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Analysis of Experiments for Vertical In-Tube Steam Condensation with Noncondensable Gases using the modified RELAP5/MOD3.2 code

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Abstract

The standard RELAP5/MOD3.2 code was modified using the non-iterative modeling, which is developed to simulate steam condensation in the presence of noncondensable gases in a vertical tube. The modified RELAP5/MOD3.2 code was used to simulate two kinds of vertical in-tube experiments involving the condensation phenomenon in the presence of noncondensable gases. The modeling capabilities of the modified RELAP5/MOD3.2 code as well as the standard code for the condensation in the presence of noncondensable gases are assessed using two PCCS condensation experiments and four reflux condensation experiments. The modified RELAP5/MOD3.2 code gives good prediction over the data of both PCCS condensation and reflux condensation experiments.

1 Introduction

PCCS (Passive Containment Cooling System) provides the long-term heat sink to reject the decay heat during the operation of a nuclear power plant in an accidental condition. PCCS of CP-1300[1] uses the external condenser concept, which uses the steam condensation in condensing tubes located in a water pool outside a containment. In the condensing tube of PCCS the steam-noncondensable gas mixture flows downward through the condensing tube and the condensate also flows downward cocurrently. During the mid-loop operation of a nuclear power plant, the safety of the reactor is threatened by the loss of residual heat removal capability. The reflux condensation is a possible phenomenon in the above condition. In the inlet of the steam generator the steam-noncondensable gas mixture flows upward through a U-tube of steam generator, while the condensate flows downward countercurrently.

Therefore, the understanding of the effect of noncondensable gas on steam condensation is crucial to predict the local heat transfer transfer coefficient both in a condensing tube of PCCS and in a U-tube of steam generator. Many experimental investigations are performed to understand this phenomenon. Both Siddique[2] and Kuhn[3] performed air-steam and helium-steam condensation experiments for the cocurrent downward flow and developed their own correlations. Banerjee et al.[4] investigated experimentally the countercurrent reflux condensation in a vertical U-tube of steam generator.

The present work is to simulate two kinds of experiments, PCCS condensation[5] and reflux condensation[6] experiments, which are performed at KAIST. Those KAIST condensation experiments[5, 6] provide data on the steady-state behaviors with typical flow, pressure and air mass fraction conditions likely to be seen in a condensing tube of PCCS and in a U-tube of steam generator in mid-loop operation. The condensing tubes of PCCS and the U-tubes of steam generator during mid-loop operation are filled with steam-noncondensable gas mixture, which degrades the heat transfer rate significantly. Hence, the advanced safety analysis codes is needed to calculate accurately the condensation rate in the presence of noncondensable gases in order to predict the system behavior correctly.

The original RELAP5/MOD3.2 code has two wall film condensation models. However, its wall film condensation models, the default and the alternative, are known to give lower and higher predictions over the experimental data[5], respectively. A non-iterative condensation model is implemented into the code to give a modified version. The modified RELAP5/MOD3.2 code uses the non-iterative modeling which is developed by Park[7] to simulate steam condensation in the presence of noncondensable gases in a vertical tube. Both the standard and modified RELAP5/MOD3.2 codes have been used to model both KAIST condensation experiments[5, 6].

2 The Modified RELAP5/MOD3.2 Code Using the Non-Iterative Modeling

The standard RELAP5/MOD3.2 code has two wall film condensation models, the default and the alternative models. The default model uses the Nusselt-Shah-Colburn-Hougen correlations, and the alternative model uses the Nusselt-UCB correlations for the wall film condensation on an inclined surface.

The default model is to use the maximum of Nusselt's[8] and Shah's[9] with the Colburn-Hougen's[10] diffusion calculation when noncondensable gases are present. The default model of RELAP5/MOD3.2 separately calculates the heat flux through the liquid film and through the mixture boundary layer with an assumed interface temperature. It needs iteration to get reasonable heat transfer coefficients of h_f, h_{cv} and h_{cd} by modifying the interface temperature, T_i, until the heat fluxes converge within a specified accuracy. The alternative model of RELAP5/MOD3.2 uses the Nusselt model with UCB multipliers, which is a function of mixture Reynolds number and air mass fraction.

A Non-Iterative condensation model[7] is proposed for easy engineering application using the iterative condensation model and the assumption of the same profile of the steam mass fraction as that of the gas temperature in the gas film boundary layer. When steam condenses on the inside wall of a vertical tube in the presence of noncondensable gases, the partial pressure of the vapor at the liquid-gas interface is lowered with the presence of noncondensable gas and its saturation temperature is decreased to reduce the condensation rate.

