Evaluation on Prediction Capability of GOTHIC Code for KAERI Single Tube Condensation Experiment

Jae-Ho Bae[a*], Yeon-Jun Choo[a], Hee-Dong Kim[a], Soon-Joon Hong[a]
[a]*Department of Nuclear Thermal-hydraulic Research, FNC Technology Co., Ltd., 46, Tapsil-ro, Giheung-gu, Yongin-si, Gyeonggi-do 446-902, Korea*
[*]*Corresponding author: jhbae0822@fnctech.com*

1. Introduction

New nuclear power plant design that is including the passive safety features has been widely chosen around the world. KHNP (Korea Hydro & Nuclear Power) is currently developing the conceptual design of new generation nuclear power plant equipped with various passive safety systems. Among them, the Passive Containment Cooling System (PCCS) is suggested as new method for mitigating postulated accidents and ensuring the integrity of reactor containment building, and can replace active safety system such as containment spray system.

The condensation heat transfer is one of the most important phenomena in the PCCS heat exchanger. To evaluate a cooling performance and the condensation heat transfer characteristics of the PCCS heat exchanger, KAERI (Korea Atomic Energy Research Institute) has designed and constructed the Condensation Loop for Advanced Safety System in Containment (CLASSIC), a separate effect test facility using a prototypical single bare heat exchanger tube [1]. In this study, the separate effect test on condensation on the surface of a vertical single tube was analyzed by GOTHIC 8.3 code. For reliable analysis about heat removal capacity of prototype PCCS, it is essential to evaluate how well the code predicts condensation heat transfer. The results of GOTHIC were compared with the heat transfer coefficient suggested in the experiment of CLASSIC facility, and the appropriateness of modeling and prediction capability of the GOTHIC were evaluated in this study.

2. Test Facility

The condensation experiments with the single vertical tube were carried out in the CLASSIC facility in order to investigate the condensation heat transfer characteristics of PCCS heat exchanger tube with a prototypical geometry and to generate applicable condensation heat transfer correlation. The CLASSIC facility consists of a Containment Simulation Vessel (CSV), heater producing steam, vertical heat exchanger tube, Passive Condensation Cooling Tank (PCCT), and circulation loop of coolant. The CSV is designed with sufficient volume for simulating the actual condition inside the reactor containment building. An electric heat is a capacity of 360 kW and installed at the bottom of the CSV. The single bare heat exchanger tube is designed to have same equivalent diameter, thickness, and length as the prototypical PCCS heat exchanger [1].

The condensation experiment is conducted in a pressure range of 2 – 5 bar, and air mass fraction ranging from 0.1 to 0.7 as described in Table 1. The KAERI condensation correlation about single tube is proposed as follows:

$$Nu_D = 1.078{Gr_L}^{0.2024}{W_s^*}^{1.2575}Ja^{-0.6196}. \qquad (1)$$

Using the separate effect test results of CALSSIC facility, the heat removal capability of the PCCS is quantitatively evaluated taking into account the effect of non-condensable gas, wall subcooling, and system pressure [1].

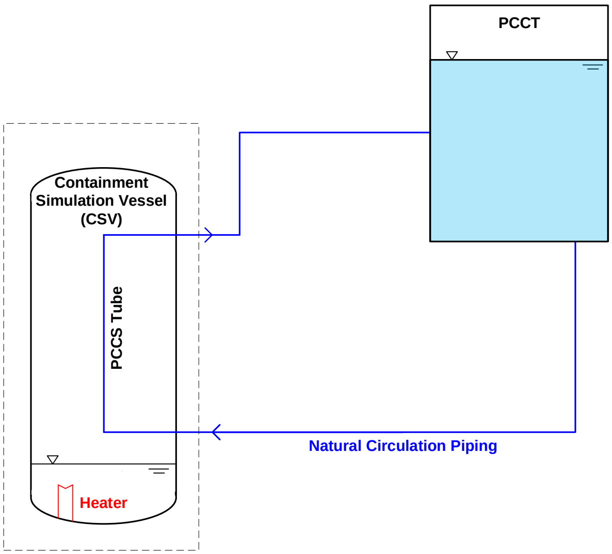


Fig. 1. Schematic diagram of CLASSIC facility

Table 1. Test condition of CLASSIC facility [1]

Parameter	CLASSIC facility
Tube length (m)	5
Tube outer diameter (m)	0.0308
NC gas type	Air
NC mass fraction	0.09 ~ 0.69
System pressure (kPa)	198 ~ 503
Average wall subcooling (K)	39.0 ~ 65.0

