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Assessment of wall condensation model in the presence of noncondensable gas for the SPACE code

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1. Introduction

Wall condensation is the process of changing a vapor near a cold wall to a liquid on the wall. A vapor containing noncondensable (NC) gases mostly was used in the cases for many postulated light water reactor accidents. The NC gases reduce the heat transfer and condensation rates even though they are present in the bulk vapor in a small amount. To understand the characteristics of condensation heat transfer in the presence of NC gases, a large number of analytical and experimental studies have performed[1-3]. SPACE code, which have been developed since 2006 as a thermal hydraulic system analysis code, also had a capability of analysis for wall condensation with NC gases. The Colburn-Hougen model[4] has been widely used in thermal hydraulic system codes, like as MARS, TRACE and RELAP5-3D. The SPACE code also employed the same model to predict the influence of NC gases on condensation. However, there are some differences of the derived equations among the system codes.

This study aims to assess the wall condensation model in the presence of NC gases considering the differences in SPACE code. To assess the model, three kinds of experiments are introduced: COPAIN test, University of Wisconsin condensation test, and KAIST reflux condensation test.

2. Methodology and Results

The Colburn-Hougen model can predict the liquid/gas interface temperature based on the principle that the amount of heat transferred by condensing vapor to the liquid/gas interface by diffusing thorough NC gas film is equal to the heat transferred thorough the condensate. Based on this principle, the heat flux, q_v'' and vapor mass flux, j_v toward the liquid/gas interface are represented in Eq (1) & (2), respectively[5].

$$q_v'' = j_v \cdot h_{fg}(P_{vb}) \tag{1}$$

$$j_v = cM_v\tilde{v}_i = cM_v\left(\frac{D}{\delta_g}\ln\left(\frac{x_{gb}}{x_{gi}}\right)\right) \tag{2}$$
$$= \frac{\rho_{vb}}{x_{vb}}\left(h_m \ln\left(\frac{1-x_{vi}}{1-x_{vb}}\right)\right) = h_m\frac{\rho_{vb}}{x_{vb}}\ln\left(\frac{1-P_{vi}/P}{1-P_{vb}/P}\right)$$

where h_{fg}, c, M, and $\tilde{v}_i$ are the latent heat, the total molar density, the molecular weight, and the average molar velocity. x and h_m are mole fraction and mass transfer coefficient (Diffusion coefficient/diffusion layer thickness, D/δ_g). g,v,b and i in subscript notations are the property in the gas phase, vapor phase, bulk species, at the liquid/gas interface.

Most of system codes including SPACE introduced the Colburn-Hougen model as represented in Eq (3). The vapor mole fraction term, x_{vb} was omitted from the vapor mass flux formulation as represented in Eq.(3) because of confusing the relationship between molar density and density in the process of deriving the equation.

$$j_v = h_m\rho_{vb}\ln\left(\frac{1-P_{vi}/P}{1-P_{vb}/P}\right) \tag{3}$$

Fig. 1 represents the comparison of condensate rate between original (Eq.(3))and modified Colburn-Hougen model(Eq.(4)) for 0.1, 0.5, and 0.9 of bulk vapor mole fraction according to the change of vapor mole fraction at liquid/gas interface. The difference between original and modified one is bigger for the cases with lower bulk vapor mole fraction or higher NC gas mole fraction. But, there is no big difference for the case with higher vapor mole fraction. Based on this, we expected that this modification of Colburn-Hougen model can much affect the results for the cases with higher NC gas mole fraction.

Eq. (3) in the SPACE code substitutes with Eq. (2) to follow the original derivation of Colburn-Hougen equation as shown in Table I. After that we need to clarify the effects of modified Colburn-Hougen model on wall condensation in the presence of NC gases. The experimental data of COPAIN test, University of Wisconsin condensation test and KAIST reflux test are used to assess them.

Table I. Comparison of vapor mass flux equations in the Colburn-Hougen model

C-H model	Original eq.	Modified eq.
Vapor mass flux	$j_v = h_m\rho_{vb}\ln\left(\frac{1-P_{vi}/P}{1-P_{vb}/P}\right)$	$j_v = h_m\frac{\rho_{vb}}{x_{vb}}\ln\left(\frac{1-P_{vi}/P}{1-P_{vb}/P}\right)$