The liquid side heat transfer coefficient is calculated using the Nusselt correlation and the condensation Nusselt number is directly calculated from several non-dimensional parameters as follows:

$$Nu_{cd} = \frac{1}{2} \cdot \frac{k_f}{k_g} \cdot \frac{Nu_f}{div1} \cdot \left[-div + |div| \cdot \sqrt{1 + 4 \cdot (1 + h_{cv}/h_f) \cdot \frac{div1 \cdot div3}{div^2}} \right], \qquad (1)$$

where

$$div = div1 + div2 - div3 = N_B \cdot P_A + Ja - Pr_g \cdot St_{AB} \cdot Re_g / Nu_f \cdot k_g / k_f. \tag{2}$$

The nondimensional parameters in equations (1)-(2) are expressed as follows: $W_{g,b} = 1 - W_{v,b}$; $X_{g,b} = 1 - X_{v,b}$; $Nu_{cd} = h_{cd} D_h / k_g$; $Nu_f = h_f D_h / k_f$; $St_{AB} = g / \rho_g u_g$; $Re_g = \rho_g u_g D_h / \mu_g$; $Pr_g = Cp_g \mu_g / k_g$; $Ja = Cp_g \cdot (T_b - T_w) / i_{fg}$; $P_A = P_t^2 / (\rho_v^2 \cdot i_{fg}^2) \cdot Cp_g / R_v$; $N_B = X_{g,b} \cdot (1 - X_{g,b}) \cdot [1 + X_{g,b} \cdot (M_g / M_v - 1)]$. The convective heat transfer, h_{cv}, and mass transfer conductance, g, can be calculated together using the heat and mass transfer analogy.

$$St = \frac{h_{cv}}{\rho_g u_g} = \frac{Nu}{Re_g \cdot Pr_g}, \tag{3}$$

and

$$St_{AB} = \frac{g}{\rho_g u_g} = \frac{Sh}{Re_g \cdot Sc_g}. \tag{4}$$

There are several methods to calculate the Stanton number, St. Gnielinski's calculation method[11] is used for smooth tubes and Dipprey's calculation method[12] is used for rough tubes, which is applied to this modeling.

$$St = \frac{c_f/2}{1.0 + \sqrt{c_f/2} \cdot (k_f [Re_g \cdot \sqrt{c_f/2} \cdot \epsilon_s / D]^{0.2} \cdot Pr^{0.44} - 8.48)}, \tag{5}$$

where $k_f = 5.19$ and

$$\epsilon_s / D = e^{(3.0 - 0.4/\sqrt{c_f/2})}. \tag{6}$$

Using the heat and mass transfer analogy, the Stanton number for mass transfer, St_{AB}, is calculated similarly.

$$St_{AB} = \frac{c_f/2}{1.0 + \sqrt{c_f/2} \cdot (k_f \cdot [Re_g \cdot \sqrt{c_f/2} \cdot \epsilon_s / D]^{0.2} \cdot Sc^{0.44} - 8.48)}. \tag{7}$$

St_{AB} and h_{cv} in equation (1) are corrected to consider the effects of high mass transfer and entrance. Equation (8) is used for the former effect and equations (10)-(11) for the latter effect.

The high mass transfer effect is considered like the followings. The Stanton number with blowing, St_b, can be expressed with the Stanton number for no transpiration, St_0, and the blowing parameter, b_h:

$$St_b = St_0 \cdot \frac{b_h}{e^{b_h} - 1}, \tag{8}$$

where b_h is the alternative heat transfer blowing parameter, which has explicit relation for St_0 rather than the implicit equation, and it can be expressed with several nondimensional parameters.

$$b_h = \frac{m_v'' / G_\infty}{St_0} = -\frac{Ja \cdot Nu_{cd}}{St_0 \cdot Pr_g \cdot Re_g} \cdot \frac{Nu_f}{Nu_f + [Nu_{cv} + Nu_{cd}] * k_g / k_f}, \tag{9}$$

where $m_v^{''}$ is the mass transfer rate of the vapor and G_∞ is the mass flux of the free stream. The entrance effect is also considered. For short tubes, where the region of fully developed flow is a small percentage of the total length, the local value of the Nusselt number for uniform velocity and temperature profile in the entrance region is given based on the experimental data for gas[13].

