Modification of the Condensation Heat Transfer Model of the MELCOR Code under the Thermal-Hydraulic Conditions of a PWR Containment

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1. Introduction

The condensation heat transfer model is very important for the accident analysis of nuclear power plants, because it is closely related to the prediction of the pressure behavior of the containment. At normal operation, the containment is filled with air at atmospheric pressure. During an accident such as a loss-of-coolant accident and a steam-line-break accident, steam is released to the containment, and nitrogen or hydrogen may be added. The noncondensable gases (NCGs) have a negative impact on condensation heat transfer in the containment. Therefore, the condensation heat transfer model has been developed so that it can consider the influence of NCGs.

The MELCOR code has been developed for the analysis of severe accident in light water reactors. It employs the stagnant film model (SFM) to calculate the steam condensation under the presence of NCGs. Several researchers [1-3] have conducted evaluation and improvement of the MELCOR condensation model, but most of these focused on limited thermal-hydraulic conditions for a boiling water reactor. This study deals with the assessment and improvement of the condensation heat transfer model of MELCOR code under thermal-hydraulic conditions in a pressurized water reactor (PWR) containment during accidents.

2. Condensation heat transfer models

The SFM of the MELCOR code is derived from Fick's law of diffusion theory [4]. This model calculates the heat and mass transfer in a direction perpendicular to the wall assuming that the diffusion layer formed by the accumulation of NCGs and the film formed by steam condensation are in a stationary state. This concept is illustrated in Fig. 1. It is known that the MELCOR model generally under-predicts the condensation heat transfer [1-3]. In this regard, three additional condensation heat transfer models among the well-known existing models were evaluated to find a candidate for the MELCOR model improvement. The Uchida model [5] is a purely empirical model, which is frequently adopted in conservative system codes. The Liao model [6] is one of the most advanced theoretical models, and the Dehbi model [7] is a semi-theoretical model, which has been developed recently for the containment thermal-hydraulics of an advanced PWR. Table 1 shows the four models.

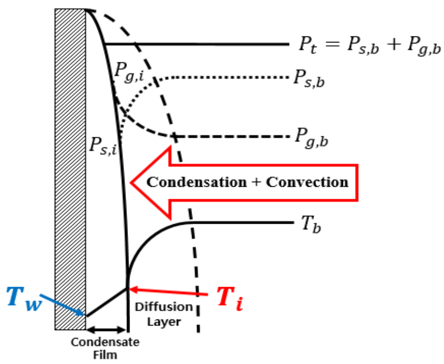

Fig. 1. Concept of the steam condensation under the presence of NCGs

3. Selected experiments for model evaluation

The thermal-hydraulic conditions in the containment during accidents include a pressure range of 1.0-5.0 bar, a wide range of NCG mass fraction, and gas-phase flow from forced to natural convection. Condensation in a PWR containment occurs mainly in the wall (vertical plate) and, for an advanced reactor, heat exchanger of passive containment cooling system (vertical pipe). Considering these conditions, six condensation experiments were selected for the model assessment. These are listed in Table 2. The first four experiments [8-11] use a vertical plate and the last two [12, 13] use the outer surface of a vertical pipe as a condensing surface. In these experiments, air is used as NCG.

Table 1. Correlations of the selected experiments

Models	Type	Correlation
MELCOR	Theoretical	$h_f(T_i - T_w) = h_{fg}h_m\rho_v ln\left(\frac{P_t - P_{s,i}}{P_t - P_{s,b}}\right) + h_{conv}(T_b - T_i)$
Uchida	Empirical	$h = 380\left(\frac{W_s}{1 - W_s}\right)^{0.7}$
Liao	Theoretical	$h_f(T_i - T_w) = h_{cond}(T_b^{sat} - T_i) + h_{conv}(T_b - T_i)$
Dehbi	Semi-theoretical	$h = 0.185D^{2/3}(\rho_w + \rho_b)\left(\frac{\rho_w - \rho_b}{\mu}\right)^{1/3}\frac{h_{fg}}{(T_b - T_w)}ln\left(\frac{1 - W_{s,w}}{1 - W_{s,b}}\right)$