3. GOTHIC Input Modeling

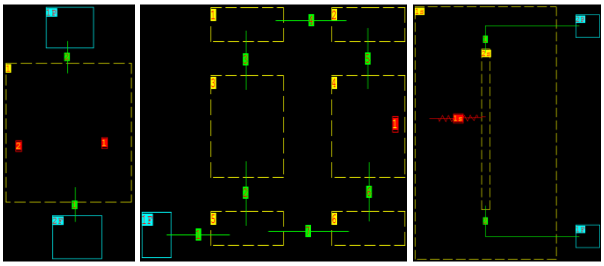
The GOTHIC input models, which are lumped volume model, multi-compartment model and sub-divided volume model, were developed for the condensation experiment with single vertical tube of CLASSIC facility as shown in Fig. 2. Key feature of these modeling includes heat removal capacity of the PCCS heat exchanger tube due to the steam condensation with the presence of non-condensable gas in the CSV under the natural convection situation. In lumped volume model (Fig. 2 (a)), this study only focused on prediction performance of the condensation model when the experimental conditions are maintained. Therefore, the CSV is modeled as one volume and the heat exchanger tube is modeled through a heat conductor component in which wall temperature given in the experiment is fixed. In the condensation experiment of CLASSIC facility, steam is generated through the heater immersed in the water under the CSV as shown in Fig. 1. Instead of modeling of the heater, the generated steam is injected through the flow boundary.

The multi-compartment modeling approach (Fig. 2 (b)) considers the internal flow occurred by condensation on the surface of vertical tube. For that, the CSV is divided so that the volume is 1:1 along the radial direction around the heat exchanger tube. This modeling also does not model the heater, and the heat exchanger tube is modeled using heat conductor component like the lumped model. The supplied steam rate into the CSV is calculated assuming that the amount of injected steam into the CSV is equal to the amount of removed steam by condensation on the surface of the tube as follows:

$$\dot{m}_{stm} = \frac{\bar{h}A(T_{bulk}-T_{wall})}{h_{fg}}. \quad (2)$$

The nodalization of sub-divided volume model is shown in Fig. 2 (c). This modeling can be useful to simulate the multi-dimensional effect in the CSV. In the case of sub-divided model, as shown in Fig. 3, the shape of the CSV is reflected to modeling and the lower heater is also modeled for generating steam. Also, unlike the previous two modeling approaches, the heat exchanger tube is modeled as a hydraulic component to simulate the actual phenomenon as shown in Fig. 4, and it allows heat exchange with the CSV through heat conductor.

For condensation model on the outer surface of heat exchanger tube, the Diffusion Layer Model (DLM) [2] of GOTHIC and the KAERI condensation correlation on single vertical tube (Eq. (1)) are used. Since the GOTHIC can be extended by linking the additional custom for special applications as Dynamically Linked Libraries (DLLs), the KAERI correlation is implemented in the GOTHIC.



(a) (b) (c)

Fig. 2. GOTHIC nodalization on condensation experiment of CLASSIC facility: (a) lumped volume model, (b) multi-compartment model, (c) sub-divided model

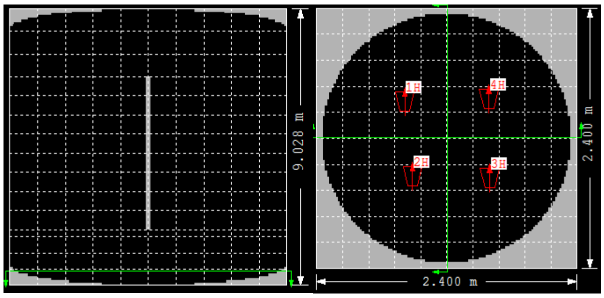


Fig. 3. Details of sub-divided model of CSV

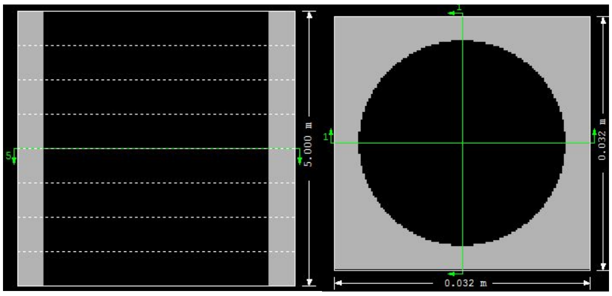


Fig. 4. Details of sub-divided model of heat exchanger tube

4. Results and Discussion

In order to analyze the heat removal capacity of PCCS heat exchanger tube using GOTHIC, the heat transfer coefficients were compared. Figure 5 compares the heat transfer coefficient calculation results of the lumped model with separate effect test data on condensation of CLASSIC facility. In the case of DLM, the heat transfer coefficient is slightly overestimated, however it shows that the results are well matched within +20%. The KAERI correlation shows very good agreement with test data. The GOTHIC analysis results of multi-compartment model are compared with experimental data as shown in Fig. 6. It also shows similar trends and results with lumped model. In the case of sub-divided volume model as shown in Fig. 7, this study selected 8 cases considering the calculation time. The results show that both DLM and KAERI correlation calculate heat transfer coefficient similar to experimental data within ±20%. As a result of comparing the heat transfer coefficient of these three modeling approaches, the GOTHIC accurately predicts experimental data and properly calculates the performance of the heat exchange tube.