$$Nu_e = 1.5 \cdot (\frac{x}{D})^{-0.16} \cdot Nu_0, \qquad for \;\; 1 < \frac{x}{D} < 12, \tag{10}$$

and

$$Nu_e = Nu_0, \qquad for \;\; \frac{x}{D} > 12. \tag{11}$$

As div is always positive and y is a very small value compared with 1, the square root term of equation (1) can be expanded and approximated from the expansion of the Taylor series:

$$\sqrt{1+y} \approx 1 + \frac{1}{2}y, \tag{12}$$

where

$$y = 4 \cdot (1 + h_{cv}/h_f) \cdot \frac{div1 \cdot div3}{div^2}. \tag{13}$$

Using the approximation of equation (12), equation (1) can be simplified as follows:

$$Nu_{cd} = (1 + h_{cv}/h_f) \cdot \frac{Pr_g \cdot St_{AB} \cdot Re_g}{N_B \cdot P_A + Ja - Pr_g \cdot St_{AB} \cdot Re_g/Nu_f \cdot k_g/k_f} \tag{14}$$

As the convective heat transfer coefficient, h_{cv}, is negligibly small compared with the film side heat transfer coefficient, h_f, equation (14) can be further simplified as follows:

$$Nu_{cd} = \frac{Pr_g \cdot St_{AB} \cdot Re_g}{N_B \cdot P_A + Ja - Pr_g \cdot St_{AB} \cdot Re_g/Nu_f \cdot k_g/k_f} \tag{15}$$

The definition of Nusselt number for condensation includes the parameters of St_{AB}, Re_g, Pr_g, Nu_f, k_g/k_f, Ja, N_B, and P_A. The developed correlation for the condensation Nusselt number is composed of several nondimensional parameters used for empirical correlations by several investigators[2, 3, 14, 15, 16, 17].

3 RELAP5/MOD3.2 Nodalization

3.1 PCCS Condensation Experiments

The PCCS condensation experiments in the presence of noncondensable gas on the inside wall of a vertical tube, typical of a condensing tube of PCCS, are performed at KAIST[5]. Fig. 1 shows the schematic diagram of the experimental facility, which consists of a steam tank including a $100kW$ heater, a steam-noncondensable gas mixture supply line, a test section with a condensing tube and its surrounding coolant jacket, a lower plenum, venting and draining systems, and a unit of data acquisition system.

The test section consists of an inner condensing tube and an outer coolant jacket. The inner tube of the test section is a stainless steel pipe of $50.8mm$ in outer diameter, $1.65mm$ in thickness, and $2400mm$ in length. At 12 different axial locations each J-type

