Assessment of TRACE Condensation Model Against Reflux Condensation Tests with Noncondensable Gases

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1. Introduction

The TRACE is the latest in a series of advanced, best-estimated reactor systems code developed by U.S. Nuclear Regulatory Commission for analyzing transient and steady-state neutronic-thermal-hydraulic behavior in light water reactors [1].

As an alternative model, the TRACE adopts the special model for condensation in the presence of noncondensable (NC) gases which employs the mass transfer conductance approach developed by Kuhn et al. [2]. This special model is expected to replace the default model in a future code release after sufficient testing has been completed.

This study assesses the special condensation model of TRACE 5.0-patch4 against the counter-current flow configuration. For this purpose, the predicted results of special model are compared to the experimental and to those of default model. The KAST reflux condensation test [3] with NC gases are used in this assessment.

2. Facility Description

Figure 1 shows the schematic diagram of the experimental apparatus. The main components of the system are the test section, the steam and air supply system. To simulate the geometry of the steam generator U-tube, an inverted U-tube with the inner diameter of 0.0162 m was installed in a rectangular pool. The tube was made of stainless steel 304. The height and thickness of the tube are 2.8 m and 0.0055 m, respectively. The upflow side of U-tube was equipped with 32 thermocouples to measure the heat fluxes.

During the filmwise reflux condensation mode, the vertical counter-current flow of steam-gas mixture and condensate is formed in the upflow side of U-tube. To investigate the local heat transfer phenomena, a series of tests was performed for various combinations of the inlet steam flowrate (m_s), the inlet air mass fraction (W_{air}), and the secondary pool temperature (T_{cw}) under atmospheric condition.

In the experiment, the total heat transfer coefficient (HTC) at any axial location was defined as

$$h_t = \frac{q''_{w,i}}{T_b - T_{w,i}} \qquad (1)$$

where $q''_{w,i}$ is the inner-surface wall heat flux, T_b is the gas-vapor mixture temperature at the tube center, and $T_{w,i}$ is the tube inner-surface wall temperature. The estimated uncertainties of the HTCs were in the range of 2.4-21.7% (at an average of 7.2%).

3. TRACE Model Description

The TRACE nodalization is shown in Fig. 2. The upflow side of U-tube, the condenser tube, is modeled using the vertical PIPE component (150).

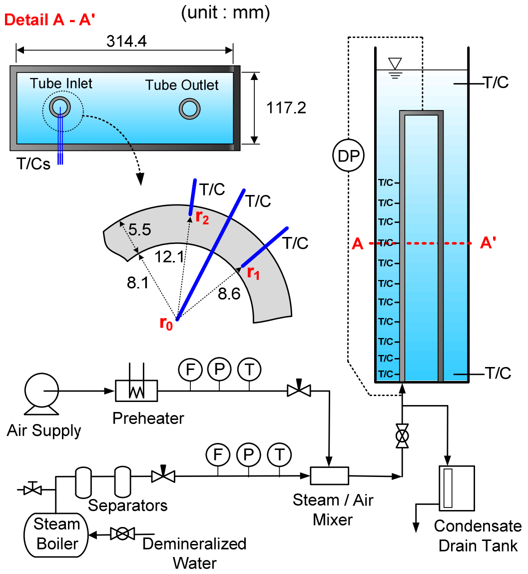

Fig. 1. Schematic Diagram of Experimental Apparatus.

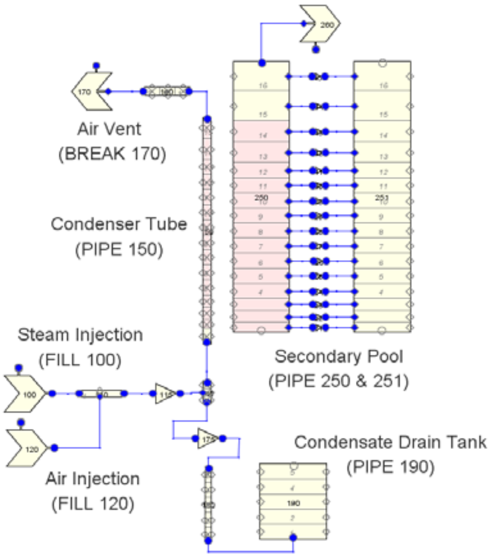

Fig. 2. TRACE Model of Reflux Condensation Test.

