Assessment of condensation models in the presence of noncondensable gases with vertical rectangular duct and in-tube tests using MARS and TRACE

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1. Introduction

As the importance of applying the passive safety features which are available even in the absence of electricity supply increases, advanced nuclear reactor adopted the systems such as Passive Containment Cooling System (PCCS) and Passive Auxiliary Feedwater System (PAFS). The accurate prediction of condensation heat transfer on these system has been emphasized to assure the safety of nuclear reactor. Especially in the PCCS, the condensation occurs in the presence of noncondensable gases that concentrate on the condensing surface and the gases reduce the steam partial pressure and degrades heat transfer rate. In order to predict the condensation rate under this condition, MARS which backbone is RELAP5/MOD3 uses Colburn-Hougen iteration method [1]. Recently, Lee and Cho [2] found that an error was included in the condensation mass flux model of MARS as well as RELAP5/MOD3, and the model was corrected from its source code. Then, it is required to assess the prediction capability of the corrected model in the code with the existing experimental results and prediction results from another code.

In this study, six condensation experiments which described the condensation on the inner wall of the channel in the presence of noncondensable gases were simulated using MARS and TRACE. Then, the predicted heat flux and heat transfer coefficient from both codes were compared with the experimental results for evaluating the condensation models.

2. Condensation models in codes

2.1 Colburn-Hougen model in MARS

When noncondensable gases are present, MARS uses the Colburn-Hougen iteration method to solve the interface temperature between the steam and liquid. This approach is based on the energy conservation principle that the latent heat transfer on the liquid film surface is equal to the heat flow through the liquid film. Then, the determined temperature is used to calculate the condensation heat flux as:

$$q'' = h_c(T_{vi} - T_w) = h_m h_{fg} \frac{\rho_{vb}}{x_{vb}} \, ln\left(\frac{1-\frac{P_{vi}}{P}}{1-\frac{P_{vb}}{P}}\right) \qquad (1)$$

where, h_c is condensation heat transfer coefficient, h_m is mass transfer coefficient, and x_{vb} is steam mole fraction in the bulk. T_{vi} and T_w are saturation temperature corresponding to the interface vapor pressure and wall temperature respectively.

2.2 Kuhn model in TRACE

TRACE adopted the Kuhn model [3] which is similar to the classical model of Colburn-Hougen in the presence of noncondensable gases, and the condensation heat flux is expressed as follows:

$$q'' = h_{li}(T_{vi} - T_l) = h_m h_{fg} \frac{\rho_{vb}}{X_{vb}} \, ln\left(\frac{1-X_{vi}}{1-X_{vb}}\right) + q''_{sens} \qquad (2)$$

where, h_{li} is interfacial heat transfer coefficient and X_{vb} is steam mass fraction in the bulk.

Compared to the Colburn-Hougen model, the Kuhn model uses mass fraction instead of mole fraction, and considers sensible heat transfer from the gas mixture to the interface. However, the sensible heat is relatively small compared to the condensation heat, this difference can be negligible.

3. Calculation results

MARS and TRACE simulated total six experiments (COPAIN [4], UW [5], CONAN [6], Siddique [7], Park [8], Kuhn [9]). Three among them (COPAIN, Univ. of Wisconsin, CONAN) were conducted with the square duct channel and the other (Siddique, Park, Kuhn) were conducted with the pipes. Each of these features and test conditions are shown in Table 1 and Table 2.

Table 1: Features of duct channel tests

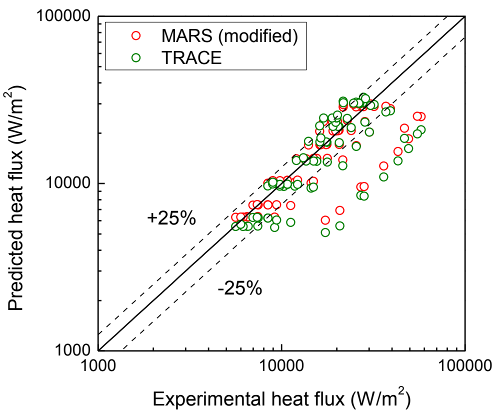
	COPAIN	Univ. of Wisconsin (UW)	CONAN
	CEA	UW	UP
Length (m)	2.0	1.07	2.0
Duct geometry (mm)	600×500	152.4×152.4	340×340
NC gas type	Air helium	Air	Air
Steam flow (m/s)	0.1~3.0	1.0 ~ 3.0	1.5 ~ 3.5
Inlet NC mass fraction (%)	0 ~ 100	0 ~ 80	0 ~ 75
Pressure (MPa)	0.1 ~ 0.7	0.1	0.1