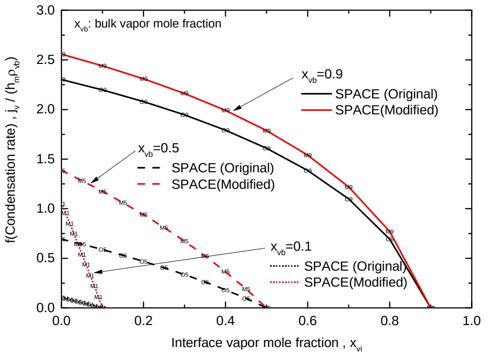

Fig. 1. Comparison of tendency of condensation rate for the cases of 0.1, 0.5, and 0.9 of bulk vapor mole fractions (x_{vb}) according to the change of vapor mole fraction at liquid/gas interface (x_{vi})

2.1 Simulation of the COPAIN tests

The COPAIN tests[6] were conducted forced convection condensation with NC gases. The test facility consists of a 0.6 m × 0.5 m of vertical rectangular channel with 2.5 m vertical length and, the condenser with a uniform temperature is 2 m long and 0.6 m width. All experimental parameters of the COPAIN tests are represented in table II. Fig. 2 shows the nodalization of SPACE for COPAIN test.

Fig. 3 shows the comparison of SPACE results between original and modified equation with experimental results for COPAIN tests. The original calculations tend to underpredict the heat flux results for all cases. The calculated results using modified equation are more well-matched with experimental results compared to the original ones.

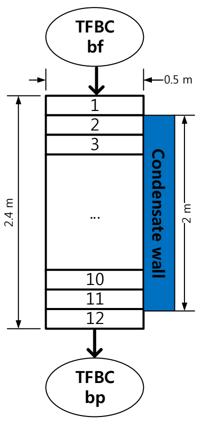

Fig. 2. Nodalization schematic of COPAIN tests

Table II. Experimental conditions of the COPAIN tests

Test	Inlet velocity (m/s)	Absolute pressure (bar)	Inlet temperature (K)	Wall temperature (K)	Air mass fraction
P0441	3.0	1.02	353.2	307.4	0.767
P0443	1.0	1.02	352.3	300.1	0.772

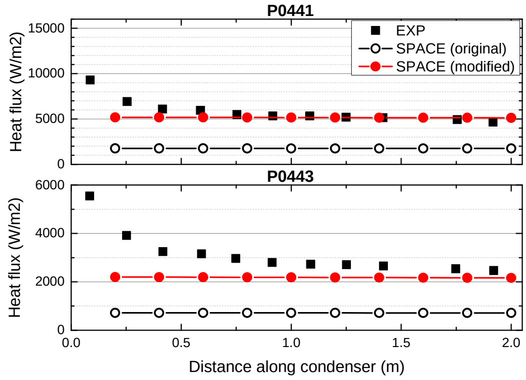

Fig. 3. Comparison of heat flux using SPACE with COPAIN data for tests P0441 and P0443

2.2 Simulation of University of Wisconsin condensation tests

University of Wisconsin (UW) condensation tests[7] were conducted with a variable orientation of the condensing surface, a variable air-steam mass fraction 0~0.87 and a mixture velocity of 1~3 m/s. The experimental error in heat transfer coefficient measurements was determined to be approximately 10%. In this study we only simulated the vertical condensation test cases as shown in Table III. Fig. 4 show the nodalization of SPACE for UW condensation test. The test section in condensation part is a 0.152 m square duct and 1.905 m long.

The calculated results of heat transfer coefficient (HTC) and experimental averaged HTC are represented in fig. 5. The calculated results using modified model shows more similar to experimental data compared to original ones. Especially, the calculated results for case 48 & 50 with higher air mass fraction are more increased and have a better agreement with experimental data.

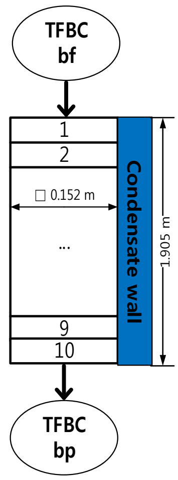

Fig. 4. Nodalization schematics of UW condensation tests

Table III. Experimental conditions for UW condensation tests

Test	Inlet temperature, T_{wall}-T_{in} (K)	Air quality (%)	Inlet velocity (m/s)
Case 48	50	65	1
Case 50	50	65	2
Case 83	50	23	1

