Gas Stratification and Condensation Heat Transfer in Steam-Air-Helium Mixture

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1. Introduction

Vapor condensation has been applied to various industrial systems, especially in nuclear power plants [1-4]. However, the potential deterioration of condensation heat transfer coefficient in presence of noncondensable gas has not been fully identified. Especially, the effect of light gas on condensation heat transfer and gas stratification should be evaluated. This is because the H2 could be present in the mixture gas in case of a severe accident including core melt in nuclear power plant [5]. To investigate the effect of additional light gas in the mixture, helium was considered for the experiments as a surrogate for H_2 in the previous studies [6-9]. However, there is a lack of data to evaluate the effect of light gas on condensation heat transfer coefficient.

In this study, we discuss the experimental result which has been conducted at Jeju National University. We focused to identify how the light gas affects the condensation heat transfer and the condition that can cause the gas stratification. Furthermore, we evaluate the parameters that have a dominant effect on the heat transfer coefficient.

2. Methods and Results

2.1 Experimental Facility and condition

An experimental study was performed in the condensation test facility as shown in Figure 1[10-11]. The facility comprises a steam generator, condenser, condensate tank, test tank, and a pump as shown in Figure 1. The facility was modified to measure the mole fraction of helium to noncondensable. For that, we constructed a gas sampling system which includes gas sampling lines, helical cooling tubes, condensate tanks, moisture filters, micropumps, and gas analyzers (FTC300, Messkonzept GmbH) as shown in Figure 2.

For identifying the deterioration of heat transfer coefficient because of the light gas, the mole fraction of helium to noncondensable gases (X_{He}/X_{nc}) is considered from 0.1 to 0.5 and the mass fraction of noncondensable gas ($W_{nc}=W_{Air}+W_{He}$) was ranged from 0.1 to 0.7. The pressure of the test tank was maintained to be 3.0 bar in every case. The inlet temperature of condensing water and the flow rate were controlled to control the wall subcooling degree on the condenser tube at 40 K in every case. The test condition was set to sustain the desired mass fraction of steam, the mole fraction of helium to noncondensable gas, and the subcooling degree.

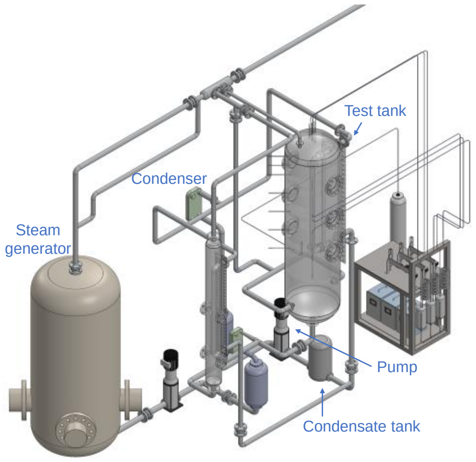

Figure 1. Drawing of test facility

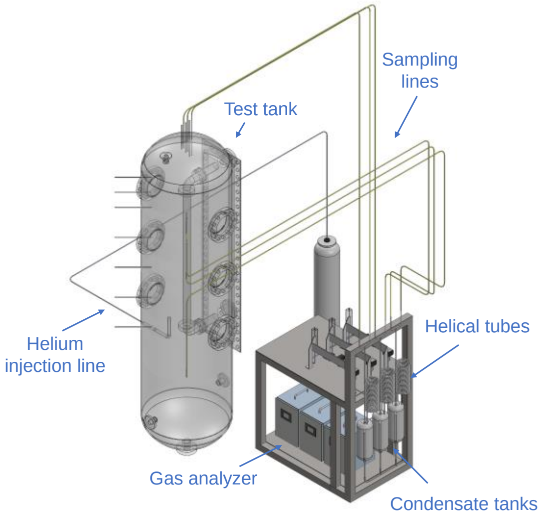

Figure 2. Drawing of gas sampling system

2.2 gas stratification

Figure 3 presents temperature profiles along with the height of the test tank. We determined the occurrence of gas stratification based on the temperature profiles along with the height. Furthermore, we observed the increases of mole fraction of helium to noncondensable gas at the corresponding locations. The degradation of gas temperature in the upper part was observed where the mole fraction of helium is high and the mass fraction of noncondensable gas is low as shown in Figure 4. The criteria to determine the stratification is 1.5K of temperature difference in 500 mm of height. Evaluation of the heat transfer coefficient was considered for the cases without gas stratification.

