Analysis of air-steam condensation on the surface of vertical tube under forced convection conditions

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1. Introduction

In order to prevent further damage and released radioactive materials to the environment when an accident of Nuclear Power Plants (NPPs) is happened, to ensure the integrity of containment building has been emphasized and is an important issue. After the Fukushima accident, various passive safety systems are being introduced and studying to operate passively, instead of active safety systems, during Station Block-Out (SBO) accident. Among them, Passive Containment Cooling System (PCCS) has been proposed to remove released vapor mass and energy in order to maintain the pressure and temperature of containment building below the design limit.

For nuclear safety analyses related to containment, the GOTHIC code has been conventionally used. The thermal performance of the PCCS is governed by the condensation heat transfer rate of the air-steam mixture. It is essential to evaluate how well the GOTHIC predicts condensation heat transfer phenomenon. In this study, the air-steam condensation experiment under forced convection condition performed in Jeju National University (JNU) was analyzed with the GOTHIC 8.3 version and its results were compared with experiment results to confirm the performance of the GOTHIC code.

2. Air-Steam Condensation Experiment Under Forced Convection Conditions

2.1 JNU Experiment Facility

Jeju National University (JNU) performed the air-steam condensation experiment on the surface of vertical tube under forced convection. The experiment facility is mainly composed of the primary and secondary loops. The primary loop is condensation section and consists of test section which installed tube inside, steam generator, condensation water tank, and recirculation pump. The secondary loop is responsible for supplying cooling water into the inside of vertical tube. The experiment facility is shown in Fig. 1. The steam condensation experiment under forced convection was carried out in section A.

The diameter of test section is 158.4mm and height is 1720mm. A vertical tube of 40mm O.D. and 30mm I.D. is installed inside of the test section and effective length is 1000mm. The steam generated in the steam generator is mixed with air before entering into the vessel. The vapor is condensed on the surface of the tube as it flows from top to bottom of the vessel.

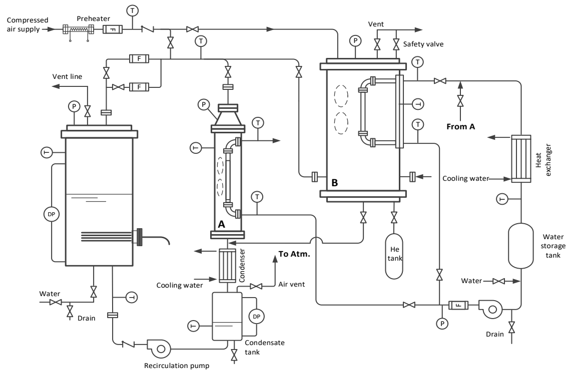


Fig. 1. JNU condensation experimental facility

2.2 Experiment Conditions

The JNU condensation experiment was conducted in a pressure range of 2-4 bar, and air mass fraction ranging from 0.1 to 0.6. The inlet velocity of air-steam mixture is between 0.1 and 0.6 m/s. The injection velocity is obtained by the mass flow rate of the gas mixture as follows:

$$V_{mix} = \frac{\dot{m_{mix}}}{\rho_{mix} A}. \quad (1)$$

The difference of axial heat transfer coefficient of experiment is noticeable, so averaged heat transfer coefficient is calculated as follows:

