Ahn model shows a good agreement with experimental data in all pressure conditions unlike the original Ahn model.

In Fig. 6, when the PASCAL test facilities are simulated with steam generator, the modified Ahn model predicts the experiment well from low pressure conditions to high pressure conditions while the original Ahn model only predicts the experiment well at low pressure conditions only.

As presented in Fig. 7, the modified Ahn model calculates more accurately than the default model in the KAIST-SCOP[7] simulations.

JAEA-PCCS test[8] and Purdue-PCCS test[9] were conducted with noncondensable gas. As shown in Fig. 8, the modified Ahn model predict the heat flux of JAEA-PCCS test[8] better than condensate heat transfer model of MARS-KS 1.3. Fig. 9 and 10 compare the heat fluxes of the Purdue-PCCS experimental data[9] and calculated results. In Table 3, mean errors and deviation errors are calculated to compare the difference more accurate between the modified Ahn model and condensate heat transfer model of MARS-KS 1.3. In the case of 1% AMF, the modified Ahn model predicts the heat transfer better than the default model of MARS-KS 1.3 as shown in Fig. 9 and mean error has a marginal improvement but deviation error is improved significantly as shown in Table 3(a). But in the case of 20% AMF, there is no noticeable difference between the modified Ahn model and condensate heat transfer model of MARS-KS 1.3. Mean errors and deviation errors are also similar as shown in Table 3(b).

5. Conclusions

In this study, the modified Ahn model has been suggested and it was implemented into MARS-KS 1.3. The results of the assessment using various experimental data show that the modified Ahn model predicts well the condensation heat transfer occurred in horizontal or nearly horizontal condition. But there is no noticeable difference under the presence of high noncondensable gas levels. Further improvement is needed for this.

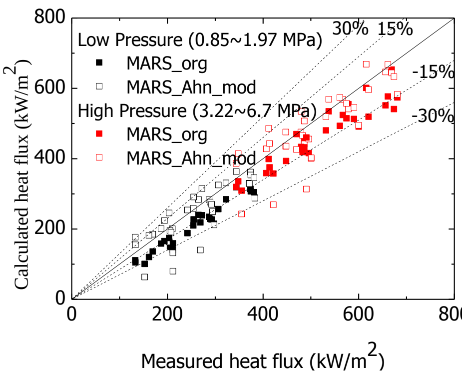

Fig. 5 Comparison of heat flux with PASCAL in same location (modified Ahn model)

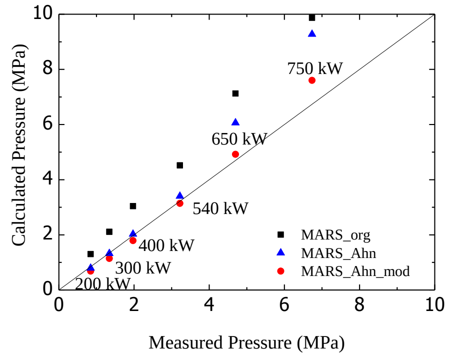

Fig. 6 Comparison of steam generator pressure in PASCAL

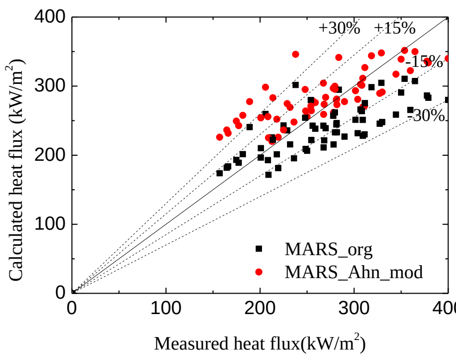

Fig. 7 Comparison of heat flux with KAIST-SCOP in same location

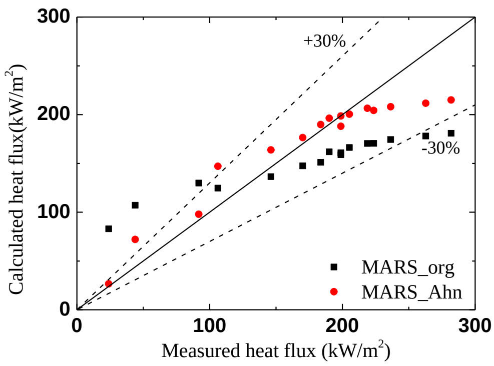

Fig. 8 Comparison of heat flux with JAEA-PCCS in same location

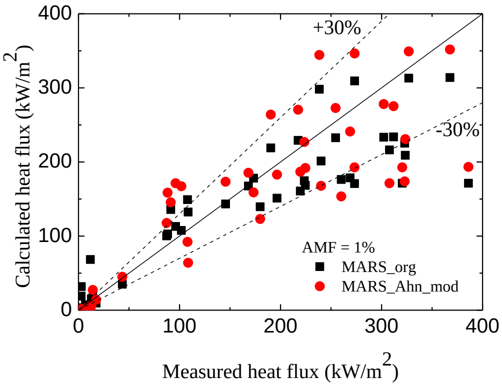

Fig. 9 Comparison of heat flux with Purdue-PCCS in same location (AMF=1%)

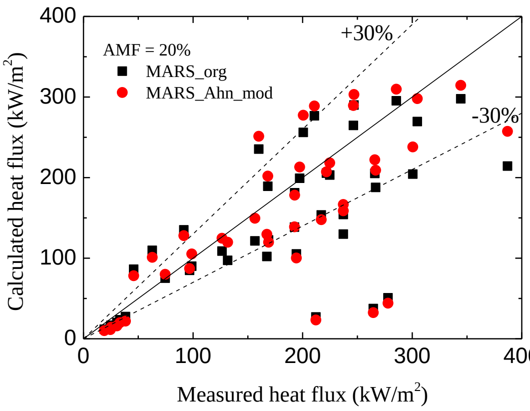

Fig. 10 Comparison of heat flux with Purdue-PCCS in same location (AMF=20%)

Table 3 Mean error(ϵ_{avg}) and deviation error($\epsilon_{ABS-avg}$) of two models

(a) AMF = 1%

	MARS_org	MARS_Ahn_mod
mean error	0.359957	0.336061
deviation error	0.818529	0.422514

(b) AMF = 20%

	MARS_org	MARS_Ahn_mod
mean error	0.316210	0.309050
deviation error	0.392253	0.388585

$$\epsilon_{avg} = \frac{1}{n}\sum_1^n \left[\frac{(h_{pre}-h_{exp})}{h_{exp}}\right] \times 100 \qquad (6)$$

$$\epsilon_{ABS-avg} = \frac{1}{n}\sum_1^n \left[\frac{|h_{pre}-h_{exp}|}{h_{exp}}\right] \times 100 \qquad (7)$$

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