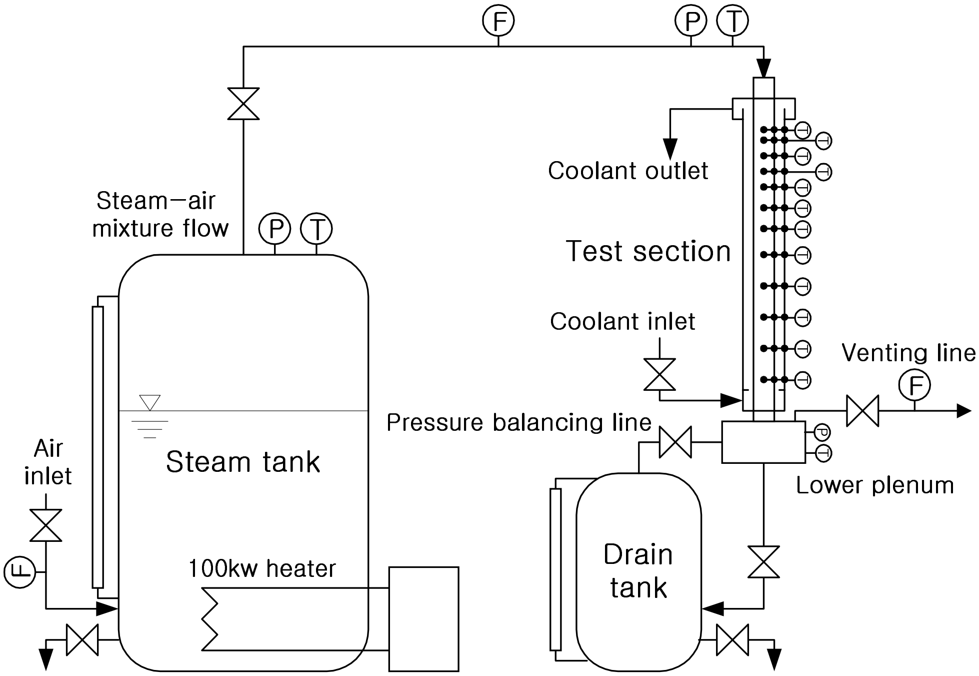

Fig. 1: A schematic diagram of PCCS condensation experimental facility

thermocouple is welded on the outer surface of the condensing tube to measure the outer surface temperatures, welded through the condensing tube to measure the mixture bulk temperatures, and installed on the outer side of the coolant jacket to measure the coolant temperatures. The steam-air mixture is injected downward into the vertical condensing tube as boundary conditions at various air mass fractions and steam flow rates.

Fig. 2 shows the nodalization scheme of RELAP5/MOD3.2 for the PCCS condensation experiments. The present RELAP5/MOD3.2 nodalization used for this simulation contains 41 control volumes, 6 junctions, a valve and a heat structure. The steam-air mixture is injected into the PCCS at constant flow rates. The RELAP5/MOD3.2 model simulated this behavior by using a time-dependent volume and a time-dependent junction to specify flow and pressure boundary conditions. Time-dependent volumes acting as infinite sources or sinks are used to represent boundary conditions both for the steam-noncondensable gas mixture flow in a condensing tube and for the coolant flow in a coolant jacket. For the simulation of the coolant jacket, two time dependent volumes 200 and 280 are connected to the annulus 240 with 11 volumes via a time dependent juction 210 and a single junction 270. Similarly, for the simulation of the steam-noncondensable gas mixture flow two time dependent volumes 100 and 180, a pipe with 13 volumes, a time dependent juction 105 and a single juntion 151 are also used. A branch 120 is used to simulate an upper plenum and three pipe volumes 150, 160 and 157 are used to simulate a lower plenum, a drain tank and a connecting pipe between the lower plenum and the drain tank, respectively. The above three pipes are connected using single junctions 155, 156 and 158. A valve 175 is used to regulate the venting of the mixture of the residual steam and the noncondensable gas. A heat structure 140 with 11 volumes is used to represent the heat transferred from the steam-noncondensable gas mixture to the coolant through the condensing tube.

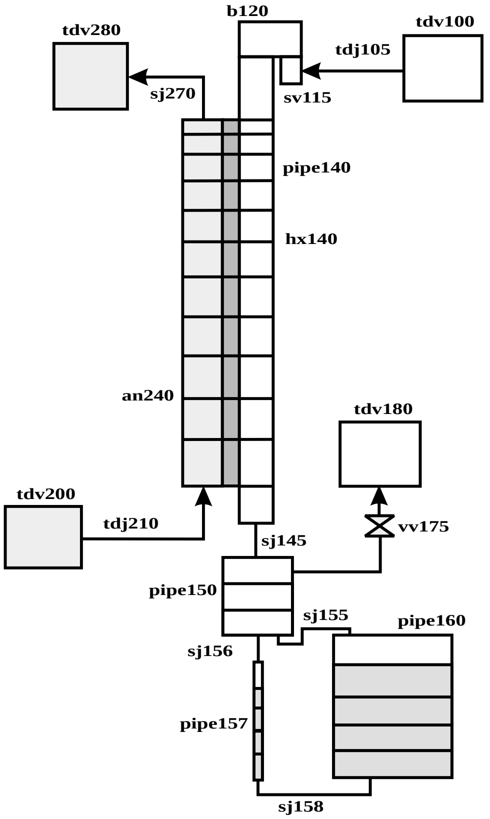

Fig. 2: Nodalization scheme of RELAP5/MOD3.2 for PCCS condensation experimental facility