$$\bar{h} = \frac{1}{L} \int h_j dL. \quad (2)$$

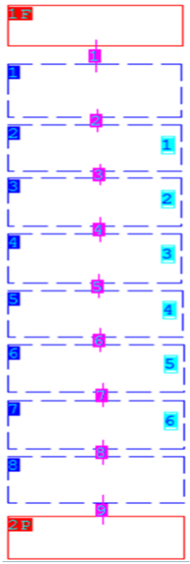
3. The GOTHIC Code Analysis

3.1 The GOTHIC Code Modeling

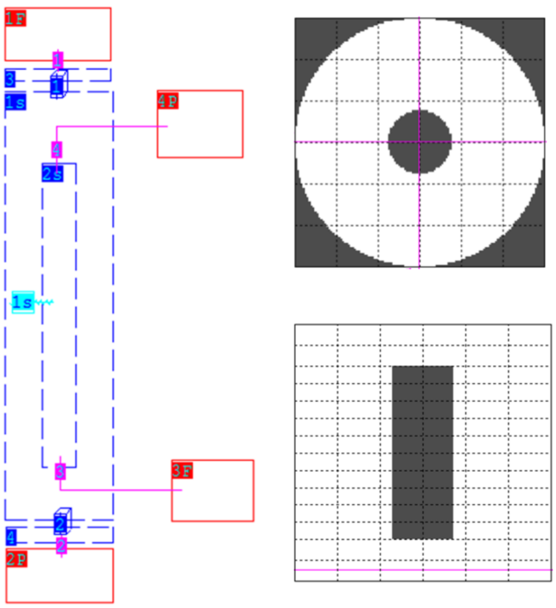
Figure 2 shows the nodalization of experimental facility for the GOTHIC simulation. Fig. 2 (a) is multi-volume modeling, and Fig. 2 (b) is subdivided-volume modeling. In case of multi-volume modeling, the test section is divided into 8 lumped volumes, and 6 volumes in the middle are section in which the heat exchanger tube is located. The secondary side dose not modeled and condensation tube is modeled by adding the experimental wall temperature to the thermal conductor component. In subdivided-volume modeling, the test section is divided into $6 \times 6 \times 12$ volumes, and secondary side also contains in the subdivided modeling.

The heat exchange occurs between the primary and secondary loops through thermal conductor component.

The Diffusion Layer Model (DLM) of the GOTHIC is used for condensation model. The DLM calculates the condensation rate and sensible heat transfer rate using heat and mass transfer analogies [1].



(a) Multi-Volume



(b) Subdivided-Volume

Fig. 2. The GOTHIC nodalization of experiment facility

In the experiment, air was not pre-heated and was mixed with steam before entering in the test section. As a result, air-steam mixture with a temperature lower than saturation temperature was injected into the test section. Since it is not possible to model in the GOTHIC code, the initial conditions and injected vapor conditions was established assuming that the temperature of the mixed vapor being injected is saturated. Since the temperature difference between the experiment and code is not significant, it is judged that this does not cause major error in analyzing the experiment.

3.2 Analysis Results

Figure 3 compares the heat transfer coefficient in the experiment and the predicted heat transfer coefficient according to vapor velocity at 2 bar (Wa: 39%, subcooling: 35-45 K). The heat transfer coefficients calculated in the GOTHIC are shown to be under-estimated than in experiment. This is also shown in Fig. 4. Figure 4 compares the heat transfer coefficient with the vapor velocity at 4 bar (Wa: 36%, subcooling: 36-42 K). Again, the results of the GOTHIC calculations are less than in the experiment. In most cases, the code calculates the heat transfer coefficient low, but when the velocity of vapor is low (approximately 0.1 m/s), the heat transfer coefficient in the experiment and the code are similar. In other words, the GOTHIC code results do not match well when velocity is high or when forced convection is dominant.

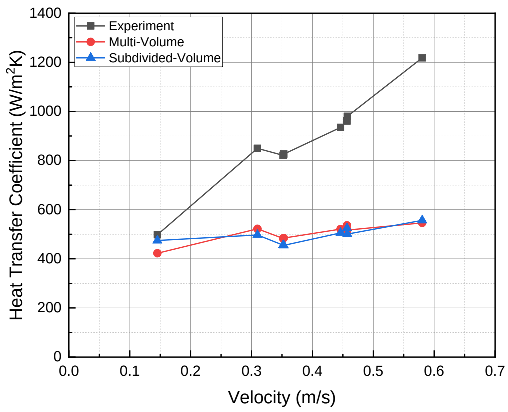


Fig. 3. Heat transfer coefficient according to vapor velocity at 2 bar (Wa: 39%, subcooling: 35-45K)

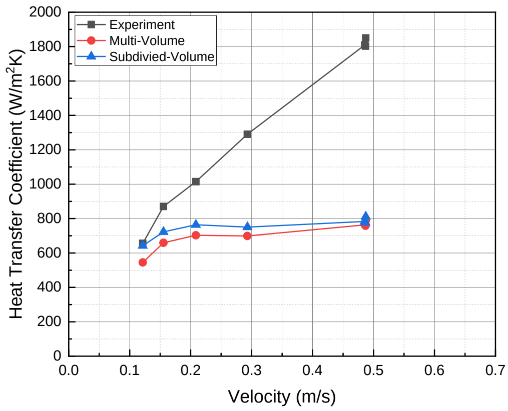


Fig. 4. Heat transfer coefficient according to vapor velocity at 4 bar (Wa: 36%, subcooling: 36-42 K)

Figure 5 and 6 compare the heat transfer coefficients according to the air mass fraction. Figure 5 shows the result of heat transfer coefficient at 0.3 m/s vapor velocity in 2 bar (subcooling: 32-36 K), and Fig. 6 shows results when the vapor velocity is 0.19 m/s in 2 bar (subcooling: 28-45 K). In most results, the calculated heat transfer coefficient is predicted lower than the experimental heat transfer coefficient. As with the previous results, heat transfer coefficients are calculated more similarly to experiment when vapor velocity is low as shown in Fig. 6. And, in the case of low air mass fraction about 0.1, heat transfer coefficient of the GOTHIC is larger than experiment.