Table 2. Matrix of the selected experiments

Experiment (geometry)	Air mass fraction	Pressure (bar)	Wall subcooling (K)	Steam superheating (K)	Flow condition	Number of data sets
COPAIN (plate)	0.49-0.87	1.0-4.0	14-45	10	Natural – Forced	6
CONAN (plate)	0.13-0.72	1.0	40-45	0	Mixed	10
Park (plate)	0.20-0.70	1.0	20-50		Natural – Forced	16
Anderson (plate)	0.40-0.86	1.0-3.0	10-60		Natural	32
Dehbi (pipe)	0.25-0.87	1.5-4.5	10-50		Natural	42
Kang (pipe)	0.10-0.70	1.0-4.0	10-50		Natural	52

4. Assessment and improvement

This section deals with the assessment results of the condensation heat transfer models. Based on the results, a base model is selected for improvement of the model is carried out.

4.1. Assessment results

Figures 2 through 5 show the results of calculations for the four models. Because the COPAIN and CONAN experiments provide wall heat fluxes and the others provide heat transfer coefficients, two figures are presented for each model

To calculate the accuracy, the standard deviation (SD) and the mean absolute error (MAE) are calculated as shown in the following equation.

$$MAE = \frac{\sum_i^n |C_i - M_i|}{n}, \quad (1)$$

$$SD[\%] = \sqrt{\frac{\sum_i^n \left(\frac{C_i - M_i}{M_i}\right)^2}{n-1}}, \quad (2)$$

where C_i and M_i are the calculated and the experimental data. n is the number of data.

To get the precision of the results, a linear fitting of the calculated values versus experimental data is obtained using a least-square approach:

$$C_i = aM_i + b,$$

where coefficient a and b are slope and intercept of the linear function. These are found, which minimize

$$f(a,b) = \sum_{i=1}^n (aM_i + b - C_i)^2.$$

The deviation from the fitted line (DFL), that is, the precision is given by

$$DFL = \frac{1}{n}\sqrt{\sum_i^n (aM_i + b - C_i)^2}. \quad (3)$$

The accuracy and precision of each model obtained from Eqs. (1)-(3) are listed in Table 3.

The results in Figs. 2~5 and Table 3 can be summarized as follows. The Uchida model was not suitable as an alternative model because both accuracy and precision were not good. The Liao model was more accurate than the other models. However, the standard deviation is about 35%, which is still a big error, and in terms of precision, it is worse than the MELCOR model. The Dehbi model showed good results for experiments within certain application range. However, it was less accurate for some experiments, such as COPAIN, CONAN and Park tests. The results of the MELCOR model are less accurate than those of the Uchida and Dehbi models, but much more precise than those of the Liao model. Also, the difference of the slopes between two linear fittings for heat flux and heat transfer coefficient was the smallest among the four models. This indicates the MELCOR model yielded relatively consistent results compared to other models. In conclusion, there was no superior model to replace the MELCOR model. Therefore, we decided to improvement the MELCOR condensation model itself.

4.2. Improvement of the MELCOR model

The results of the MELCOR model show three problems. First, the prediction error for the vertical pipe tests is relatively larger than that of the vertical plate tests. Second, the MELCOR model consistently under-predicts most of the experimental data by about 40 %. Third, the MELCOR model greatly over-predicts the heat flux of the COPAIN experiment, which is a superheated steam test.

In general, a curved surface has a larger solid angle than a flat surface and it is known that heat and mass transfer is more effective at the curved surface. To reflect the curvature effect, the correlation proposed by Popiel [14] is inserted into the MELCOR model.

$$Nu_{pipe} = Nu_{plate} \times \left(1 + 0.3\left(\sqrt{32}Gr^{-1/4}\frac{L}{d}\right)\right)^{0.909}, \quad (4)$$

where L and d are the length and diameter of the pipe.

Next, to improve the biased results, we introduce a correction factor, 1.71, derived through the best-fit method. It is multiplied by the Nusselt number.

$$Nu_{new} = 1.71 \times Nu_{original}. \quad (5)$$

The correction factor is assumed to include various heat transfer enhancement effects, such as suction, film waviness, and fog formation.