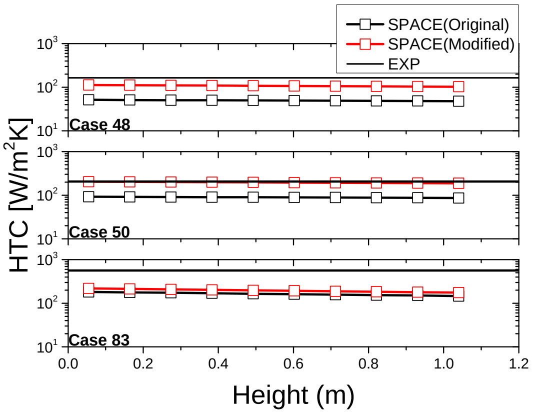

Fig. 5. Comparison of HTC with averaged HTC for UW condensation data

2.3 Simulation of the KAIST reflux condensation tests

KAIST reflux condensation tests[3] were conducted in a vertical tube with NC gases. In this experiments, the gas mixture flows upward thorough the tube while, the condensate flows downward in a counter-current direction. The test section in the reflux condensation part is a vertical tube with 19.05 mm diameter and 2.4 m length surrounded by the coolant block. The experimental errors in heat flux represented approximately 10.3% uncertainty.

Fig. 6 shows the nodalization scheme of SPACE for the KAIST reflux condensation tests. Among the variable experimental conditions, test RA02 & RC13 were chosen to assess the condensation model as summarized in Table IV.

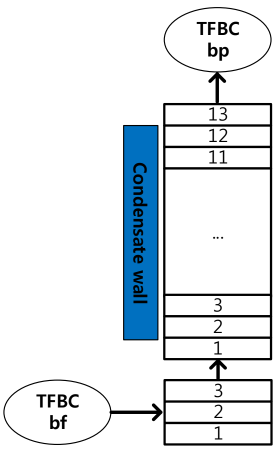

Fig. 6. The nodalization schematic of KAIST tests

Table IV. Steady-state test condition of the KAIST reflux condensation tests

Test	Saturated Temperature (℃)	Air mass fraction	Total pressure (kPa)	Steam flow rate (kg/h)	Air flow rate (kg/h)
RC13	91.0	0.418	105.4	1.50	1.08
RA02	95.3	0.291	266.0	2.59	0.80

Fig. 7 shows the simulation results of heat transfer coefficient (HTC) for RA02 & RC13. The calculated HTC in lower part of condensation tube is slightly higher than the test data, regardless of the used models between original and modified one. However, HTC in codes and experiments can be differently calculated according to the definition of temperature difference between wall and vapor. It is difficult to assess the model using the HTC parameter only. Additionally, the simulation results of heat flux for RA02 are compared with experimental data as shown in Fig. 8. The calculated result using modified model is more well-matched than the one using original model with experimental results. Although the calculated HTC shows higher, we can conclude that the modified calculations are reasonable and improved.

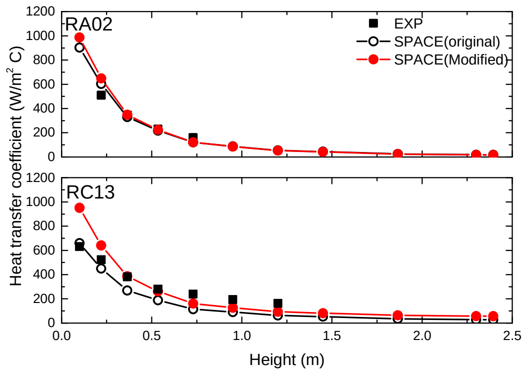

Fig. 7. Comparison of HTC using SPACE for test RA02 & RC13

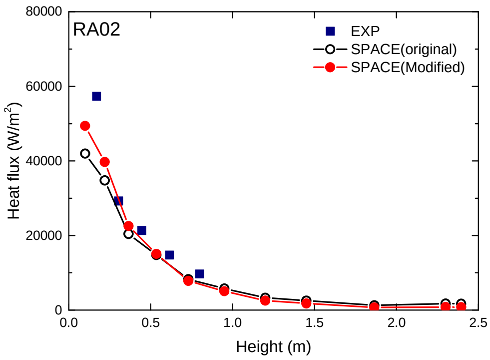

Fig. 8 Comparison of heat flux using SPACE with KAIST reflux condensation data for test RA02

3. Conclusions

The Colburn-Hougen model has been widely used in thermal hydraulic system codes for the wall condensation problem in the presence of noncondensable (NC) gases. However, we notice that there is a mistake in the used derived equation. The assessment of the modified Colburn-Hougen model was conducted by validating with variable experiments: COPAIN, University of Wisconsin condensation test, and KAIST reflux condensation test.

Through the comparison of calculated results using SPACE with experimental data, we concluded that modified Colburn-Houngen model can more precisely simulate wall condensation heat transfer. And, calculated results have a better agreement with experimental data. Commonly, the calculated heat flux and vapor mass flux with higher air mass fraction cases are more increased and show a better agreement with experimental data.

Acknowledgment

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