Transactions of the Korean Nuclear Society Spring Meeting
KNS Autumn Meeting 2022. October 19-21. Changwon Exhibition Convention Center

Gas stratification of the steam-air-helium mixture under condensing condition for steady and transient states

Il Woong Park[1], Jia Yu[2], Yeon-Gun Lee[2*]

[1] Department of Mechanical Engineering, Inha University, Republic of Korea
[2]Department of Nuclear and Energy Engineering, Jeju National University, Republic of Korea
Corresponding author: yeongun2@jejunu.ac.kr

1. Introduction

Vapor condensation is an important phenomenon for various industrial systems, including nuclear systems [1-4]. Especially, a passive containment cooling system (PCCS) has been considered to control the containment pressure after accidents in a nuclear power plant [5-6]. Meanwhile, it has been reported that the additional hydrogen should be considered for this system in terms of degradation of heat transfer and gas stratification [7-11]. To understand the behavior of light gas in terms of nuclear safety, studies have been performed internationally [12]. However, it was commented that the details of the hydrogen distribution have not been well studied. Thus, it would be important to perform experiments to study the details of the behavior of light gas.

In this study, we performed experiments to investigate the gas stratification occurred by injecting helium as an inert substitute for hydrogen. Especially, tests were performed in the presence of the condensing tube that has been considered as part of PCCS and can play a role to circulate the gas. We considered both steady and transient states for injecting light gas. We observed the stratification of temperature and helium concentration along the height for various conditions in the steady state. Moreover, we observed the occurrence of stratification during the helium injection by varying the flow rate in the transient condition.

2. Methods and Results

2.1 Experimental Facility and condition

We performed experiments in the condensation test facility as depicted in Figure 1 [13-14]. It includes a test tank, a steam generator, a pump, a condenser, a pre-heater, and a heat exchanger. Furthermore, there are sampling lines, helical tubes, condensate tanks, and three gas analyzers (FTC300, Messkonzept GmbH) to measure the helium concentration after removing steam. The helium concentration and the temperature at close points can be measured at six points in the test tank as shown in Figure 2. It was possible to measure three points at the same time.

In this facility, we can control the conditions of the gas composition, such as the mass fraction of noncondensable gas, and mole fraction of helium to noncondensable gases. The location and the direction of helium supply line are also described in Figure 2.

The condition for the experiment is described in table 1. To identify the occurrence of gas stratification in a steady-state condition, the mole fraction of helium to noncondensable gases (X_{He}/X_{nc}) is considered from 0.1 to 0.6 and the mass fraction of noncondensable gas ($W_{nc}=W_{Air}+W_{He}$) was varied from 0.1 to 0.7. We selected 891 mm from the top of the test tank as the reference location for representing the helium concentration of the test condition. The pressure was maintained at 3.0 bar and the wall subcooling on the condenser tube was 40 K in every case. In the transient state, the pressure was increased from 2 bar to 4 bar by injecting helium. And the initial condition for the mass fraction of noncondensable gas was 0.5 and for the mole fraction of helium to non-condensable gas was zero. The wall subcooling degree was 40 K for the initial condition.

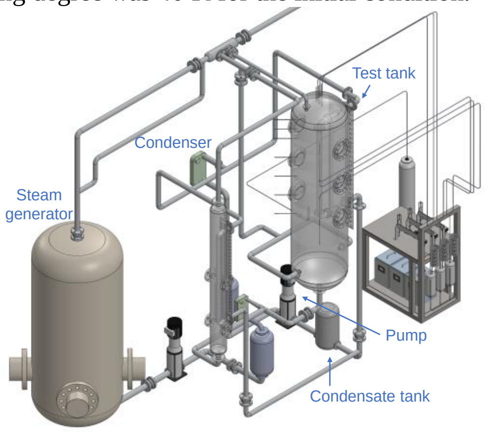

Figure 1. Drawing of test facility

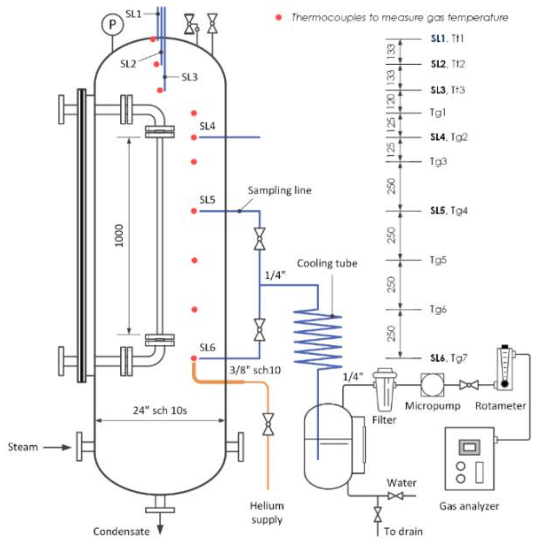

Figure 2. Helium measurement system

Table 1. Experimental conditions

Conditions	P [bar]	W_{nc}	X_{He}/X_{nc}
Steady-state	3	0.1 – 0.7	0.1 – 0.6
Transient	2 → 4	0.5 (at t=0)	0→ 0.6

2.2 Gas stratification in steady state

Figure 3 shows the conditions of gas stratification which was determined by the criteria whether the gas temperature difference in 500 mm of height exceeds 1.5 K. We can observe that gas stratification easily occurs in the high mole fraction of helium to noncondensable gas and in the low mass fraction of noncondensable gas.