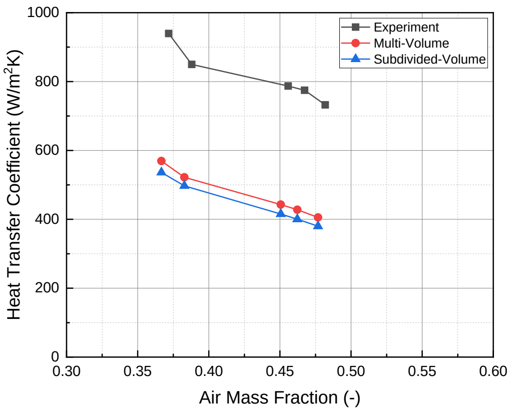


Fig. 5. Heat transfer coefficient according to air mass fraction at 2 bar (velocity: 0.30 m/s, subcooling: 32-36 K)

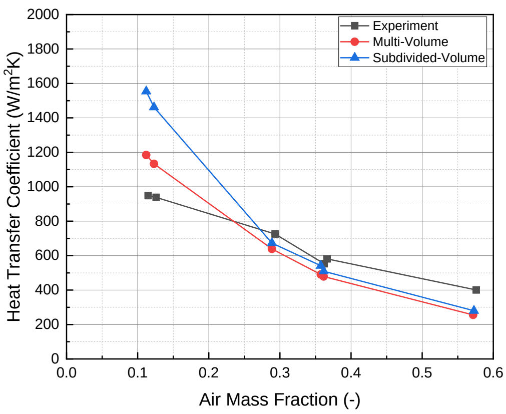


Fig. 6. Heat transfer coefficient according to air mass fraction at 2 bar (velocity: 0.19 m/s, subcooling: 28-45 K)

Figure 7 shows a comparison of the total heat transfer coefficients of the experiment with the heat transfer coefficients of the GOTHIC. Most of the calculated heat transfer coefficients are lower than the experimental values. In experimental cases with low air mass fraction, the GOTHIC shows that the heat transfer coefficient is highly predicted compared to the experiment.

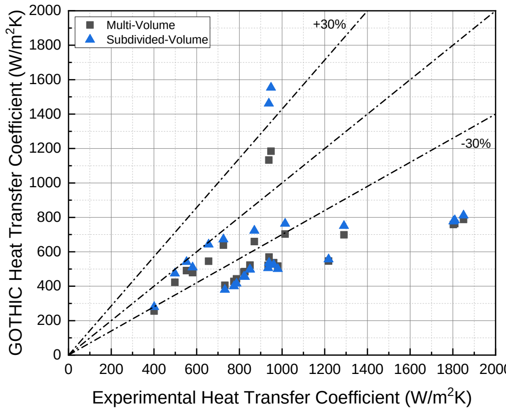


Fig. 7. Comparison of heat transfer coefficient in experiment and heat transfer coefficient in the GOTHIC code

3. Conclusions

In this study, air-steam condensation experiment under forced convection conditions conducted by JNU is analyzed using the GOTHIC code. In most cases, the heat transfer coefficient calculated by the GOTHIC code is under-estimated. In most cases, the heat transfer coefficient calculated by the GOTHIC code is under-estimated. On the other hand, when the air mass fraction is low, the GOTHIC code calculates the heat transfer coefficient higher than the experiment. That is, the GOTHIC code predicts conservatively low heat transfer coefficient. In the present results, the heat transfer coefficients calculated by the GOTHIC code are not suitable at higher velocity and at lower air mass fraction.

4. Future Works

Unfortunately, the calculation results of the GOTHIC code are lower than the experimental value. To improve this, various condensation models are to be used for evaluation. A review of the conditions of the experiment is necessary.

5. Acknowledgement

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[1] EPRI, GOTHIC Thermal Hydraulic Analysis Package Technical Manual Version 8.3(QA), Electric Power Research Institute, 2018