The nodalization is set so that the cell centers are aligned with the thermocouple elevations. Two FILL components (100 and 120) are used to model the steam and air injections. The BREAK component (170) is used for the air vent line. The condensate drain tank is modeled using PIPE (190).

The secondary rectangular pool is modeled using two parallel vertical PIPEs (250 and 251). The cells are connected by the single junctions to simulate the cross flow. The HTSTR component is used to model the heat transfer between the condenser tube and the secondary pool. The default stability-enhancing two-step (SETS) is used for the time integration method throughout the calculations.

4. TRACE Film Condensation Model

During film condensation, the heat transfer occurs in a two-step process, whereby heat is removed from the two-phase interface by interfacial heat transfer, and then from the subcooled liquid to the wall. When NC gases are present, the additional heat transfer resistance must be added to that of the interfacial heat transfer. This section describes the TRACE default and special models for the interfacial heat transfer.

4.1. Default model for condensation

The TRACE default model for condensation invoked whenever $\left|T_l \le T_{sv}\right|$ and the special film condensation model is not selected. T_l and T_{sv} denote the liquid film temperature and the saturation temperature at the bulk vapor partial pressure, respectively. The default model is based on the empirical correlation of Sklover and Rodivilin [4], and is given by

$$\frac{h_{li,NC}}{h_{li}} = 0.366 \cdot \left(\frac{\rho_g - \rho_{NC}}{\rho_{NC}}\right)^{0.2} \cdot \left(\frac{G_s}{G_l}\right)^{0.2} \qquad (2)$$

where $h_{li,NC}$ is the liquid-side interfacial heat transfer that NC gases effect has been added, ρ is the density, and G is the mass flux. The above model is highly empirical and is strictly applicable only to the specific configuration for which it was developed.

4.2. Special model for condensation

The alternative model is invoked when the pipe type of condenser tube is set to the special film condensation. The special condensation model is based on the principle that the heat flow through the liquid film is equal to the sum of the heat flow due to latent and sensible heat transfer on the film surface as given by Eq. (3):

$$-\Gamma'' \cdot h_{fg} + h_{sens} \cdot (T_g - T_i) = h_{li}(T_i - T_l) \qquad (3)$$

where Γ" is the condensation mass flux, T_g is the gas-vapor mixture temperature, T_i is the interface temperature, and T_l is the liquid temperature. The condensation mass flux is determined from

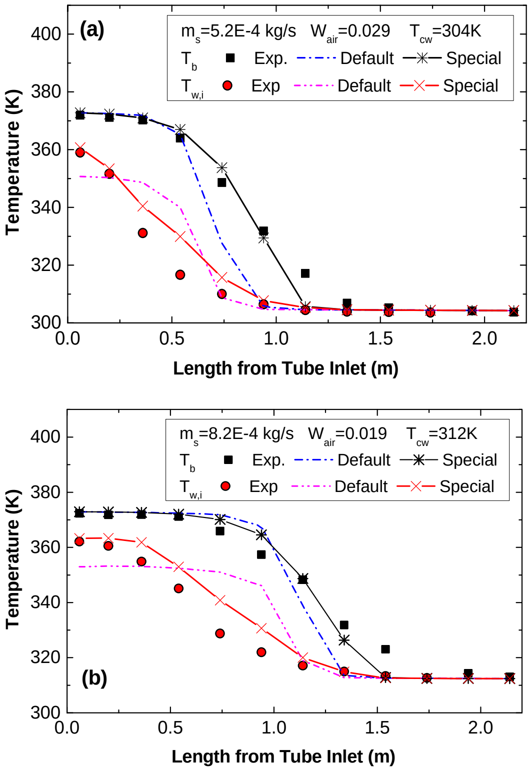

Fig. 3. Temperature profiles along the tube: (a) low inlet steam flow rate, (b) high inlet mass flow rate.

$$\Gamma'' = \left(\frac{\rho_g \cdot D_0}{d}\right) \cdot B_f \cdot Sh \cdot b \qquad (4)$$

where ρ_g is the density of gas-vapor mixture at free stream condition, D_0 is the diffusion coefficient, d is the characteristic length, B_f is the blowing factor, Sh is the Sherwood number, and b is the mass transfer potential.