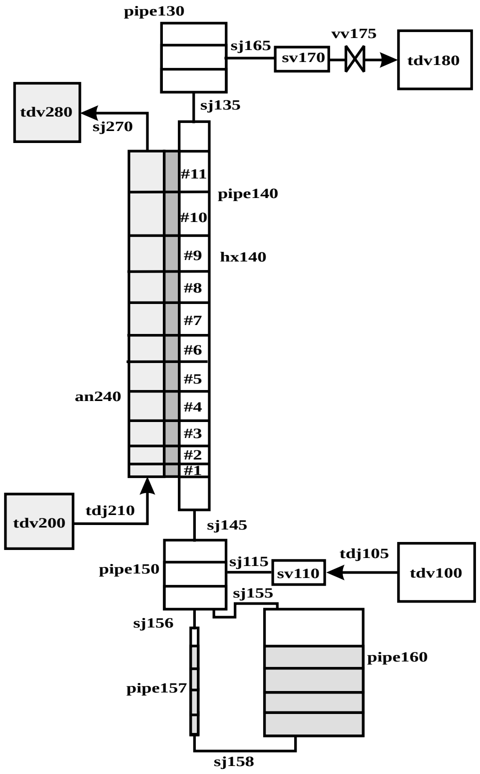

Fig. 3: Nodalization scheme of RELAP5/MOD3.2 for reflux condensation experimental facility

Two PCCS condensation experiments are simulated using RELAP5/MOD3.2, and their steady state test conditions are listed in Table I. Tests are performed varying the following input parameters: the saturated steam temperature at the inlet, T_{sat}, the inlet air mass fraction, AMF, its inlet total pressure, P_{tot}, the inlet steam flow rate, SF, and the inlet air flow rate, AF. The local heat transfer coefficients and void fractions are calculated to be compared with the experimental data.

3.2 Reflux Condensation Experiments

The reflux condensation experiments in the presence of noncondensable gas in a vertical tube, typical of a U-tube of steam generator, are performed at KAIST[6]. Fig. 4 shows the schematic diagram of the experimental facility for reflux condensation in the riser part of a U-tube. The reflux condensation experimental facility is similar to the facility for PCCS condensation experiments but its condensing tube has different diameter and thickness. The condensing tube has the same diameter and thickness as those of the steam generator U-tube used in YGN3 nuclear power plant, which are $19.05mm$ and $1.245mm$, respectively. The test section simulates the U-tube riser. 29 sets of the reflux condensation data are obtained. The test matrix is composed of three main parameters including the system pressure, the inlet steam flow rate and the air mass fraction and their parametric

Table I: Steady state test conditions of KAIST condensation experiments

I.D.	T_{sat} (^oC)	AMF	P_{tot} (kpa)	SF (kg/h)	AF (kg/h)	Experiments
E4d	129.0	0.102	281.3	32.8	3.7	PCCS condensation
E13b	110.5	0.303	185.4	18.2	7.8	
RC16	101.6	0.0	107.3	1.35	0.0	Reflux condensation
RC13	91.0	0.418	105.4	1.50	1.08	
RC02	95.3	0.291	107.4	2.29	0.94	
RA02	123.7	0.237	266.0	2.59	0.8	

effects are analyzed. The active condensing region is approximately 1.5m, which is shorter than the vertical length of 2.4m of the test tube, so the reflux condensation phenomena can be locally observed near the inlet of the U-tube of steam generator. The steam-air mixture is injected upward into the riser part of the U-tube of steam generator as boundary conditions at various air mass fractions and steam flow rates.

Fig. 3 shows the nodalization scheme of RELAP5/MOD3.2 for the reflux condensation experiments. The present RELAP5/MOD3.2 nodalization used for this simulation also contains the same number of volumes and junctions. Compared with downward condensation experiments, this nodalization is different in that the flow direction of the steam-air mixture is opposite. Four reflux condensation experiments are simulated using RELAP5/MOD3.2 and their steady state test conditions are listed in Table I. The local heat transfer coefficients are compared for the tests with different air mass fractions and system pressure (or inlet saturated steam temperature).

4 Results and Discussion

The RELAP5/MOD3.2 code was evaluated with the results of two separate tests. The condensation model of the standard RELAP5/MOD3.2 code is modified by the implementation of the non-iterative model to produce the modified RELAP5/MOD3.2. The results of RELAP5/MOD3.2 simulations are compared with the data both from PCCS condensation experiments and from reflux condensation experiments. Both simulations show that the modified RELAP5/MOD3.2 code predicts the condensation heat transfer in the presence of noncondensable gases better than the original RELAP5/MOD3.2 code.

4.1 PCCS Condensation Experiments

The PCCS condensation experiments had ranges of inlet air mass fractions from 0.10 to 0.41, inlet steam flow rates from 7.6 to 40.0kg/hr and inlet mixture temperatures from 110.4 to 140.6^oC. Two tests of *E13B* and *E4D* are selected to be compared. *E13B* has relatively high inlet air mass fraction and low inlet steam flow rate and *E4D* has relatively low inlet air mass fraction and high inlet steam flow rate.