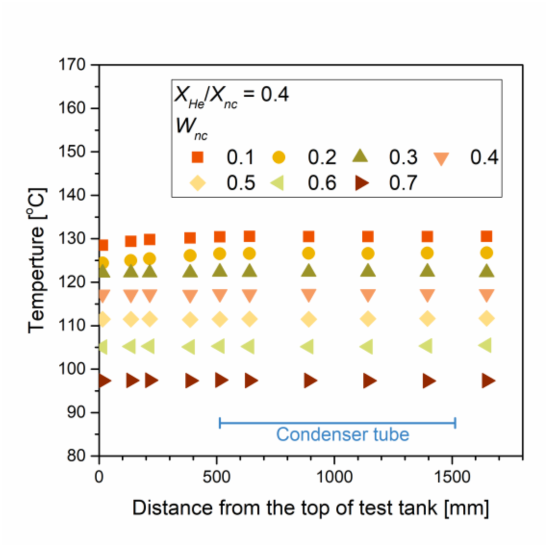

Figure 3. Temperature profiles in test tank

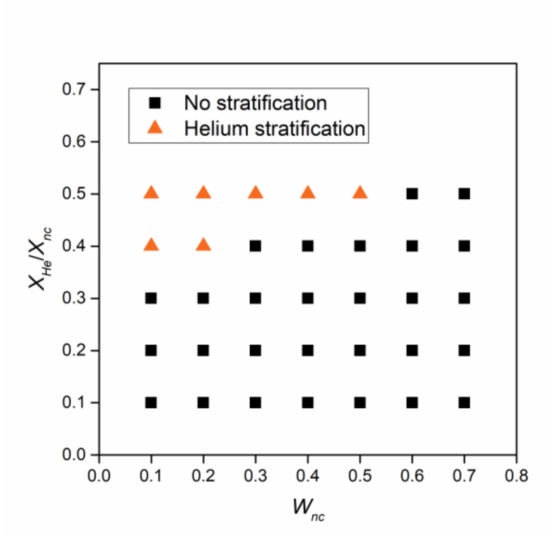

Figure 4. Conditions for gas stratification

2.3 Condensation heat transfer coefficient

We measured the condensation heat transfer coefficient as depicted in Figure 5. We can observe that the heat transfer coefficient decreases as the mass fraction of noncondensable gas increases and the mole fraction of helium to noncondensable gas increases. We evaluated the correlation for predicting the heat transfer coefficient as shown in Figure 6. We used correlations for the heat transfer coefficient and the diffusion coefficient (model-2) from the previous studies as [6, 12]:

$$h = CD^{\frac{2}{3}}(\rho_w + \rho_b)\left(\frac{\rho_w - \rho_b}{\mu}\right)^{\frac{1}{3}} \frac{h_{fg}}{(T_b - T_w)} \ln\left(\frac{1 - W_{s,w}}{1 - W_{s,b}}\right).$$

where C is 0.163 for the steam-helium-air mixture and 0.185 for the steam-air mixture.

It shows that the predicted condensation heat transfer coefficient has a good agreement with the experimental data in a sigma level. Further investigation to identify the effect of subcooling and the pressure will be performed in the condition of the presence of light gas in noncondensable gas.