Figure 8 shows a comparison of results of all modeling approach. For KAERI correlation, the lumped and multi-compartment models are comparable. In the case of sub-divided model, it seems that the results are slightly different for most cases. The DLM of GOTHIC also shows same effects. This is because it is difficult to maintain steady-state and to make same condition of the CSV and wall temperature with experiment for sub-divided model, since the system pressure and temperature of vapor are kept by the heater and secondary side is modelled as well. Nevertheless, the GOTHIC properly calculates the heat removal capacity for the KAERI experiment. Also, as a result of the three modeling approaches, the difference in the results indicates that the choice of the condensation model is more prominent than in the modeling approach.

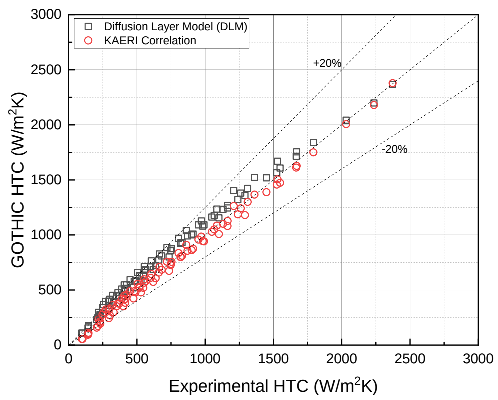


Fig. 5. Comparison of heat transfer coefficient in experiment and lumped volume model

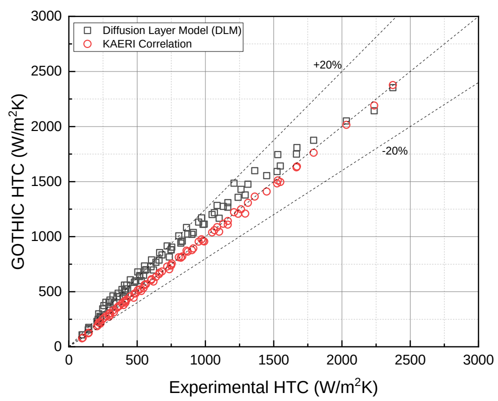


Fig. 6. Comparison of heat transfer coefficient in experiment and multi-compartment volume model

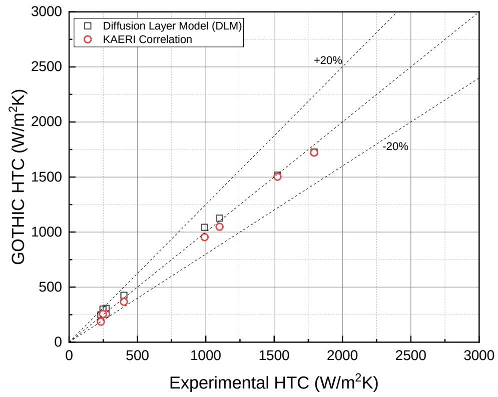


Fig. 7. Comparison of heat transfer coefficient in experiment and sub-divided volume model

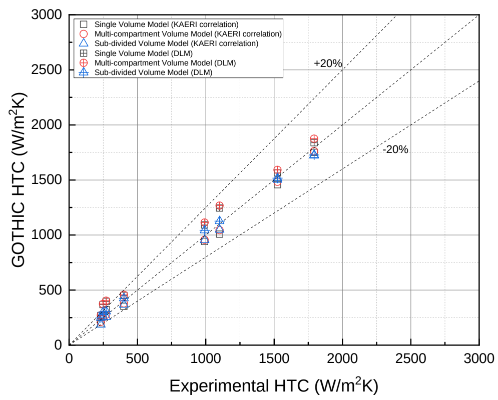


Fig. 8. Comparison of heat transfer coefficients for all modeling

5. Conclusions

In this study, the prediction capability of GOTHIC code is evaluated on condensation heat transfer through separate effect test of CLASSIC facility. Three modeling approaches of lumped volume model, multi-compartment model, and sub-divided volume model were prepared. The results showed very good agreement with test data and gave the useful information about modeling approaches and condensation model.

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