Table 2: Features of intube condensation tests

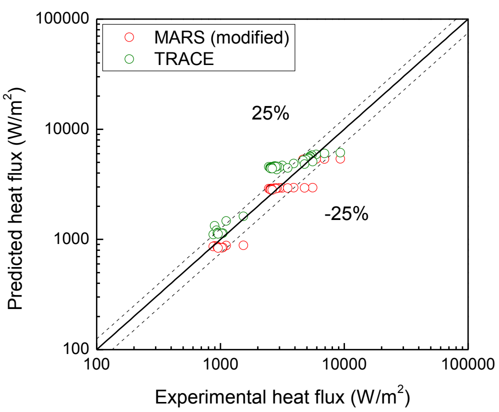
	Siddique (1993)	Park (1999)	Kuhn (1997)
	MIT	KAIST	UCB
Length (m)	2.54	2.4	2.4
Tube ID (mm)	46	47.5	47.5
NC gas type	Air helium	Air	Air helium
Steam flow (kg/s)	2.4 ~ 8.9	2 ~ 11	8.2 ~ 17
Inlet NC mass fraction (%)	10 ~ 35	10 ~ 70	0 ~ 40
Pressure (MPa)	0.1 ~ 0.5	0.17 ~ 0.5	0.1 ~ 0.5

3.1 Comparison results in rectangular duct channel tests

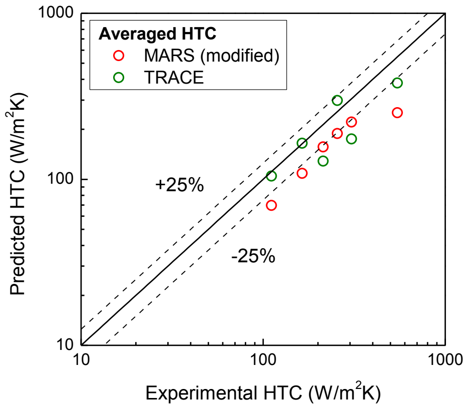
The predicted heat flux and local wall heat transfer coefficient obtained from duct channel tests are compared to the experimental results in Fig. 1. Most of the predicted data lie within the error band of 25%. In UW test, codes tended to underestimate the data because only averaged heat transfer coefficient along the channel which reflects entrance effect was provided. One thing to be noted is that the calculated results with TRACE are higher than that with MARS in certain cases of COPAIN and UW test where the heat transfer regimes are estimated to be natural convection. This discrepancy between the results of two codes was found to come from using different mass transfer coefficient in natural convection by quantitative analysis.



(a) CONAN



(b) COPAIN

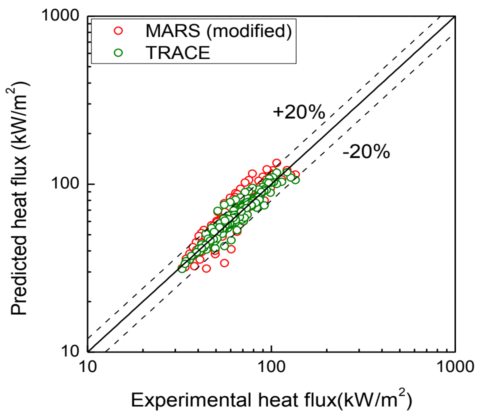


(c) UW

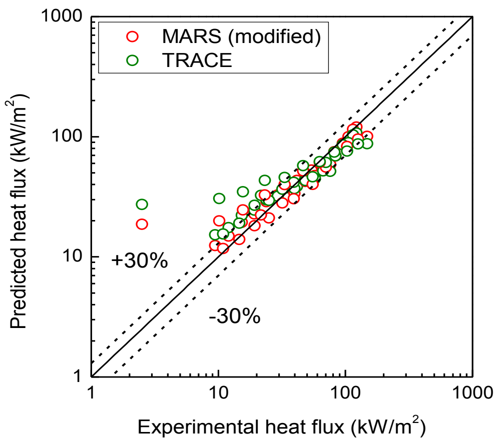
Fig. 1. Comparison results in duct channel tests

3.2 Comparison results in pipe tests

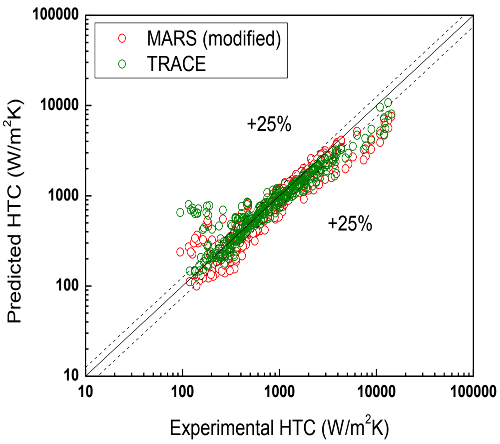
The comparison results in pipe tests are shown in Fig. 2. The predicted heat flux shows fairly good agreement with the experimental results in Park and Kuhn tests. However, in Siddique test, both codes tend to under-predict the heat transfer coefficient especially in large heat transfer coefficient region.



(a) Kuhn



(b) Park



(c) Siddique

Fig. 2. Comparison results in pipe tests

4. Conclusion

In this study, the bug-fixed condensation model in MARS was assessed with six experiments. In order to compare the prediction ability of the model, TRACE which uses similar model with MARS was utilized. As a result, in most cases, the predicted data lie within the error band of 25% and comparable results between MARS and TRACE were obtained. However, in natural convection, the discrepancy between two codes was observed due to using different mass transfer coefficient, and it is required to investigate better model for enhancement of code prediction.

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