Figs. 5 and 6 show the local heat transfer coefficients along the tube length for PCCS condensation experiments *E13B* and *E4D*, respectively. They show the comparisons be-

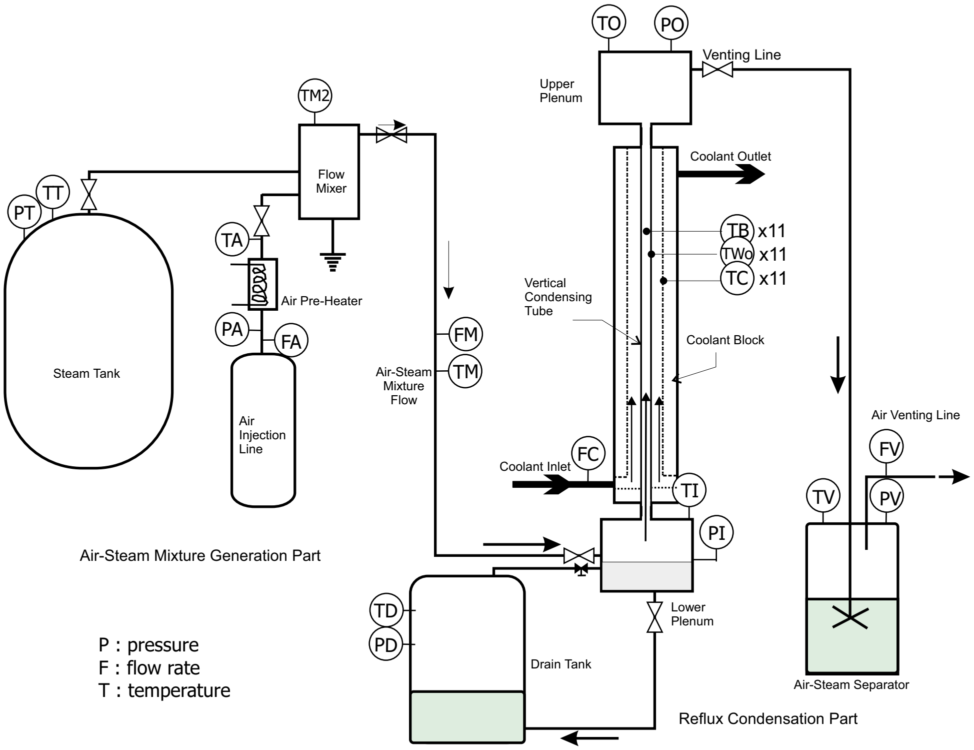

Fig. 4: A schematic diagram of reflux condensation experimental apparatus

tween the experimental heat transfer coefficients and three RELAP5/MOD3.2 predictions.

The calculated heat transfer coefficients from the default model are always lower than those from the alternative model throughout the condensing tube, as shown both in Figs. 5 and 6. Their difference decreases as the inlet steam flow rate increases and the inlet air mass fraction decreases. In most of cases such as *E13B*, the calculated one from the alternative model is always higher than the experimental data, while the calculated heat transfer coefficient from the default model is always lower than the experimental data. However, in case of *E4D* with low air mass fraction and high steam flow rate, the calculated one from the alternative model is always higher than the experimental data, while the calculated heat transfer coefficient from the default model is much increased to be similar to the experimental data. The heat transfer coefficient simulated using the modified RELAP5/MOD3.2 code shows similar tendencies in the outlet of the condensing tube but it also shows reasonable agreement with the experimental data. Four heat transfer coefficients, or three simulated results and one experimental data, are greatly different in the inlet of the test section, but they are similar in the outlet of the condensing tube, where the amount of steam is greatly reduced by condensation and the convective heat transfer is dominant. Good agreement between the simulated results and experimental data suggests that the wall film condensation model is properly modeled in RELAP5/MOD3.2 and this non-iterative modeling can be used to compute heat transfer coefficient in the presence of noncondensable gases.