For the condensation of superheated steam, the vapor should be cooled down to a saturation point. It means that more energy and time are required for superheated steam than saturated steam. This causes condensation heat transfer to be reduced.

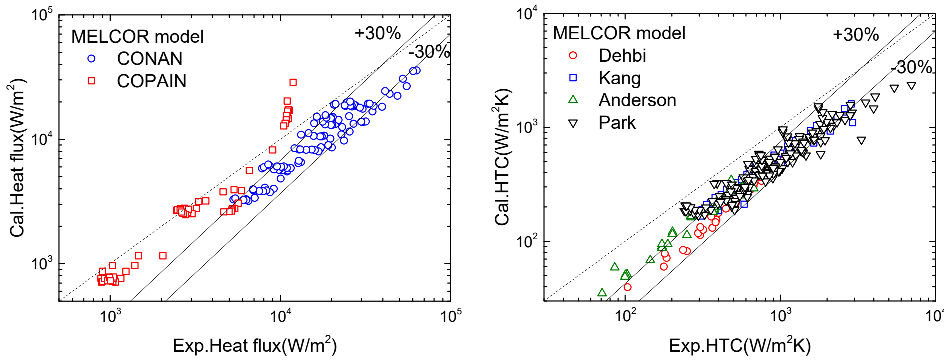

Fig. 2. Assessment results of the MELCOR model

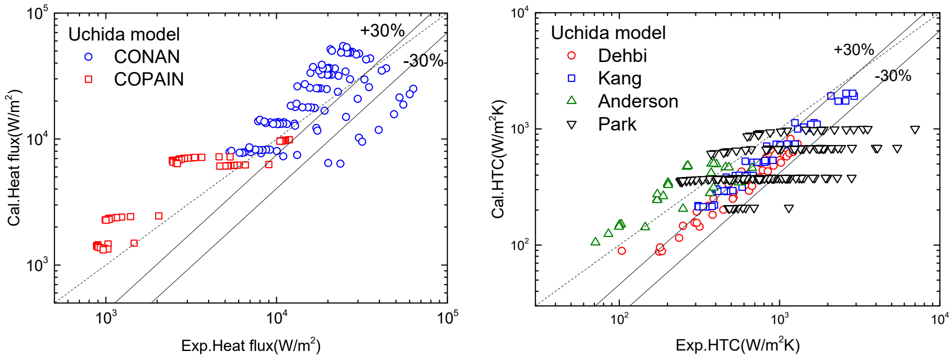

Fig. 3. Assessment results of the Uchida model

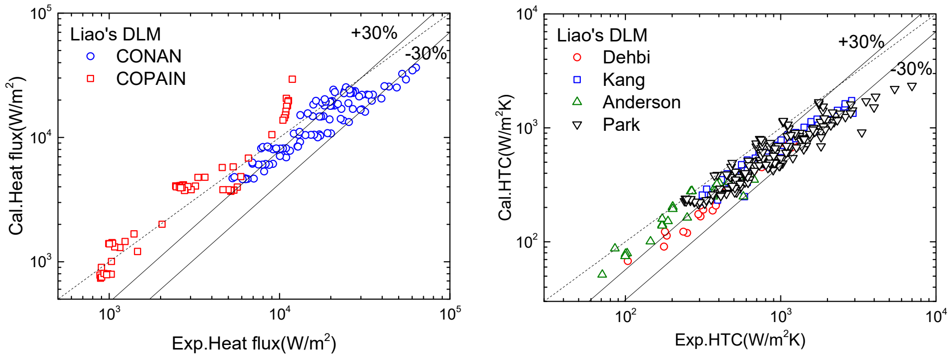

Fig. 4. Assessment results of the Liao model

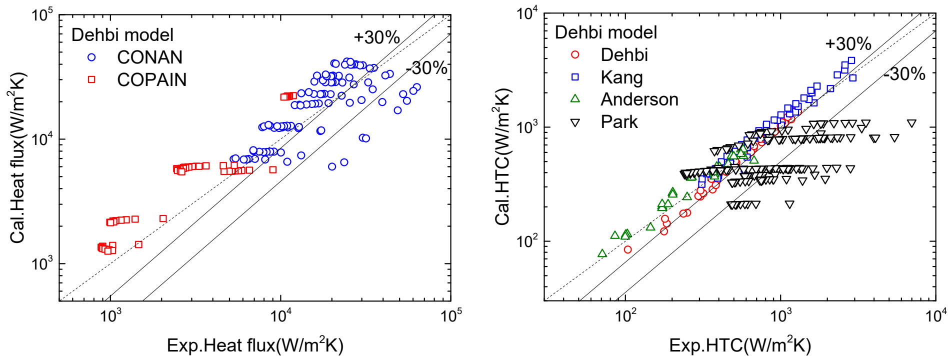

Fig. 5. Assessment results of the Dehbi model

To consider the superheated steam effect, a degradation factor is derived by using the COPAIN experimental data:

$$f\left(\Delta T_{sup}\right) = \frac{1}{1+0.0032\Delta T_{sup}{}^{2.4214}}. \qquad (6)$$

Eq. (6) is multiplied to the Sherwood number correlation used to determine the mass transfer coefficient.

Eqs. (4)-(6) were implemented into the MELCOR model and, then, we assessed the modified model. The results are shown in Figs. 5 and 6. The standard deviation was 19.2 % for HTC and 26.4 % for heat flux. The mean absolute error was 173.55 for HTC and 2469.74 for heat flux, which were much smaller than other models in Table 3.

Table 3. Accuracy and precision of each model