Figures 4 and 5 present the temperature profile and the mole fraction of the helium profile. Based on the profiles the partial pressure was calculated as shown in Figure 6. In the case of 0.5 of the mole fraction of helium to noncondensable gas, we can observe the drastic decrease of helium pressure along the elevation for the low mass fraction of noncondensable gas while there is no gas stratification with the high mass fraction of noncondensable gas.

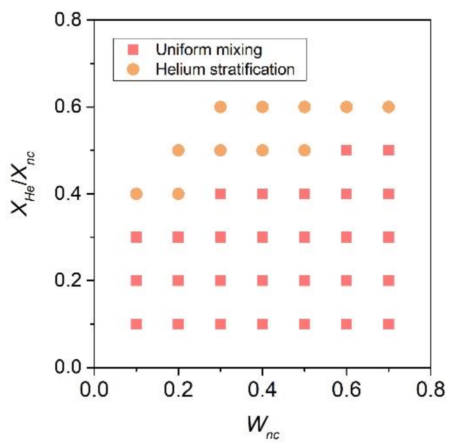

Figure 3. Conditions for gas stratification

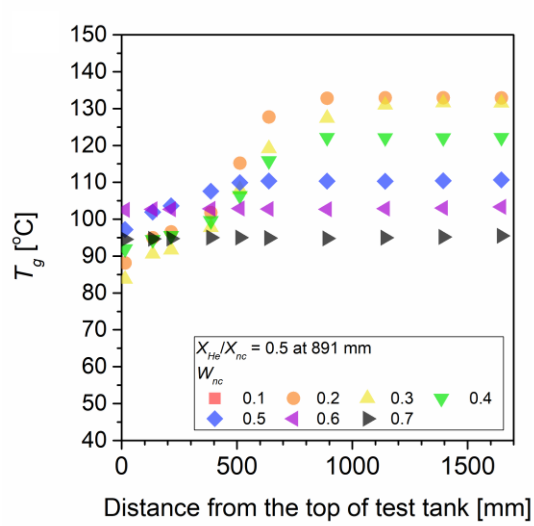

Figure 4. Temperature profile

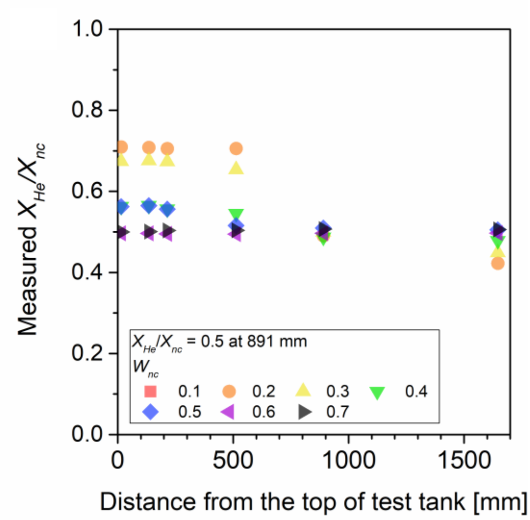

Figure 5. Helium concentration profile

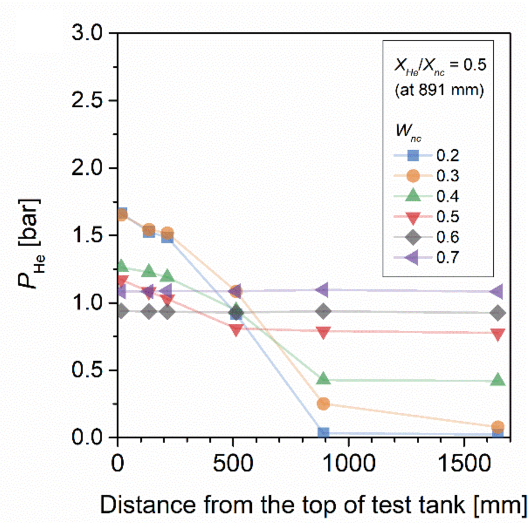

Figure 6. partial pressure profile

2.3 Gas stratification in transient state

For the transient case, we set the initial condition as described in Table 1. After that, we injected helium as shown in Figure 7. We aimed to inject the same amount of helium by varying the flow rate. The injection was terminated when the system pressure reached 4.0 bar. Based on the temperature profile and the helium fraction profile from the gas analyzers, we obtained the transient profile of partial pressures for steam, air, and helium as shown in Figure 8. On the upper side, close to the top of the test tank (15 mm distance from the top of the test tank), the injected helium was accumulated after the injection was triggered. However, there was a delay in the increase of helium pressure in the case of the lower side (891 mm of distance from the top of the test tank). Note that, a drastic increase in steam pressure was observed on the lower side while it was not observed on the upper side. It would be possible to explain that there is a propagation of a steam rich layer to the bottom when there is an injection of helium and the condensing tube.