Figs. 7 and 8 show the local void fractions along the tube length for PCCS condensation experiments *E13B* and *E4D*, respectively. They also show the comparisons between the

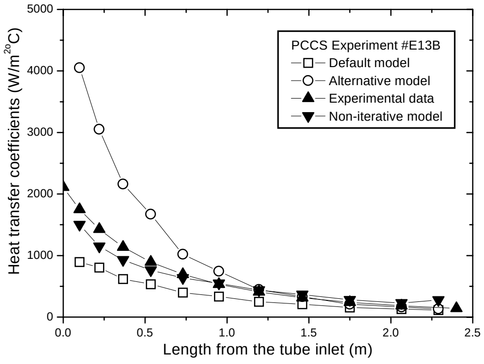

Fig. 5: Heat transfer coefficients along the tube length for PCCS condensation experiment *E13B*

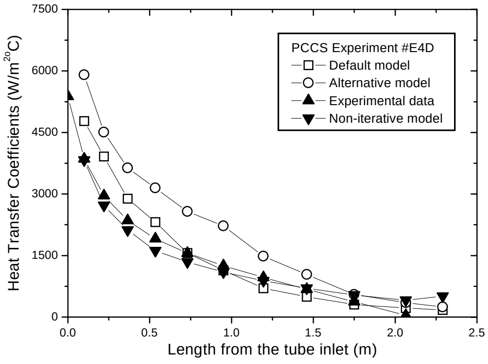

Fig. 6: Heat transfer coefficients along the tube length for PCCS condensation experiment *E4D*

experimental ones and three RELAP5/MOD3.2 predicted ones. The void fraction, α, can be calculated from the known condensate film thickness, δ, and the inner tube diameter, D, as follow:

$$\alpha \; = \; 1 \; - \; \frac{4 \; \delta}{D} \; . \tag{16}$$

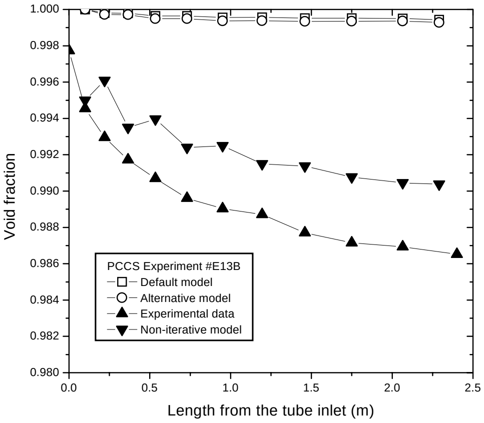

Fig. 7: Void fractions along the tube length for PCCS condensation experiment *E13B*

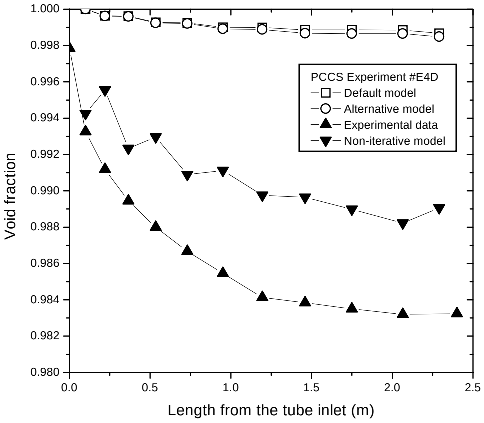

Fig. 8: Void fractions along the tube length for PCCS condensation experiment *E4D*

The void fractions calculated from both models of the standard RELAP5/MOD3.2 code show much higher values than those from the experimental data. It is due to the underestimated two phase friction factor in RELAP5/MOD3.2. The void fraction simulated with the modified RELAP5/MOD3.2 code shows a little higher than the experimentally obtained void fraction but its discrepancy is very small.

4.2 Reflux Condensation Experiments

The reflux condensation experiments had ranges of inlet air mass fractions from 0.0 to 0.55, inlet steam flow rates from 1.348 to 3.282kg/hr and system pressures from 104.0 to 263.3kpa. Two tests of *RC16* and *RC13* have different inlet air mass fractions with similar inlet saturated steam temperatures and inlet steam flow rates, and two tests of *RC02* and *RA02* have different inlet saturated steam temperatures with similar air mass fractions and inlet steam flow rates.