An iterative solution is used to find the interface temperature (T_i) that satisfies Eq. (3). Once the iterative solution for the interface temperature has conversed, the condensate rate is known and the resulting interfacial HTCs can be determined. The liquid-side interfacial HTC in the presence of NC gases becomes

$$h_{li,NC} = \frac{\Gamma'' \cdot h_{fg}}{(T_l - T_{sv})} = h_{li} \cdot \frac{(T_l - T_i)}{(T_l - T_{sv})} \qquad (5)$$

5. Results and Discussion

The TRACE calculation results are compared with the experimental data. The transient calculations were run for 200 seconds with the maximum timestep size of 0.01s. The predicted values are taken at the end of calculation when the secondary pool temperature reaches experimental value.

Figure 3 shows the comparison of the predicted temperature distributions of gas-vapor mixture and tube inner-surface wall along the condenser tube with experimental data. For the default model, there are large discrepancy between predicted values and experimental

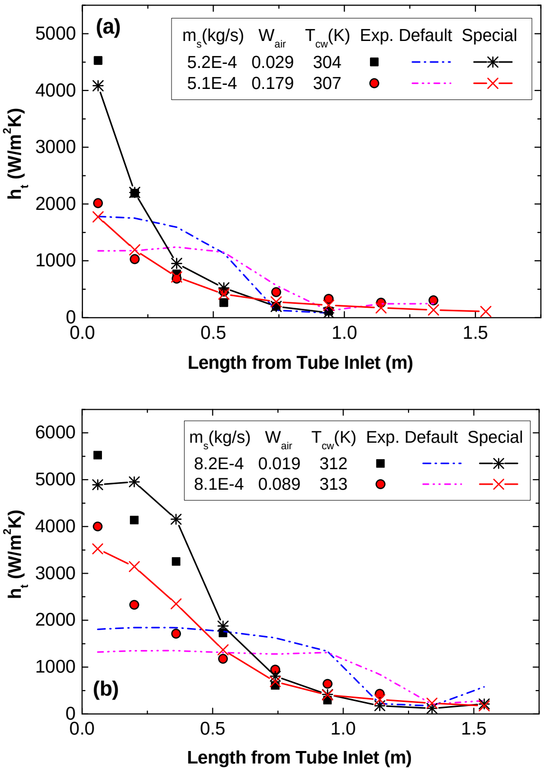

Fig. 4. Predicted HTCs: (a) low inlet steam flow rate, (b) high inlet steam flow rate.

data. When compared with the default model, the special model predicts well the temperature values but tends to over-predict the tube inner wall temperature.

Figure 4 compares the predicted total HTCs with the experimental data. A total of four tests are analyzed. In this comparison, the definition of predicted HTC is consistent with that of experimental data.

As expected from the temperature results, using the default model results in the large discrepancy between predicted HTCs and the data. The original form of default model was developed for subcooled water jets with an air-steam cross flow. It is obvious that the default model is not applicable to counter-current flow configurations of gas-vapor mixture and condensate.

The special model using the mas transfer conduction approach, on the other hand, does a good job of approximating the data with it being a little more accurate at relatively low inlet steam flow rate (Fig. 4(a)). At relatively high inlet steam flow rate (Fig. 4(b)), the predicted values slightly over-predict the total HTC in the high HTC region except the tube entrance region where the model under-predict the HTC.

The results validates that the special condensation model of TRACE provides a good estimate for reflux condensation mode in the presence of NC gases.

6. Conclusions

We assessed the special model for film condensation of TRACE 5.0-patch4 against the data of the reflux condensation test in the presence of NC gases. The special condensation model of TRACE provides a reasonable estimate of HTC with good agreement at the low inlet steam flow rate.

Acknowledgements

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