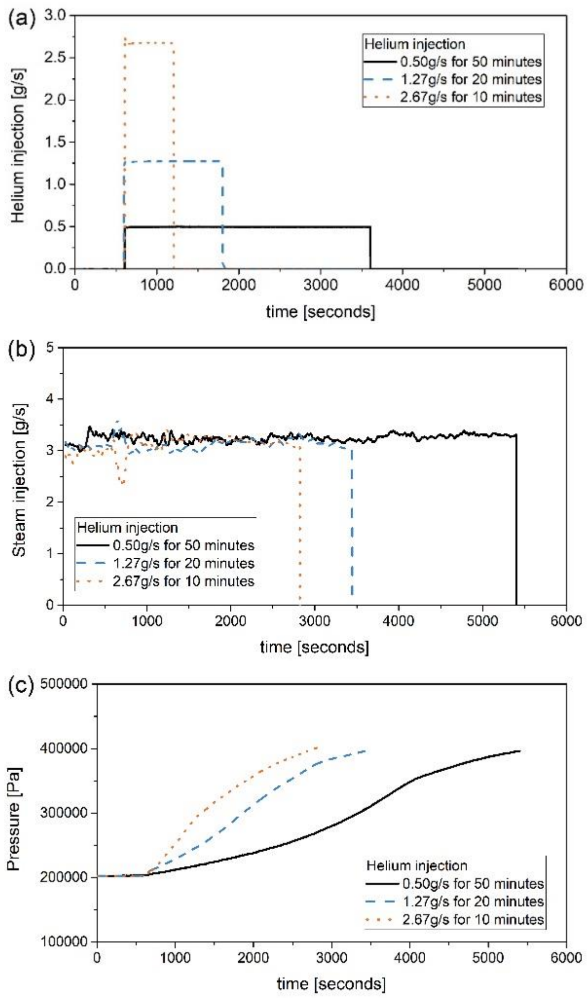

Figure 7. Gaseous conditions (a) Helium injection, (b) steam injection, and (c) pressure

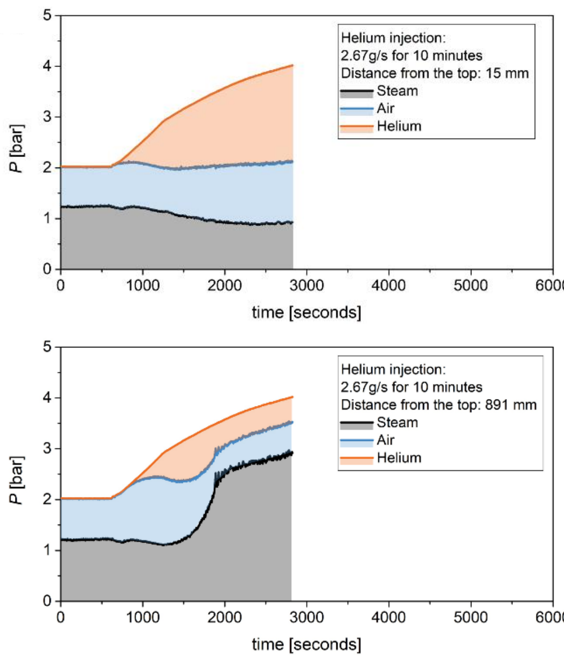

Figure 8. Partial pressure under transient condition

3. Conclusions

The experiments for gas stratification of the steam-air-helium mixture because of helium injection with a single condensing tube were conducted for steady state and transient states. We measured the temperature profile and helium fraction profile along the elevation. From that, we could find the condition for gas stratification and discuss the process of gas stratification.

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, RS-2022-00144355).

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] Oh, S., & Revankar, S. T. (2006). Experimental and theoretical investigation of film condensation with noncondensable gas. International Journal of Heat and Mass Transfer, 49(15-16), 2523-2534.

[6] Caruso, G., & Di Maio, D. V. (2014). Heat and mass transfer analogy applied to condensation in the presence of noncondensable gases inside inclined tubes. International journal of heat and mass transfer, 68, 401-414.

[7] 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.

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

[9] 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.

[10] 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.

[11] 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.

[12] Agrawal, N., Prabhakar, A., & Das, S. K. (2015). Hydrogen distribution in nuclear reactor containment during accidents and associated heat and mass transfer issues—a review. Heat Transfer Engineering, 36(10), 859-879.
[13] Park, I. W., Yang, S. H., & Lee, Y. G. (2022). Degradation of condensation heat transfer on a vertical cylinder by a light noncondensable gas mixed with air-steam mixtures. International Communications in Heat and Mass Transfer, 130, 105779.
[14] Park, I. W., Yang, S. H., & Lee, Y. G. (2021). Effect of light gas on condensation heat transfer of steam–air mixture and gas stratification. International Journal of Heat and Mass Transfer, 179, 121716.