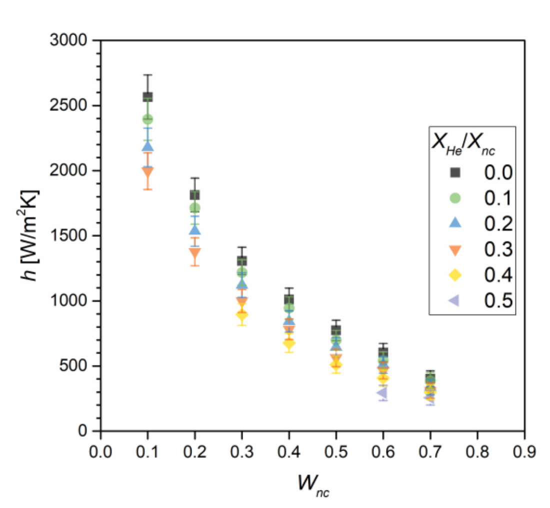

Figure 5. Measured condensation heat transfer coefficient

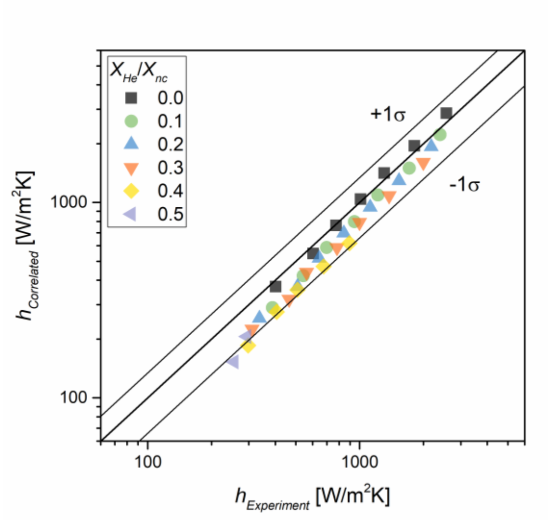

Figure 6. Evaluation of models for condensation heat transfer coefficient

3. Conclusions

The experimental facility was modified to measure the mole fraction of helium to noncondensable gas. The gas stratification was observed when the mass fraction of noncondensable gas is low and the mole fraction of helium to noncondensable gas is high. We measured the condensation heat transfer coefficient. The model to predict the heat transfer coefficient was evaluated by the experimental data.

Acknowledgments

The authors acknowledge Dr. Jongtae Kim of Korea Atomic Energy Research Institute for technical advice regarding helium measurement system in the test facility. This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean Government (MSIT) (NRF-2019M2D2A1A01059317).

References

[1] Hao, C., Liu, Y., Chen, X., Li, J., Zhang, M., Zhao, Y., & Wang, Z. (2016). Bioinspired interfacial materials with enhanced drop mobility: From fundamentals to multifunctional applications. Small, 12(14), 1825-1839.

[2] Huang, Z., Hwang, Y., & Radermacher, R. (2017). Review of nature-inspired heat exchanger technology. International Journal of Refrigeration, 78, 1-17.

[3] Cho, H. J., Preston, D. J., Zhu, Y., & Wang, E. N. (2016). Nanoengineered materials for liquid–vapour phase-change heat transfer. Nature Reviews Materials, 2(2), 1-17.

[4] Oh, J., Birbarah, P., Foulkes, T., Yin, S. L., Rentauskas, M., Neely, J., ... & Miljkovic, N. (2017). Jumping-droplet electronics hot-spot cooling. Applied Physics Letters, 110(12), 123107.

[5] Dehbi, A. (2016). A unified correlation for steam condensation rates in the presence of air–helium mixtures under naturally driven flows. Nuclear Engineering and Design, 300, 601-609.

[6] Dehbi, A. A. (1990). Analytical and experimental investigation of the effects of noncondensable gases on steam condensation under turbulent natural convection conditions. US: MIT.

[7] Liu, H., Todreas, N. E., & Driscoll, M. J. (2000). An experimental investigation of a passive cooling unit for nuclear plant containment. Nuclear engineering and design, 199(3), 243-255.

[8] Su, J., Sun, Z., Fan, G., & Ding, M. (2013). Experimental study of the effect of non-condensable gases on steam condensation over a vertical tube external surface. Nuclear Engineering and Design, 262, 201-208.

[9] Anderson, M. H., Herranz, L. E., & Corradini, M. L. (1998). Experimental analysis of heat transfer within the AP600 containment under postulated accident conditions. Nuclear Engineering and Design, 185(2-3), 153-172.

[10] Kim, U. K., Yoo, J. W., Jang, Y. J., & Lee, Y. G. (2020). Measurement of heat transfer coefficients for steam condensation on a vertical 21.5-mm-OD tube in the presence of air. Journal of Nuclear Science and Technology, 57(8), 905-916.

[11] Lee, Y. G., Jang, Y. J., & Choi, D. J. (2017). An experimental study of air–steam condensation on the exterior surface of a vertical tube under natural convection conditions. International Journal of Heat and Mass Transfer, 104, 1034-1047.

[12] Benteboula, S., & Dabbene, F. (2020). Modeling of wall condensation in the presence of noncondensable light gas. International Journal of Heat and Mass Transfer, 151, 119313.