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Implementation of New Condensation Model into the CAP Code

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1. Introduction

Steam condensation plays a key role in removing heat released to the containment building caused by Steam Generator Tube Rupture (SGTR) or Loss Of Coolant Accident (LOCA). In many containment analysis codes, containment condensation was mainly calculated by applying the Uchida [1] and Tagami [2] condensation model. However, both models were developed through small-scale experiments, and only the mass fraction of non-condensable gas was modeled as a parameter.

In this study, to analyze the condensation heat transfer more realistically, the Heat and Mass Transfer Analogy (HMTA) based condensation model was added into the CAP code. In addition, CONAN [3] and COPAIN [4] vertical plate condensation experiments were analyzed to assess the new condensation model of CAP.

2. HMTA Condensation Model

Figure 1 shows the concept of the condensation in the presence of non-condensable gases. The total pressure is maintained, but the steam pressure decreases as it approaches the condensing surface. The steam pressure difference between the bulk and interface becomes the driving force that moves the steam particles to the condensing surface by diffusion. The condensate flux calculated based on this mechanism is as follows [5]:

$$\Gamma'' = -\frac{M_s Sh D_{sg}\bar{c}}{l_{char}} ln(\frac{P_{tot}-P_{stm,i}}{P_{tot}-P_{stm,b}}). \quad (1)$$

The variables used in the above equation are as follows:

- Γ_D'': condensate flux,
- M_s: molecular weight of steam,
- Sh: Sherwood Number,
- D_{sg}: steam-gas mixture diffusion coefficient,
- $\bar{c}$: average mole density in the diffusion layer,
- l_{char}: characteristic length.

Among the above variables, Sh is calculated based on HMTA, as follows:

$$Sh_{nc} = f(Gr, Sc) \quad (2)$$
$$Sh_{fc} = f(Re, Sc) \quad (3)$$
$$Sh = \left(Sh_{nc}^3 + Sh_{fc}^3\right)^{1/3} \quad (4)$$

In the above equations, the subscripts nc and fc mean natural convection and forced convection, respectively.

Condensation heat flux and convection heat flux are as follows:

$$q''_{cond} = \Gamma'' h_{fg} \quad (5)$$
$$q''_{conv} = h_{conv}(T_b - T_i) \quad (6)$$

The temperature T_i at the interface is calculated as follows, through the heat balance between the condensate film and the atmosphere.

$$T_i = T_w + h_{film}(q''_{cond} + q''_{conv}) \quad (7)$$

where,

$$h_{film} = \frac{k_l}{\delta_{film}}, \quad (8)$$
$$Re_{film} = \frac{4\Gamma'' H}{\mu_l}, \quad (9)$$

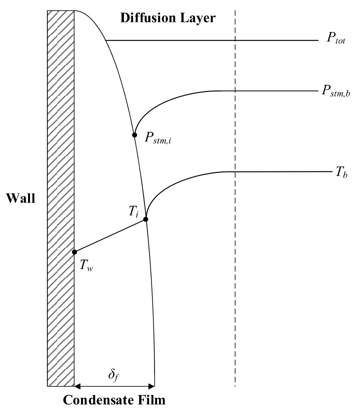

Fig. 1. Concept of the condensation under the presence of NCGs

3. Model implementation

The above condensation model based on HMTA was added into the CAP code.

McAdams [6] model was used to calculate Sh for natural convection, and Dittus-Boelter [6] model was used to calculate Sh for forced convection. The binary mixture diffusion coefficient (D_{sg}) was calculated by Fuller's model [7]. The physical properties of the steam-gas mixture were calculated at the bulk temperature (T_b).

4. Assessment results

The new condensation model and existing model (Uchida) of the CAP code were evaluated using CONAN and COPAIN experiments. Both experiments were modeled as a constant wall temperature using the measured wall temperature in the experiment. Table I summarizes the experimental conditions used for evaluation. The CONAN experiment used for evaluation was performed under forced convection conditions, and COPAIN was performed under both natural and forced convection.

Table I: The test conditions

Exp.	RH [%]	Pressure [bar]	Inlet velocity [m/s]	Number of data
CONAN	100	1.0	2.48 ~ 2.63	80
COPAIN	100	1.0	0.3 ~ 3.0	40

Figure 2 shows the comparison of experimental data and CAP analysis results. The new condensation model predicts the experimental data with an error of within ±30% overall, however the Uchida model over-predicts the heat flux compared to the experimental data.

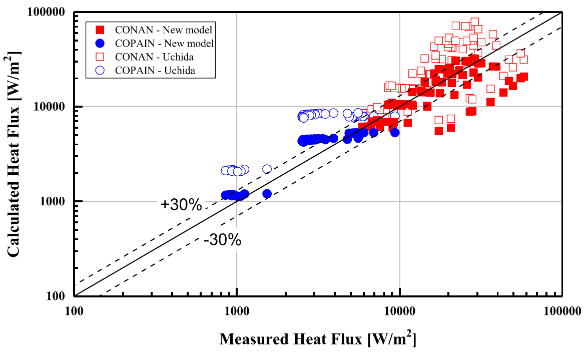

Fig. 2. CAP calculation results

Figures 3 and 4 show the comparison results between CAP calculation results and experimental data along the axial distance from the inlet. In case of CONAN experiment, the new model under-predicts the heat flux in the entrance region, however closely predicts in the fully developed region (Figure 3). On the other hand, in case of COPAIN experiment which is performed in free convection, the new model over-predicts in the fully developed region (Figure 4).

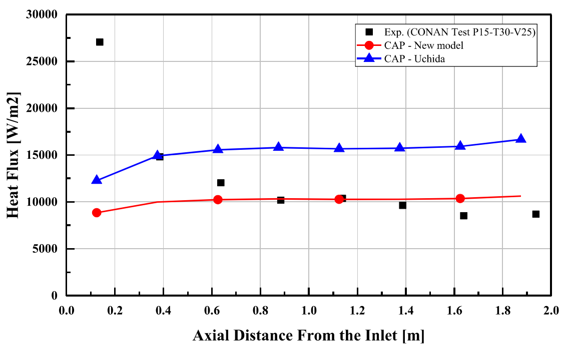

Fig. 3. CONAN test P15-T30-V25 calculation results

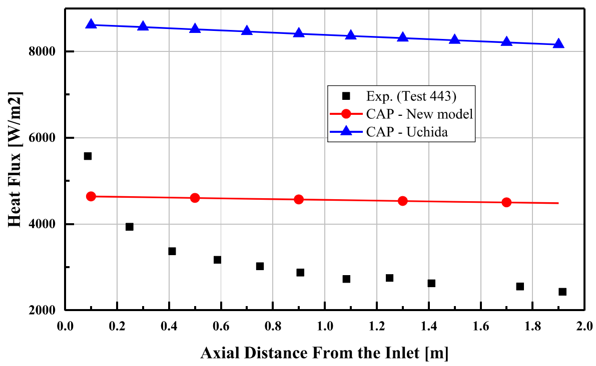

Fig. 4. COPAIN test 443 results.

5. Summary

In this study, the HMTA(Heat and Mass Transfer Analogy)-based condensation model was added into the CAP code. In order to evaluate the new condensation model, CONAN and COPAIN experiments were selected. In addition, the calculation results were compared with Uchida, the existing condensation model of CAP.

The Uchida model generally over-predicted the experimental data, but the new condensation model overall predicted the experimental data within ±30% error range.

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