Figs. 9 through 12 show the local heat transfer coefficients along the tube length for PCCS condensation experiments *RC16*, *RC13*, *RC02*, and *RA02*, respectively. The heat transfer coefficients increase as the inlet air mass fraction decreases and the system pressure or the inlet saturated steam temperature decreases. The local heat transfer coefficients are well predicted with the modified RELAP5/MOD3.2 code but they are under-predicted by the default model and over-predicted by the alternative model. Also the modified RELAP5/MOD3.2 code predicts better the experimentally obtained active

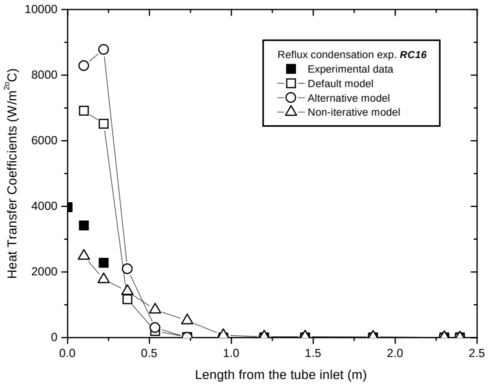

Fig. 9: Heat transfer coefficients along the tube length for reflux condensation experiment *RC16*

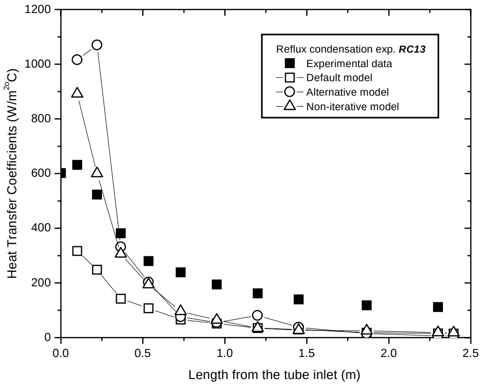

Fig. 10: Heat transfer coefficients along the tube length for reflux condensation experiment *RC13*

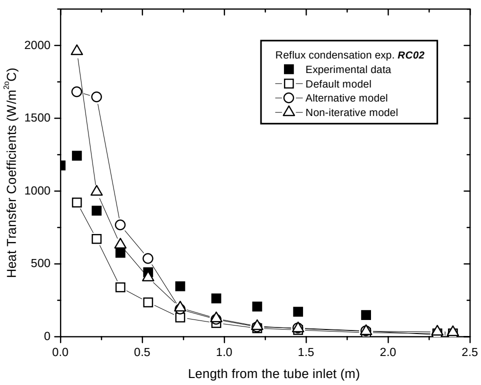

Fig. 11: Heat transfer coefficients along the tube length for reflux condensation experiment *RC02*

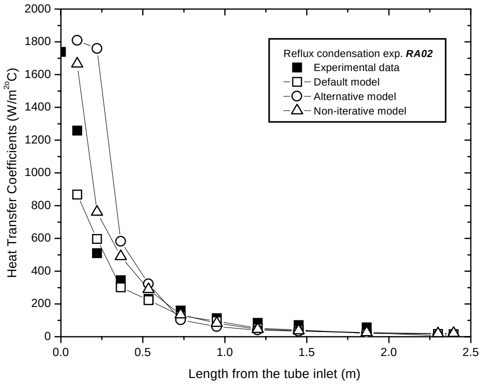

Fig. 12: Heat transfer coefficients along the tube length for reflux condensation experiment *RA02*

condensing region and its length than the original code does.

5 Conclusions

A mechanistic model to calculate steam condensation in the presence of noncondensable gas is developed. It does not need any interfacial data such as the temperature at the liquid-gas mixture. This model is incorporated in the RELAP5/MOD3.2 code. Selected two PCCS condensation experiments and four reflux condensation experiments are simulated using the modified code as well as the standard RELAP5/MOD3.2 code. The conclusions are listed as follows:

- Both the default and alternative models of the original RELAP5/MOD3.2 code have tendencies to over-predict and under-predict the heat transfer coefficients, respectively. The RELAP5/MOD3.2 implementation of the non-iterative model gives good prediction over the data of both PCCS condensation and reflux condensation experiments.
- The void fractions calculated from both models of the standard RELAP5/MOD3.2 code show much higher values than those from the experimental data. It is due to the underestimated two phase friction factor in RELAP5/MOD3.2. The modified model shows similar values to the experimentally obtained void fractions.
- The modified RELAP5/MOD3.2 code predicts well the active condensing region and its length as well as the heat transfer coefficients for the reflux condensation experiments.
- The non-iterative model, which is used in the modified RELAP5/MOD3.2 code, would predict well the wall film condensation in the presence of noncondensable gas, and the model can easily be incorporated in any transient thermal-hydraulic system analysis computer code.

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