Model		Mean absolute error	Standard deviation	Linear fitting		Deviation from the fitted line
				Slope, a	Intercept, b	
MELCOR	HTC	454.27	47.9	0.43	80.21	7.61
	Heat flux	5544.2	39.2	0.54	1615.8	265.7
Uchida	HTC	471.36	47.2	0.23	285.17	14.40
	Heat flux	7572.4	71.7	0.76	6139.0	877.1
Liao	HTC	340.46	33.9	0.47	163.07	10.12
	Heat flux	4042.3	35.3	0.62	2957.8	319.9
Dehbi	HTC	392.23	39.6	0.33	350.15	25.46
	Heat flux	6404.1	63.3	0.69	6510.3	681.4

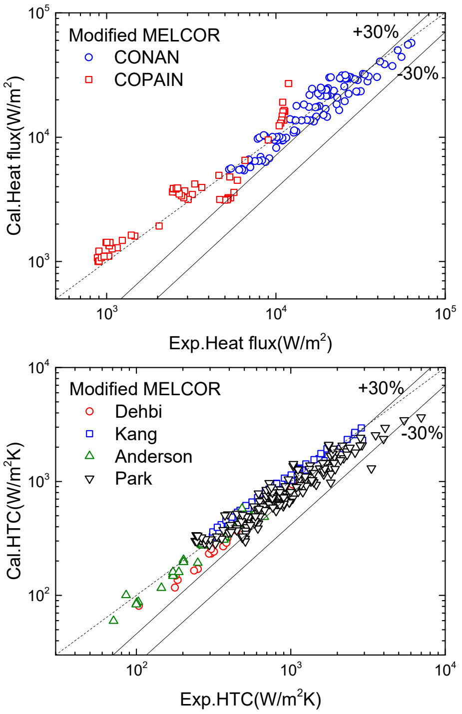

Fig. 6. Assessment of the improved MELCOR model

5. Conclusions

In this study, the condensation heat transfer model of MELCOR code and the existing condensation heat transfer models (Uchida, Liao, Dehbi) were assessed. The evaluation range was limited to the thermal-hydraulic conditions of the PWR containment during accidents. For model assessment, six condensation experiments were selected. From the results of assessment, the condensation heat transfer model in MELCOR code was selected as a basis for improvement. Three factors for the curvature effect, superheated steam effect, and overall correction were implemented. The modified model predicted most of the experimental data within ±30 % error.

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